AN INTERNATIONAL SURVEY OF SHOCK AND VIBRATION TECHNOLOGY

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Henry C. Pusey, Rudolph H. Volin,
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PREFACE

This report may well be the first of its kind. It is a very broad survey of a technology from an international viewpoint. There was no attempt to cover any subject within the technology in great depth. This would be impractical in a report of this scope, since each subject area in the shock and vibration field could well be the topic for a treatise all its own. The many references cited were for the purpose of indicating trends, and, perhaps, to offer some direction to those interested in specific areas covered in this report. Of the more than 7000 abstracts scanned, there are undoubtedly many worthy works that were not cited herein. In this case, omission is not to be taken as criticism, for that was not the intent of the authors.

The word "technology" is used frequently. Sometimes it is misused. Webster defines the term both as "technical language" and "applied science". In this report, both of these definitions are applicable. The intent here is to view international research and development efforts involving the technology of shock and vibration for the purpose of establishing trends in progress and to gain some insight regarding future research requirements. It is, in fact, urgent requirements or needs that provide most of the incentives leading to technological advancements which also fosters applied and basic research.

It is quite clear to the authors of this report that technical advancements in shock and vibration are truly international in scope. All of the countries mentioned herein have significant interests and capabilities in the various aspects of the technology that are applicable to their own requirements. It is equally clear that all countries mentioned would derive significant benefit from free interchange of technical information on an international basis. There are some major barriers, such as language, but these problems can be overcome. In this connection, the authors are very grateful for the many in-depth responses to a letter of inquiry sent to experts outside the United States. The spirit of cooperation shown by these responses is testimony to the fact that it is not all that difficult for different countries to learn from one another.

In a report of this scope it seems probable that certain areas will have been covered too lightly, or some may have been inadvertently omitted. The authors would be pleased to have the readers call attention to any such deficiencies. Any comments related to the usefulness of this report would also be appreciated.

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INTERNATIONAL TECHNOLOGY - AN OVERVIEW

INTRODUCTION

The preparation of this survey has been both a difficult and an interesting task. Even with the care that was exercised in conducting the survey, there are surely areas that are not adequately covered. The broad scope of the study inhibits its usefulness for specific applications. There are language barriers which tend to eliminate much useful work from an english language survey. Proceedings of important conferences are sometimes difficult to find and copies are not readily available. In general, the machinery for assuring completeness in such a survey is only partially developed.

On the plus side, it is felt that we have made a good beginning. Many outstanding technical organizations and their areas of expertise have been identified in this report. Significant interest and cooperation is indicated by the excellent response to the mail survey. We are encouraged to continue the dialogue and to expand on it. Work is already underway to extend the study with respect to countries in the eastern world. Consideration is being given to increasing the depth of analysis for more specific technological areas within the shock and vibration field. Ever increasing interchange of technical information on an international basis can have immeasurable beneficial effects.

TECHNOLOGY GROWTH

One way to look at the growth of technology is to study the evolution of scientific study from the development of general basic concepts to more specific applications of these concepts. In this survey, this kind of trend is evident. It is sometimes called vertical technology transfer. In the shock and vibration field, the most noticeable contributions are applications. These applications are spurred by increasing performance requirements for new, more sophisticated systems. The basic analytical and materials developments generally do not receive much publicity until they are applied in this way, much the same as a work of art that can not be appreciated until it is on display. At the same time, many new techniques are not as widely accepted as they could be. For shock and vibration applications, these include techniques related to statistical energy analysis, mobility or mechanical impedance, optimization, and parameter identification. Wider application requires a broader understanding of the basic concepts.

It is encouraging to note that the use of analytical methods to solve shock and vibration problems is significantly on the increase and, furthermore, that the results of these analyses are more believable. This is true in spite of the fact that a large portion of our progress is based on a design-test-fix-test kind of philosophy. The advantage of this philosophy is that it has led to the rapid advancements in test hardware and software, the computer-controlled test and on-line data analysis capabilities that we now enjoy. Along similar lines, the rapid growth of computer program capabilities enhances our analytical potential. Increased emphasis on modeling and methods of software evaluation will make this potential even greater.

Developments in materials and materials properties seems to have kept pace with requirements, although increased emphasis is expected in such areas as damping, damping materials, fatigue and composite materials development. Methods for understanding the properties of these new materials and their response to dynamic loads are rapidly being developed, usually as required by some special application. Instrumentation techniques, such as acoustic emission, have enhanced our ability to detect imminent material and structural failure.

In general, it is felt that we can look at the growth of our technology with a touch of pride regarding our progress. This progress has been driven mainly by new systems development efforts around the world. The indicators seem to show that our technology will continue to grow, perhaps at an accelerated rate, as new systems evolve from concept to reality. The basic food to nourish our progress will come from the inventiveness of our fundamental researchers. The progress will be fulfilled by the creative ability of engineers and scientists to solve practical problems.

USING THIS REPORT

There is a comprehensive Table of Contents, as well as a subject index, to guide the reader to areas of particular interest. For summary discussions, the reader is referred to Chapter 9. Only those references published by the Shock and Vibration Information Center are available therefrom. U.S. Government Reports and certain foreign publications may be obtained from the National Technical Information Service, Springfield VA 22151, by citing the AD-, PB-, or N-number. Most doctoral dissertations are available from University Microfilms (UM), 313 N. First Street, Ann Arbor, MI. All other publications must be requested from the source.

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Chapter 1

BACKGROUND AND APPROACH

INTRODUCTION

The rate of development of new science and technology continues to increase both in the United States and abroad. Charles M. Huggins, General Electric's manager for international programs, has assumed that 60 percent of all new developments originate outside the United States. Whether or not this estimate is correct is not really relevant. What is of concern is whether new technology flows as readily into the United States as domestically-financed research results are made available to our friends abroad. This does not appear to be the case.

About 75 percent of all scientific and technical papers produced in the United States are offered for sale by the National Technical Information Service (NTIS). Approximately 10 percent of NTIS sales are to foreign countries, indicating an aggressive pursuit of U. S. technology by key countries around the world. Most other countries have nothing resembling NTIS. They cannot be criticized for this, nor can the U.S. Government be criticized for establishing NTIS. Rather, these facts provide a signal that the United States, in its own best interests, should change its present indolent pursuit of foreign technology into a very active program.

There is ample evidence to support this need. Dr. Ruth M. Davis in the keynote address at the DoD Materials Technology Conference, February 1978, said, "In a global sense, it must be concluded that the U. S. is no longer the world leader in Materials Technology." Dr. Alan M. Lovelace said at a meeting of the AIAA, "Yet, we see a growing overseas competition in areas where the United States has traditionally been a leader; high power transmitters, low-cost space systems, efficient small receivers, effective use of very high frequencies--these are becoming the province of other national industries such as the Japanese, the Germans, and the Canadians."

Is the U. S. at the forefront in all phases of shock and vibration technology? Are there developments in other free world countries that would assist us in advancing our own Navy, DoD and NASA shock and vibration programs? This study, performed by the Shock and Vibration Information Center under the sponsorship of the Naval Material Command, was conducted to answer these questions and to identify potentially useful foreign research results and their areas of application.

BACKGROUND

The Shock and Vibration Information Center (SVIC) came into existence late in 1946 as the Centralizing Activity for Shock and Vibration, serving only R & D elements of the Navy. The importance of foreign interchange was recognized even then, and technical information was mutually shared, under an appropriate national security blanket, with the U. K., Canada and Australia. In 1949 SVIC became a DoD activity and continued as such until it evolved into a DoD Information Analysis Center in 1964. As limitations permitted, foreign technology was intermingled with that of the U. S. in the Shock and Vibration Bulletin and other SVIC publications. In 1969, with the creation of the Shock and Vibration Digest, the first systematized collection of foreign technical papers began. The collection has grown over the years and the information has been used, as appropriate, in response to many user inquiries. Until now, however, there has been no organized SVIC effort to assess foreign developments as related to U. S. efforts with a view to determining the application of this information to domestic R & D programs. With the encouragement and sponsorship of the Naval Material Command, this study represents a first effort toward that end.

PURPOSE

The purpose of this study is to review and assess the state of shock and vibration technology in the United States and other Free World countries, to determine the relative status of this technology in the United States as compared to other countries, and to identify advances in foreign technology which could be used to complement domestic capabilities and Navy needs.

SCOPE

Information examined in this study includes shock, vibration, acoustics and related dynamics areas from the standpoint of analysis, design, measurement, testing and application. Areas in which advancement is significant are emphasized. The technical output from all Free World countries was examined, but only those countries with significant interest in dynamics discussed in this report.

APPROACH

The first step in the study was a complete search of the Free World literature. An initial search using the Shock and Vibration Digest and Data Base produced more than 7000 abstracts of technical papers and reports from around the world since 1975. Trial searches of other sources including NTIS, Engineering Index, Applied Mechanics Reviews and NSF Grants were conducted and compared with the results of the first search. It was established that the first search provided substantially complete information, therefore, the information obtained from that search forms the basis for discussion of published information in this report.

Letters were written to key investigators in the United States inquiring after their suggestions concerning colleagues in other countries worthy of contacting during this survey. More than 400 letters were dispatched to scientists in 21 countries concerned with various aspects of shock and vibration using names provided from the U.S. survey coupled with selected authors revealed during the search. The responses received from this survey were incorporated in this report as discussion of work-in-progress, principal interests, and areas of the technology in need of further investigation. A sample of the letter sent and a list of the scientists responding are included as Appendix A to this report.

Examination of the search results revealed that 21 countries have generated information on shock and vibration which has been selected to be included in this report. For convenience, some countries have been grouped for discussion as a unit. Thus, through the report the following 13 countries or groups will be discussed as separate units relative to the United States:

1. Australia - New Zealand
2. United Kingdom
3. Canada
4. France
5. India
6. Israel
7. Italy - Greece
8. Japan
9. Netherlands - Belgium
10. Sweden - Norway - Denmark
11. Switzerland
12. West Germany
13. Other countries

The technology has been assessed in a special categorical breakdown as discussed in the following section.

TECHNOLOGY BREAKDOWN

Shock and vibration technology is extremely complex, defying simple definition, since it is applications oriented. In the real world there are both man-made and natural dynamic loads produced that can have deleterious effects on equipment, structures, and people. The more advanced and complex our society becomes, the more dynamic loads from various sources are likely to be produced. Increased loads are produced by increased requirements for power and speed. This, coupled with increased limitations on size and weight, the tendency toward more flexible structures, and greater requirements for noise reduction, increase the difficulty of the technical problem.

For this report, a technological breakdown has been chosen which has proved to be successful and efficient for the storage and retrieval of shock and vibration technical information. There are seven major category headings as follows:

1. Analysis and Design
2. Computer Programs
3. Environments
4. Phenomenology
5. Experimentation
6. Components
7. Systems

The Analysis and Design category includes the mathematical and analytical techniques available to calculate or predict responses to dynamic loads and the application of these techniques to particular design problems. For example, Nonlinear Analysis, Optimization Techniques, Statistical Methods, Finite Element Methods, Modal Analysis and Synthesis fall into this category. Included in the Computer Programs section would be newly developed shock and vibration software as well as the application of such software to the solution of specific problems.

The third category considers the Environments that produce the dynamic loads. Are they shock (earthquake, gun blast, explosion), vibration (random, periodic, complex) or acoustic? How are these environments measured and defined in terms applicable to design? Phenomenology is a broad term to describe the fundamental properties of materials and structures required to be understood before one can effect an acceptable design. Among the more important properties to be considered are those related to damping and fatigue. The Experimentation category includes information on methods of testing for proof of design, test facilities and techniques for controlling and monitoring tests.

The final two categories, Components and Systems, contain the bulk of applications information. Here, design techniques, analysis methods, response calculations and test procedures are included which are specifically applicable to structural or mechanical components or, indeed, to complete systems.

Chapter 2

ANALYSIS AND DESIGN

INTRODUCTION

Mathematical analyses of modeled engineering problems, including those involving shock and vibration, continue to grow at a phenomenal rate--both in the solution of routine problems and in the development of new techniques. Since individual hardware oriented solutions will be discussed under COMPONENTS and SYSTEMS, this section will be devoted to the development of techniques involved in the mathematical analysis and design-related methods where shock and vibration considerations are important.

It should be made clear at the outset that literature on design-related methods historically lags that of analysis. This is due in part to the fact that university researchers find applications problems less interesting from an academic viewpoint. Furthermore, design-related problems are generally less well understood since they are closely related to engineering practice, and are subject to diffusion by the process of technology transfer. Such methods may also be hidden in computer software that may be proprietary or may otherwise be unsuited for separate publication.

The really significant work in this area has involved the development of numerical methods and the finite element modeling technique for solution of large, complex problems on the digital computer. Modeling as an engineering science still lags the development of fast efficient, stable numerical computational techniques. Damping is a good example. It is easy to compute the damped vibration response of structures after damping forces are quantified. The lack of solid experimental data accounts for the gap in the technology. The past three years have brought steady development in the areas of modal synthesis, bond graph methods, statistical methods, and nonlinear analysis; however, none of these developments have been spectacular. The evolution of parameter and system identification methods has not lived up to expectations--probably because of a lack of genuine applications.

This area is described by six major headings using appropriate subheadings. Any attempt at separation of information in this way is, at best, difficult and is subject to individual interpretation. Hopefully, the composite discussion will result in reasonably complete coverage of significant advancements. Although there will be some general discussion under each subject category for the United States, this procedure will not necessarily be followed for the other countries. In all cases, as suggested in the Scope, information that advances the technology will be emphasized.

UNITED STATES

Analogs and Analog Computation

Since the completion of the development of the first electronic digital computer in 1945 and the phenomenal development of hardware and software since then, analog devices seem to have received less and less emphasis. The use of hybrid systems employing combinations of digital and analog computers has increased; however, due to the cost and specialized nature, these computational devices have not kept pace with the digital computer. Although it is still true that the analog computer is used in certain industrial control processes where a constantly varying quantity can be monitored and, to an extent, in laboratory simulation for design purposes, this area cannot be considered one in which notable new developments are being made in the U.S. Perhaps this is as it should be. As computer technology advances at a rapid rate, the proven analog methods are offered only very specialized opportunities for application. It should not be forgotten, however, that the concept of mechanical analogs of electric quantities has produced significant advancement in the use of mechanical impedance and mobility for the solution of shock and vibration problems.

Analytical Methods

Most analytical methods are concerned with the solution of differential or integral equations which mathematically represent the dynamic behavior of physical systems. The detail required in solutions and the background and experience of the engineer dictate the selection of an analytical method. Hannibal has published a two part article (1, 2) on modeling of vibrating systems. In the first part classical force balance and energy methods are discussed. Special techniques such as mechanical impedance, transfer-matrix, finite element and bond graphs are covered in the second part. Ample references are given in these articles.

Nonlinear Analysis

While it is customary to linearize the equations of motion of a physical system, certain physically observed phenomena cannot be described in this manner. They require consideration of certain nonlinearities. In general there is no method which will yield an exact solution to an arbitrarily selected nonlinear differential equation. Thus the available methods are all approximate. The basic mathematical ideas and techniques were developed by Poincare (3). The classical techniques for the solution of nonlinear differential equations were reviewed by Agrawal (4) and will not be repeated herein.

New methods for nonlinear analysis are as varied as the physical problems that motivated their development. Demoulin and Chen (5), Polak (6), and Jones and Roderick (7) have developed new nonlinear analysis techniques which utilize local linearization of properties. Convergence of these iteration processes is discussed at length. In addition a correction term involving estimated incremental displacement is claimed (7) to save significant computing time in the assemblage of higher order finite elements.

Utz (8) offers a method to obtain periodic solutions of second order differential equations with nonlinear, nondifferential damping. A direct method for locating normal modes in certain holonomic, scleronomous, conservative nonlinear two degree of freedom dynamical systems has been presented by Rand (9). The system studied does not have to be close to a linear system.

New techniques have been developed by Dubowsky and Grant (10) and Dendy (11), to deal with time dependent problems. A solution approach using modern automatic symbolic manipulation techniques was presented (10). Use of these techniques will result in substantial computational savings for a wide class of problems. Dendy (11) analyzes some Galerkin schemes for the solution of nonlinear time dependent problems to determine error estimates. Wu (12) has discussed adjoint operators associated with boundary value problems. These techniques allow solution of a general set of boundary value problems.

In the area of acoustic wave propagation an alternative to the method of characteristics for the solution of multidimensional nonlinear problems has been described by Ginsberg (13). The approach consists of applying Lighthill's technique of strained coordinates in the physical plane, instead of the conventional asymptotic solution which utilizes characteristic variables. The problem is posed in terms of a velocity potential function.

Stability, existence, and uniqueness--all problems in solutions to nonlinear problems--have been discussed by Park (14), Smith and Morino (15), Robinson (16), and Kuzanek (17). Park describes an improved stiffly stable method for direct integration of nonlinear structural dynamic equations. Smith and Morino deal with the general theory of stability analysis of nonlinear differential autonomous systems of a special type. A stability theory for systems of inequalities in differentiable nonlinear systems is posed by Robinson. The theory involves linearization of the system about a point. The Euler equations for an isoperimetric eigenvalue problem, made up of a singular Sturm-Liouville equation coupled to a second-order nonlinear ordinary differential equation are described by Kuzanek. Existence and uniqueness of solutions are discussed.

Morris (18) describes the application of the modal superposition technique to the calculation of the nonlinear dynamic response of structures. Stricklin and Haisler (19) presented a survey of the formulations and solution procedures for nonlinear static and dynamic structural analysis.

Variational methods for analysis have been well developed for many years. These techniques have provided the basis for development of approximate mathematical numerical methods such as the finite element method. Dym (20) recently published a paper which reviews the recent literature including available books. The review delineates the current use and development of variational principles. A recent paper by Reddy (21) describes the use of Vainberg's theory of potential operators to develop variational principles for linear dynamic theory of viscoelasticity.

The theory and solution of integral equations are well developed. Recent developments in this area involve the solution of physical problems using integral equations. da Silva (22) has introduced a method for finding first integrals of motion of a system of equations written in Hamiltonian form where no "classical integrals" exist. Tai and Shaw (23) obtained eigenvalues and eigenmodes for the homogeneous Helmholtz equation for arbitrary domains. Physical laws and constraints involved in layered inhomogeneous systems with or without forcing functions as represented by sources and boundary conditions were formulated by Hassab (24). A Fredholm integral equation of the second kind was developed by Ahner (25) to predict wave propagation in the composite region of a wedge.

The use of bond graph techniques, based on electrical network theories, has continued to grow as applications to new problems increase. A bibliography (26) of bond graph oriented literature, 1961-1976, has been published. This bibliography indicates the widespread use of this new technology. Actually it is one of the new methods of modeling and solution of physical problems available for the engineer. As any other technique it provides improved physical interpretation and solution of some physical problems.

Numerical Methods

The advent of the digital computer has spurred the development of numerical analysis techniques. This technology is among the fastest growing areas today as engineers seek ways to solve the vibration problems involved in larger and more complex structures. Numerical methods are being developed which are numerically stable, can be used with larger time steps, and describe physical problems with greater accuracy.

A general paper on the analysis and design of numerical integration methods for structural dynamics has been published by Hilber (27). The objective of this work was to develop one-step methods for integration of the equations of structural dynamics which are unconditionally stable, have an order of accuracy of not less than two, and possess natural dissipation which can be controlled by a parameter other than the time-step. Four new families of algorithms are discussed from this point of view and compared with the Newmark, Wilson, and Houbolt methods.

Specialized numerical methods have recently been published by Belytschko and Schoeberle (28), Hughes (29), Friedmann et. al.(30), and Serth (31). Belytschko and Schoeberle devised a new convergence criterion, based on discrete energy, for the implicit Newmark β-method. Hughes discusses the stability, convergence and growth, and decay of energy of the average acceleration method used for nonlinear structural dynamics. Friedmann et. al. published a new numerical treatment for periodic systems with application to stability problems. Serth offers the solution of stiff boundary value problems using orthogonal collocation.

Lumped parametric methods for modeling dynamic behavior of systems are well developed; however, several new methods have recently arisen. Kayser and Bogdanoff (32) describe a new method for response estimation of complex lumped parameter linear systems under random or deterministic steady state excitation. Relaxation procedures are used with a suitable error function to find the estimated response. Jacquot (33) has developed a technique to calculate the forced vibration response of membranes, beams, plates, and shells when they have attached to them at a single point a linear lumped parameter element or assembly of elements.

Efforts in the area of development of finite difference equations for numerical solution of shock and vibration problems have been sparse. Ciment and Leventhal (34) developed higher order compact implicit schemes for the wave equation. Hsu (35, 36) has coauthored two excellent papers on the determination of global regions of asymptotic stability for difference dynamical systems and on the behavior of dynamical systems governed by simple nonlinear difference equations. In the former paper an effective method is presented for the determination of a global region of asymptotic stability in state space. In the latter paper, the locally asymptotically stable periodic solutions of nonlinear difference equations are investigated.

The finite element method of modeling machines, vehicles, and structures has become universally accepted in the past five years. It provides a means of modeling which can be local or global in character. The method is used to break up a massive, elastic continuum into a finite number of elements connected together by points called nodes. There are two basic finite element techniques available.

The matrix displacement or stiffness method where the displacements are chosen as unknowns and the matrix force or flexibility method where forces are unknown are used. In both cases the infinite continuum is divided into a finite number of elements connected by node points where geometric compatibility must be satisfied. If the mass and elastic properties of the continuum are known, the matrix equations which are obtained from the formulation can be solved. As the size of the elements is decreased, more local behavior is obtained and the solution approaches that obtained for a continuum. Seshadri (37) has written an excellent review of the finite element method and its application to practical shock and vibration problems.

Selection of elements to characterize the continuum has become the center of research attention along with the development of numerical techniques to solve the matrix equations obtained in the formulation of the problem. Some recent developments in this area will be reviewed here. Fried (38) has studied numerical integration of the curvilinear finite elements with respect to accuracy and problem size reductions by lumping mass. In a later paper Fried (39) reports on convergence in the numerical integration process associated with finite element modeled systems. The formulation of large finite element modeled problems has been studied by Bathe et. al. (40) and Belytschko et. al. (41). In the paper by Bathe, the formulations for nonlinear static and dynamic analysis are reviewed. A consistent summary, comparison, and evaluation of the formulations which have been implemented have been given. Belytschko gives an efficient computational scheme for transient, nonlinear analysis of structure-media interaction problems. This "direct method" is faster and requires less computer core than conventional methods. Here computer costs are lowered in the numerical integration scheme. In order to decrease error and computational time, higher-order-linear finite elements have been devised. Birkhoff (42) has reviewed the trade-off between more complex elements and size of the element required.

Many studies have been devoted to the application of the finite element method to the solution of specialized problems. Among the many papers published Wu (43) presents solutions to initial value problems by use of finite elements obtained with a variational formulation. Extension of techniques used in boundary value problems is pursued. Parekh et. al. (44) apply isoparametric elements to problems in vehicle structural mechanics. Oden (45) discusses a theory of mixed finite element approximations of nonself-adjoint boundary value problems. In addition Oden and Wellford (46) describe the finite element analysis of shocks and acceleration waves in nonlinearly elastic solids.

A method of combined finite element-transfer matrix structural analysis has recently been published by McDaniel and Eversole (47). This method was developed to study the dynamics of orthogonally stiffened structures. Finite element procedures are used to formulate the transfer matrices for structural components which are not one dimensional. The resulting transfer matrices are used to reduce the large number of unknowns occurring in a standard finite element analysis by obtaining transfer matrix relationships over large units of the structure.

The growth of model size to the degree that computation becomes expensive has motivated studies on reduction of the number of finite elements required to model a structure. Among the recent papers involving <u>substructure modeling</u> and analysis

Craig and Chang (48) review the technology. The state-of-the-art of substructure coupling for dynamic analyses including some assessment of accuracy is given. Schemes for reduction of problem size in finite element modeled structures are given by Hughes et. al. (49), Gordon and Boresi (50), Meirovitch and Hale (51), Tolani and Rocke (52), and Craig and Chang (53). Hughes et. al. (49) describe a method of substructuring based upon a variational theorem in which it is admissible to describe the inertial properties of structures by way of independent displacement, velocity, and momentum fields. Gordon and Boresi (50) describe modifications of substructure stiffness and mass matrices to permit substructure mode shape to conform more accurately to the complete system mode shape. Computational algorithms are used to determine the substructure mode shapes associated with the lowest natural frequencies. Tolani and Rocke (52) present a unified approach to a group of structural dynamics analyses using the substructures techniques. A consistent basis for the selection of the substructure principal modes as required by this method is provided. Substructure frequency roots and strain energy in the principal modes are two criteria evaluated for the selection of substructure principal modes. Craig and Chang (53) discuss fixed interface and free interface methods of substructure couplings for dynamic analysis. Three methods for reducing the number of coordinates required by fixed interface methods are introduced.

The techniques of component mode synthesis allied with finite element model reduction schemes have been reported by Craig (54). Agrawal (55) describes a modal synthesis technique for determining the normal modes, natural frequencies, and response of three dimensional complex structures with flexible joints. Lagranges's equations are used to develop the equations of motions of the structures. Hintz (56) has developed a technique for modeling a structure using a severely truncated mode set. Implications of transforming finite element model equations of motion into a new generalized coordinate space and truncating the new degrees of freedom are examined. Rubin (57) devised a method which employs an incomplete set of free boundary normal modes of vibration augmented by a low frequency account for the contribution of neglected (residual) modes.

Optimization techniques for selection of optimum parameters of a system continue to be developed. However the application of these techniques continues to lag. In all probability this is the case because the limiting criteria are not easily evaluated mathematically. Mayne (58) reviews optimization techniques for shock and vibration isolator development. The classical methods of optimization such as nonlinear programming, time domain analysis, and optimal control concepts are described. Pilkey and Wang (59) describe techniques for finding the limiting performance of mechanical systems subject to random inputs. The limiting performance is defined to be the optimal response of a dynamic system in which certain subsystems are permitted to act as generic forces as controllers with no particular design configurations. Chen and Adams (60) discuss parameter optimization of vibration absorbers and shock isolators by root-locus technique. The problem is treated with classical feedback control techniques. Tests on a mechanical isolation system were used to confirm the optimization results of Ng and Cunniff (61). The primary goal of this technique is to seek a minimum maximum point so that the objective function of the system is maximized with respect to frequency and minimized with respect to damping. An optimization technique for structures, reported by Twisdale and Khachaturian (62), is formulated as a multistage decision process by decomposition of the structure into a series of substructures.

Perturbation methods in numerical analysis are well developed; however, some interesting variations of old techniques have been reported by Statson and Palma (63) and Anderson (64). Statson and Palma developed the inverse problem of changing parameters with resulting response changes in a structure. By using first order perturbation theory the structural changes necessary to effect a given change in vibration modes are obtained. The inverse problem of required parameter changes for prescribed response is gaining in popularity due to savings in design time. A method that uses multiple time scales for the purpose of obtaining uniform asymptotic solutions of nonlinear ordinary differential equations is modified by introducing a new small parameter. Perturbation techniques are used to develop the solutions.

Statistical Methods

Statistical methods of analysis have not been widely accepted by the engineering profession even though many process oriented excitations and parameters are statistical in nature. This fact occurs because of the deterministic training of engineers. Publication of papers on new techniques continues but practical usage lags.

The statistical energy analysis (SEA) method, for instance, was widely publicized but does not yet get common usage. Maidanik (65) uses SEA on complex dynamic systems coupled by dissimilar media. A general formalism dealing with the response of a complex dynamic system is developed. Maidanik (66) also published some elements in SEA involving two coupled basic dynamic systems--resonant response of structures and noise control systems.

Papers on the statistical solution of dynamic problems have been published by Bendat (67), Chen and Soroka (68), and Atalik and Utku (69). Bendat (67) published new solutions for the general, multiple input/output problems involving arbitrary stationary random processes by using a special representation for random records. Chen and Soroka (68) determined the response of a multidegree of freedom dynamic system with statistical properties to a deterministic excitation. A perturbation technique is used to solve the set of governing equations of motion. Atalik and Utku (69) develop the response of nonlinear multiple degree of freedom dynamic systems to stationary Gaussian excitation using an equivalent linearization technique.

Statistical methods are gaining wide popularity in the area of data analysis. The implementation of the fast Fourier transform on the digital computer has resulted in widespread usage of spectral analysis methods in the analysis of random processes. Walker and Womack (70) report on the development of some useful statistical methods for analyzing spectral estimates. The application in this paper is to road profile data from transportation or highway engineering.

Vibration studies concerned with disordered lumped parameter and distributed parameter structural systems has been presented from a statistical point of view by Soong and Cozzarelli (71). The term disordered is used to mean randomness of the parameter values. A study on the dynamic response of structures with statistical uncertainties in their stiffnesses has been published by Prasthofer and Beadle (72).

Parameter Identification

The literature on parameter identification techniques continues to grow; however, the application of these techniques to practical problems is still lacking--probably because of their mathematical nature. Wells (73) describes the techniques involved in stochastic parameter estimation for dynamic systems. Berman (74) reviewed the theory and application of parameter identification techniques to mechanical systems. Mathematical methods of parameter identification have been published regularly. Spalding (75) presents a method for identifying linear distributed parameter systems using time transformed, noise free systems. Measurements of system response are combined with Green's function method of analysis to obtain integral equations that can be solved for unknown spatial operators or coefficients. A frequency domain synthesis of optimal inputs for linear system parameter estimation has been published by Mehra (76). The problem is formulated to estimate parameters in linear single input multioutput dynamic systems as a regression problem in the frequency domain. Gersch, et. al. (77) published a two stage least squares parameter estimation procedure using covariance function data. Natural frequency and damping parameters of randomly excited structural systems were obtained. Caravani, et. al. (78) suggests a method of identifying structural parameters such as damping and stiffness from its time response under dynamic excitation. Ibrahim and Mikulcik (79) describe the theoretical aspects and the experimental verification of a time domain modal vibration test technique to lumped parameter and distributed parameter systems.

Design Techniques

Analytically oriented design techniques have not achieved wide spread usage because of the lack of necessity in many situations. However, where optimization is truly required these techniques can effect savings in time and money; and, in some cases, save the frustration of pursuit of impossible design solutions. The available design techniques involve strategies for the design of total systems as well as methods for the design of simple components. It is evident, however, that development of analytical design methods still continues well ahead of applications.

Whitman, et. al. (80) describe a seismic decision analysis procedure for organizing the information required to arrive at a balance between cost of designing for earthquake resistance and vulnerability to damage. The probability of ground shaking at various intensities is evaluated using Cornell's risk model. Building performance is expressed by damage probability matrices. For minimum weight design of trusses and frames Gorzynski and Thornton (81) describe a method involving the maximization of the member energy ratios. The energy ratio of a member is the ratio of the strain energy stored in the member when the structure is subjected to a particular load to that which could be stored in the member. Ray, et. al. (82) published a series of studies concerned with the identification and simulation of the response of multistory framed buildings as a function of design variables and earthquake ground motion. The methodology for design is developed via optimization theory. A new performance index for improved computer aided design of control systems has been developed by Martens and Larsen (83). The index forces the design of the control systems into a region of design space relating to acceptable system specifications. A unified data base for support of engineering systems design has been developed by Rosenberg (84) using bond graph methods. The multipart model and its associated bond graph representation serve very effectively as a unified data base, especially when devices and systems involve several energy domains. Bond graphs are processed to reveal important information about alternative input/output choices, and device level coupling factors when submodels are assembled into systems.

AUSTRALIA AND NEW ZEALAND

Analytical Methods

In Australia, the problem of the evaluation of dynamic systems has been studied. Several different schemes were examined for numerically solving boundary value problems for nonlinear first order systems. A method for evaluating the performance of dynamic systems was proposed. The aim is to define quantitative performance standards that can be used as design specifications for multivariable and non-linear systems (85).

UNITED KINGDOM

Analytical Methods

Significant effort exists on stability analysis methods in Great Britain. Two introductory studies on the stability and response of linear systems were performed. The first study presented methods for determining the stability of linear systems and how systems should be modified to achieve a stable state (86). The second study described methods of displaying stability characteristics (87).

In another study, a simple example showed how the Ritz method could be used to analyze the dynamic stability of elastic systems subjected to a nonconservative load (88). Studies relating the stability load of a structure to its stiffness and natural frequency have been performed. The effects of residual stresses were also studied. Further examinations of recent theories were made to relate stability load, stiffness, natural frequencies, and residual stress (89). Other studies on the subject of stability concerned flutter instability in imperfect structural systems, stability criterion for stick-slip motion and unstable regions in multidegree of freedom linear systems undergoing beating excitation.

Numerical Methods

Finite element modeling techniques continue to be an important part of the analysis and design efforts in Great Britain. Finite element models have been used for many applications and, in one study, an acoustic finite element model was used to analyze the acoustic modes of irregular shaped cavities (90). The finite element method was also used to analyze the response of periodic random structures to a random pressure field (91).

Continuing interest exists in developing finite elements and upgrading or extending finite element computer programs. An example of the latter is the SPADAS program which was extended to handle turbine blade disc assemblies and mixed rotating and nonrotating structures.

Statistical Methods

Work in the response of a system to random vibration is a major continuing interest in Great Britain and most of the effort involves first passage problems. First passage problem studies are concerned with predicting the probability of a failure occurring due to the first passage of the vibration amplitude above a prescribed level during a finite time interval.

One such study was performed to determine the probability of first passage failure of a linear oscillator subjected to stationary white noise (92). The probability of first passage failure of a linear oscillator that was subjected to pulse of nonstationary vibration was also investigated (93). An approximate method was developed for calculating the probability that a first passage failure of a nonlinear oscillator will occur within specified interval of time (94). Another study was concerned with predicting the probability of first passage failure for a linear oscillator excited by white noise in which the prediction process depended on the character of the envelope of the response process (95).

The results of these studies might be used to predict the probability of a fatigue failure of a single degree of freedom system, subject to random vibration, when its amplitude first exceeds a certain level during a finite time period. Most real world systems are not or cannot be approximated as single-degree-of-freedom systems, nevertheless the results of these studies are useful in developing techniques for predicting the probability of first passage fatigue failures in multidegree-of-freedom systems that are subjected to random vibration.

Two studies of the random responses of oscillators with nonlinear characteristics were conducted. One study considered the response of oscillators with nonlinear damping (96), the other study considered the response of an oscillator with nonlinear stiffness terms (97).

Interest in system identification in Great Britain is in two areas. The first area of interest is on the effect of varying structural parameters to achieve a desired response (98). The second area concerns the application of system identification techniques to flutter problems (99).

CANADA

Nonlinear Analysis

Substantial interest in techniques for solving problems in vibrations of nonlinear systems exists in Canada. A graphical procedure was developed to analyze nonlinear multivariable systems. This technique allows the user to obtain realistic estimates of stability for special classes of systems in a simple manner (100).

The Krylov-Bogoliubov-Metropolski method has been extended to obtain solutions to vibration problems involving systems with significant damping and slowly varying parameters (101) and systems with weak nonlinearities (102, 103). The behavior of a nonlinear system that is subjected to parametric excitation has also been investigated (104).

Considerable interest exists in generalized techniques for the stability analysis of vibrating systems. Two reviews of the world's literature on this subject were prepared by Canadian authors (105, 106) and in both cases Canadian authors have made many contributions.

Studies of stability include the effect of parametric random excitation on the moment stability of a damped Mathieu oscillator (107), the eigenvalue problem arising in the free vibration and stability analysis of gyroscopic type systems (108) and the stability of weakly coupled harmonic oscillators (109).

Numerical Methods

A review of the published literature concerning Galerkin's method, which is a technique for obtaining approximate solutions to differential equations of motion for vibrating systems, was prepared by a Canadian author, H. H. E. Leipholz (110). Only boundary value problems dealing with vibration were considered in the survey; however, other approximation methods such as the Ritz method, were discussed.

Statistical Methods

Studies of statistical techniques have been carried out in Canada to predict the maximum response of structures to incompletely described loads and nonstationary random loads. Stationary excitation is usually assumed when predicting the response of mechanical systems to random vibration. An investigation of the response of linear mechanical systems to nonstationary excitation was performed using the impulse response characteristics of the system. The input excitation was modeled as a product of a modulating component and a stationary white noise stochastic component of zero mean (111). There are cases where the assumption of stationarity of excitation is not valid; therefore, this technique might be useful under those conditions. Interest in techniques for predicting the probability of first passage failure of mechanical systems also exists in Canada. In this case the amplitude excursion failure of a two-degree-of-freedom system was investigated (112).

Parameter Identification

A method for identification of damping, stiffness and mass parameters from modal information was formulated. The method was applied to determine the parameters of a nine story vibrating structure (113).

FRANCE

Analogs & Analog Computation

An analog simulation technique, based on the small perturbation equation, has been applied to a transonic flow problem (114). A real time visualization system makes it possible to see the evolution of the flow.

Nonlinear Analysis

Nonlinear wave propagation in plasmas has been theoretically analyzed and compared with the experimental results for shock waves, wave-coupling and decay, etc. (115).

Numerical Methods

With respect to optimization techniques in France, O.L. Mercier (116) has reviewed the modern concepts of control theory which have evolved over the period 1960-1972. He relates these concepts to the optimum design of feedback controls, filters, etc. which are used to control dynamic systems.

Using perturbation techniques, Eckmann and Seneor (117) have applied the Maslov-WKB method on asymptotic perturbations to the 1-dimensional (an)-harmonic oscillator. It is an attempt to present Maslov's method at an elementary level. Newton-Raphson methods have been used in combination with perturbation methods for the selective calculation of modes (118). Stepwise perturbations and iterations are combined at each step.

Parameter Identification

Miramand, et. al. (119) have developed techniques for the identification of structural modal parameters using single-point dynamic excitation. The structure may have arbitrary viscous damping and practically coincident modal frequencies.

INDIA

Nonlinear Analysis

Several researchers in India have made studies of 2nd order (120, 121) and third-order (122, 123) nonlinear systems. Srirangarajan, et. al. (124) have studied the free, forced and self-excited vibrations of nonlinear two-degree-of-freedom systems. They analyze the two-degree-of-freedom system with a weighted mean square linearization approach.

Numerical Methods

A. V. K. Murty (125) has published a review of finite element modeling techniques including lumped parameter, transfer matrix, finite element displacement, finite element force, hybrid and quadratic eigenvalue methods. Applications of the methods to natural vibration problems are also given. G. V. Rao, et. al. (126) have used finite element methods to analyze the vibration characteristics of initially stressed shells of revolution.

ISRAEL

Nonlinear Analysis

R. Meidan (127) has developed time domain representations for use on general non-linear and time-varying systems.

Pnueli, et. al. (128) have developed variational methods to obtain eigenvalues associated with ordinary differential equations and variational formulations. numerically.

Numerical Methods

Israel's interests in optimization techniques centers around optimizing aircraft for flutter suppression. Two recent studies on structural optimization for flutter requirements have been published (129, 130). Sandler (131) has used a random algorithm for the dynamic optimization of mechanisms, especially gearing systems.

Parameter Identification

Sidar (132) has published a paper on parameter identification with applications to aircraft. He considers the problem of identifying constant system parameters and identifying and tracking variable parameters in multi-input, multi-output, linear and nonlinear systems.

ITALY AND GREECE

Analytical Methods

The Laplace Transform is one type of integral transform and it is commonly used to solve linear differential equations. A novel application of the Laplace Transform for determining the natural frequencies of both discrete and continuous structures is contained in the literature from Greece. The method is shown to be applicable to structures that are subjected to either random force or transient excitations (133).

Nonlinear Analysis

In Italy there is considerable interest in nonlinear analysis techniques. This subject can be divided into two topics. The first topic concerns a study of the use of Duffing's equation for the analysis of nonlinear systems subject to forced vibration. Duffing's equation is a well known approximate method for solving the equation of motion of a slightly nonlinear system. However a study of the forced vibration of a nonlinear system showed that it yields satisfactory results in cases of strongly nonlinear systems (134, 135).

The second topic concerns plasticity of structures. Several studies were performed and these include dynamic loading of rigid perfectly plastic structures, displacement bounds on elasto-plastic structures (136, 137), and optimum plastic design of structures (138). Structures are designed to resist loading in the elastic range; however, there are applications where either slight degrees of plasticity or even total plastic deformation can be tolerated. Thus the foregoing references might be useful for predicting the upper bounds on the plastic deformation of structures or for optimizing the design of the structures.

JAPAN

Analogs and Analog Computation

An analog computer has been used to check the results of the calculation of the response of a nonlinear vibratory system subjected to several harmonic excitations (139). Yamamoto, et. al. (140, 141) have studied nonlinear spring-mass systems and checked the results of the theoretical investigation against those of an analog computer.

Nonlinear Analysis

Yamamoto, et. al. (142, 143) have made many studies on simple nonlinear systems. The nonlinear response characteristics of reinforced concrete buildings during earthquakes have been studied with nonlinear modeling (144). There are few studies of nonlinear waves in solids compared to those in fluids and gases. Studies in nonlinear elastic wave propagation are being performed by Dr. Nobumasa Sugimoto (145).

Numerical Methods

Nakagawa, et. al. (146, 147) have made fundamental studies of the dynamics of wave propagation in bars where the bars have random properties, e.g., stiffness and viscosity. The bars are modeled as n-degree of freedom linear chains with the numerical values of the elements being randomly distributed. An extension of the Southwell-Dunkerley methods for synthesizing frequencies of lumped parameter systems has been published (148, 149).

The finite element technique has been applied to the design of energy-trapped electromechanical resonators (150). The dynamics of piezoelectric resonator plates such as quartz were studied.

In Japan one of the more important areas of structural optimization techniques is in the design of machine tools. A general method of algorithm has been developed for solving optimum structural designs problems in which natural frequencies are involved (151). Applications of the method are also available (152, 153). Yoshimura (154) has studied how to optimize the design of machine tools to minimize chatter modal analysis is the underlying method.

Statistical Methods

A method has been developed for calculating the probabilistic output of non-linear vibration systems subjected to arbitrary random input (155). Also, the statistical properties of road traffic noise have been investigated (156).

Parameter Identification

The significant parameters affecting the structural dynamics of machine tools were identified by experimental and theoretical means (157).

NETHERLANDS & BELGIUM

Numerical Methods

The Navier-Stokes equations for free surface flows have been numerically integrated using a Douglas-Rachford modified alternating direction implicit scheme (158). A new solution for the propagation of sound in a cylindrical tube has been obtained using a Newton-Raphson procedure (159).

Powerful analytical methods exist today for the dynamic analysis of structures (160). General purpose computer codes based on the finite element method are also available to the engineer for the analysis of the more complex structures or shapes (161). In essence, the prediction of the mode shapes, modal damping, and frequencies of structures is a well defined art. Exact values of these modal parameters are needed by environmental test labs, the controls engineer and the loads specialists. However, as powerful as the analytic methods are they cannot account for all the variabilities in the selection of materials and construction practices used in assembling a structure. The modal damping values are the most sensitive to these assembly methods. For these and other reasons it is still necessary to run modal survey tests, especially on spacecraft and aircraft. Ottens (162) has calculated the mode shapes and frequencies of a Northrop NF-5.

Recent work in the Netherlands includes a report containing general guidelines for conducting modal survey tests on spacecraft, based on their experiences gained in matrix structural analysis and modal survey testing on an Intelsat-III structure (163). In another paper the author shows how to perform an exact modal analysis of a spinning structure without using a truncated series of assumed modes or any initial lumping of springs and masses (164).

Use of the finite element method continues to increase in both countries. In Belgium recent work has been on the application of the finite element method to aeroelastic problems, like panel flutter, and to soil-structure interaction problems arising in the design of the foundations of nuclear power plants. In a paper on the finite element solution of aeroelastic problems, the author discusses the advantages and disadvantages of the common approaches, especially the standard power method (165). The failure of the power method in some cases is discussed. A summary of the advantages and limitations of lumped parameter vs. finite element methods in the design of nuclear power plants are presented including the state of the art in the determination of soil stiffness and material damping characteristics (166, 167). Recommendations are presented on a procedure for predicting the soil-structure interaction of deeply embedded foundations.

Parameter Identification

Parameter identification methods have been used successfully in the presence of noise for the estimation of a spinning spacecraft's attitude (168) and the estimation of parameters of nonlinear dynamic systems (169).

Design Techniques

In Belgium the standard design response spectra have been reviewed and a new set of design response spectra for nuclear power plants on rock sites have been *recommended* (170).

In the Netherlands they have developed a Fighter Aircraft Loading Standard for Fatigue Evaluation (FALSTAFF) (171). This is a loading history standard pertaining to fighter aircraft wing bending, primarily governed by maneuver loadings, which is used to evaluate the fatigue performance of structural materials and components and establish fatigue design charts.

SWEDEN, NORWAY AND DENMARK

Analogs and Analog Computation

Analog techniques appear to be more widely used in Europe than in the U. S. R. Upton of B. & K. in Denmark has made an objective comparison of analog vs. digital methods of real-time frequency analysis (172).

Flottorp and Solberg of the Institute of Audiology, Oslo have refined the experimental techniques available for measuring the mechanical impedance of human headbones (173). Results of impedance measurements on 60 human subjects are presented.

Numerical Methods

Bergan, et. al. (174) of the Univ. of Trondheim, Norway have developed an efficient finite element based computational procedure for the analysis of crack propagation in 3D solids under cyclic loading.

N. Olhoff of the Technical University of Lyngby, Denmark has written a survey of the available literature on the optimal design of vibrating structural elements. Part I (175) describes the unified variational technique which is used to minimize the material volume of an element with a specified frequency. Part II presents applications (176).

SWITZERLAND

Nonlinear Analysis

Investigations of nonlinear dynamic systems frequently must be made by numerical methods. Some of these methods are investigated by Grassl and Sigrist (177); other investigations use perturbation methods with Duffing's equation as an example (178, 179). In another investigation Horvath (180) combines Van der Pol's and Duffing's equation.

WEST GERMANY

Analogs and Analog Computation

M. Fritz and H. Waller (181) have developed partial differential equation mathematical models of continuous systems (e.g., bars). These mathematical equations are then translated into circuits for use on analog computers. Discussion of the methods and numerous examples have also been published.

Nonlinear Analysis

J. H. Argyris, et. al. (182) have done some recent work on step by step integration on nonlinear equations of motion, large deformations being one example. Their finite element method can handle structures with over 2000 degrees-of-freedom. Results of applying the method to a large tension roof are also given.

W. Krings and H. Waller (183) have used the algorithm of the Fast Fourier Transformation to compute the Laplace transformation. The method was applied to the calculation of vibration and creep processes.

The FFT method has been applied to the numerical calculation of mechanical built up oscillations (184) and to the determination of aerodynamic derivatives (185). Two different variations of the modal simulation of turborotors have been investigated (186).

Numerical Methods

The use of finite difference methods tends to be overshadowed by the use of the popular finite element methods. However, finite difference methods continue to be developed and used for a wide class of problems especially in computational fluid dynamics. E. Gekeler (187) has studied the convergence of finite difference approximations of parabolic initial boundary value problems. Stockl and Auer (188) developed a finite difference simulation of the dynamic behavior of a tensile crack.

J. H. Argyris, et. al. of Stuttgart Univ., Institut fuer Statik und Dynamik, ISD, have produced several papers on the use of finite element methods in structural dynamics. Most are contained in the ISD Lectures on Numerical Methods in Linear and Nonlinear Mechanics (189). Brandt (190) has developed a method based on the complementary energy principle for the calculation of vibration frequencies using hybrid elements.

Optimization techniques are popular because of the ease with which they can be implemented on computers. Such techniques have been used to compute braking for minimum stopping distance (191) and minimum noise takeoff flight paths (192). Optimization of a grinding spindle's dynamic characteristics has been accomplished with the aid of a computer (193). Perturbation methods have been used successfully in the analysis of nonlinear systems (194, 195).

Statistical Methods

The methods of statistical energy analysis have been implemented in a computer algorithm for calculating sound propagation in a complicated structure (196).

Friedrich (197) has developed a technique for the analysis of stochastically forced vibration systems. A trigonometric series analysis method is used which was developed originally for weakly-nonlinear, forced-vibration systems.

Parameter Identification

Natke (198) has discussed the problems inherent in identifying structural parameters, especially as it relates to ground and flight vibration methods. Iserman (199) has surveyed the available methods of parameter identification. Kohler (200) has developed nonlinear parameter identification techniques.

Franzmeyer (201) has discussed Germany's aircraft standard noise threshold values as well as International aircraft noise regulations.

EGYPT

Numerical Methods

R.A. Ibrahim, et. al. have made an exhaustive review of the worlds literature on parametric vibration and published a five part article in the Shock and Vibration Digest in 1978 (202,203,204,205,206). Parametric vibration refers to the oscillatory motion that occurs in a structure or a mechanical system as a result of a time-dependent (usually periodic) variation of such parameters as inertia or stiffness. The titles of the five parts are as follows:

(1) Mechanics of Linear Problems (202)
(2) Mechanics of Non-Linear Problems (203)
(3) Current Problems (1) (204)
(4) Current Problems (2) (205)
(5) Stochastic Problems (206)

Ibrahim, and the others have gone into great depth in their explanations of parametric vibration. The five parts together could easily form the basis of an entire book on the subject.

Fawzy (207) has found both the necessary and sufficient conditions which show that the modes in which a "damped" linear system oscillates are actually the principal modes defined in the absence of damping.

TURKEY

Numerical Methods

Modeling of continuous systems has been investigated by Dokumaci of Ege University (208). He has developed methods for the solution of vibration problems of continuous systems by means of discrete models. Two point eigenvalue problems are emphasized and methods for determining upper and lower bounds have been developed.

CZECHOSLOVAKIA

Nonlinear Analysis

A. Tondl of the National Research Institute for Machine Design, Bechovice has developed new methods for the analysis of nonlinear vibrations using skeleton curves and limit envelopes (209). With their aid the designer can perform a qualitative analysis in a comparatively easy and straightforward manner, and quickly gain a good idea of the effects of various parameters of the examined system. Tondl (209) shows the advantages of this method in analyzing nonlinear systems excited by external harmonic forces or parametrically. He also discusses the possibility of using the limit envelopes in the identification of the character of damping.

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Chapter 3

COMPUTER PROGRAMS

INTRODUCTION

Extremely large complex problems are being solved today on digital computers by members of the shock and vibration community. Some of the reasons for this are hardware dependent, such as larger memory capacities, faster processing speeds and better CRT terminals. Other developments, primarily in software, have been virtual memory techniques, sparse matrix techniques, sub-space iteration methods, much improved time integration algorithms, modularity in programming and improved man-machine communication techniques such as interactive-graphics.

This section deals with the computer programs that have been developed in the U. S. and Foreign countries. For the purposes of this report we have separated the discussions into two categories: General Purpose Programs and Special Purpose Programs.

UNITED STATES

General Purpose Programs

Programs that may be used for the analysis of a number of different kinds of structures and which provide for a number of options on systems characteristics and forcing functions may be classified as general purpose. By far the largest number of programs in this category are the finite-element or lumped parameter programs. The structural system to be analyzed is modeled by a series of point masses connected by spring-like elements (springs, beams, plates, etc.) chosen to represent the mass, stiffness, damping, thermal and other material or mechanical properties of the physical structure. The program computes the natural frequencies mode shapes (eigenvalues and eigenvectors) of the system and stores the results for later response calculations. A comprehensive review of structural mechanics software was published in 1974 (1). In this and other works edited primarily by Dr. Walter Pilkey of the University of Virginia, Charlottesville, USA, are contained discussions of general and special purpose programs. In (1) the capabilities of and user reactions to general purpose programs are discussed in the context of transient analysis, non-linear continua and analysis. The Shock and Vibration Information Center published a monograph on Shock and Vibration Computer Programs (SVM-10) in 1975 which was edited by Walter and Barbara Pilkey (2). SVM-10 contains detailed descriptions of the general purpose programs ANSYS, MARC, MINIELAS, NASTRAN, NISA, SAP IV, STARDYNE, STRUDUL II, and STRUDUL-DYNAL (2). Detailed reviews of the general purpose programs DAISY, MARC, NASTRAN, STARDYNE and STRUDUL II are contained in Ref. (3).

NASTRAN - Probably the most elaborate finite element program is NASTRAN. The initial N.A.S.A. contract for the development of NASTRAN was awarded back in 1965 to Computer Sciences Corporation with MacNeal Schwendler, Martin Baltimore and later Bell Aero Systems as subcontractors. NASTRAN has been discussed more than any other single program. NASA has held periodic conferences on "user experiences." (See section NASTRAN Applications & User Experiences.) The documentation is complete but requires extensive experience for proper usage. The use of the program is expensive, especially for small problems. It is capable of analyzing a wide range of static and dynamic structural analysis problems.

Previous to NASTRAN, similar capabilities were only available to industry in the form of a number of smaller stand-alone programs. NASTRAN is composed of independent but related functional modules that are controlled by the executive system and the DMAP (Direct Matrix Abstraction Program). A set of DMAP statements (control cards) define a solution procedure which is called a "rigid format." Twelve rigid formats were provided originally and these give a good basic analytic capability. It is possible to modify rigid formats with alter cards as well as construct new ones. This, however, is a job for an experienced NASTRAN programmer or analyst. Because later developed general purpose programs are similar to NASTRAN we list here the twelve NASTRAN rigid formats as being typical of those found in any general purpose programs: 1-Static Analysis, 2-Static Analysis with Inertia Relief, 3-Static Analysis with Differential Stiffness, 4-Buckling Analysis, 5-Nonlinear Material Analysis, 6-Normal Mode Analysis, 7-Direct Complex Eigenvalue Analysis, 8-Modal Complex Eigenvalue Analysis, 9-Direct Transient Analysis, 10-Modal Transient Analysis, 11-Direct Frequency and Random Response, 12-Modal Frequency and Random Response (3).

The biggest drawbacks to NASTRAN are its size, running costs and the length of time needed to learn its use. And it is a linear program. Its biggest advantages are that there are more versions of NASTRAN running on more computers with more experienced users around than any other similar program.

ANSYS - This is a versatile general purpose engineering analysis program with nonlinear capabilities. It has been used extensively by the nuclear industry (2). It has been used for piping analysis, seismic analysis and it contains an extensive element library (about 70) (2). It is most used for its material non-linear capabilities; its use for completely non-linear problems is limited, but being improved.

DAISY - This general purpose finite element code was developed originally for Lockheed Missiles and Space Company by Professor H. Kamel of the University of Arizona (3). Its flexibility and modularity have allowed for easy maintenance. The program has developed at Lockheed with close support from its original developer, Dr. Kamel. Lockheed's experiences with DAISY have led them to state that they have a great deal of confidence in its accuracy. It is an extremely reliable program, having been used successfully by Lockheed on nearly every one of their major analysis efforts from 1970 to 1973. One of the reasons Lockheed feels comfortable with the code and keeps on using it is reflected in their philosophy. They feel that no analyst should use a computer code blindly; i.e., as a "black box" he should understand completely the entire function of the code and know its potential and its limitations. As Dr. Kamel wrote the code it assumes a certain level of competence on the part of the person using DAISY; in short the program is ideally structured to suit Lockheed's demands for comprehension on the part of the user (3).

MARC-CDC is a general purpose finite element program for the static and dynamic analysis of structures. The program has capabilities for linear static and dynamic analysis, but was primarily designed for non-linear analysis, plasticity, creep and large deformations. Some users reported that the program was not easy to use and poorly documented in its earlier versions, however, significant improvements have been made in recent versions. MARC-CDC is the best known and most widely used program for non-linear analysis. Having the author, Dr. Pedro V. Marcal ready willing and able to help is a big asset in its usage. Although MARC-CDC offers the most advanced technology for non-linear static analysis, its dynamic capabilites are limited. The program is oriented toward flexibility of application and user modification; new elements can be added easily by the user. Also the agreement of the results as calculated by MARC-CDC with experimental results indicates that a high degree of confidence can be placed in an analysis using the MARC program.

NISA is a general purpose finite element computer program which has a good element library (2). It has a good mesh generation capability, a well developed plotting capability and numerous pre and post-processors. It is proprietary.

SAP-IV is a general purpose finite element program for the linear elastic analysis of structural systems. Developed originally by Drs. Klaus Junger Bathe and Edward L. Wilson at the University of California, Berkeley, it has formed the basis for many new programs such as NONSAP, GRIDSAP (2), NEPSAP, MSAP and ADINA (4). Among the reasons for its popularity are that it is inexpensive ($200), it has an excellent element library, it is user-oriented, and it can be easily modified to suit the needs of a particular organization. The unique feature of SAP-IV is that it is the <u>only</u> general purpose program that is simple enough that users have tried to modify it for their needs. The program lacks plotting and mesh generating routines and does not have a condensation or substructuring capability. SAP-IV is useful for research type problems requiring considerable interface with user routines.

STARDYNE is a general purpose finite element computer program with static, stability and dynamic analysis capabilities (3). It is designed with the user in mind. However, the program capabilities are limited to the solution of static and dynamic problems which are elastic and fall within the realm of the small displacement theory. It has a small element library. STARDYNE is used extensively in industry for the analysis of elastic structures. The program has no capabilities for large deformation or elastic-plastic analysis. Assuming the problem to be solved can be modeled with the elements in STARDYNE's library, its performance when defined on the basis of total problem cost of solution is considerably better than the performance of many of the general-purpose structural programs readily available to the user.

STRUDL II is probably the most publicized and, therefore, the most well known computer program available to the structural engineering profession. Its availability has made the greatest single impact of any computer program on the practice of structural engineering. The STRUDL system is a modular system of computer programs capable of performing the analysis and design of steel concrete members. STRUDL II is a part of the ICES system which was developed at M.I.T. during the mid-sixties and was, until recently, a very popular program in the building industry. However, after further developments on the program were stopped due to lack of support, and McDonnell Douglas developed and marketed its proprietary version, the use of STRUDL II appears to be declining. (See s.p. computer programs in Germany for recent modifications by MBB to STRUDL II.)

STRUDL-DYNAL is the proprietary version of ICES STRUDL II (2). McDonnell Douglas Automation Company and Engineering Computer International have made extensive modifications and additions to the M.I.T. version of STRUDL II. The dynamic part DYNAL is completely new. The new STRUDL DYNAL is now serviced and and supported by McAuto. As a result, many of the original bugs have been removed and the program is much more streamlined and efficient. However, the program still has some deficiencies; it has no transient analysis using direct numerical integration nor does it have the incompatible plane stress rectangle.

ADINA is a general purpose linear and non-linear static and dynamic three dimensional finite element analysis program (5,6). The code is a further development of programs NONSAP and SAP IV. Professor K. J. Bathe, now at M.I.T., is the author of ADINA which is a proprietary program available to users for a large yearly fee. Users report that ADINA is much improved over its predecessor NONSAP (See ADINA - User Experiences).

Applications and User Experiences

As was mentioned earlier, several NASTRAN User Experience conferences have been held and the entire proceedings published (7,8,9,10,11,12). A new eigenvalue extraction method, the Tri-diagonal reduction (FEER) method has been developed and implemented in NASTRAN (13). Also NASTRAN has been used to model an AH-1G Helicopter Airframe (14,15) and the results correlated with experiment (16). A large NASTRAN modal analysis of the YF-12A Aircraft was made and the results compared with ground vibration tests (17).

An ADINA conference was held Aug. 4-5, 1977 at which users presented the results of their experiences using ADINA (17).

Recent Trends

In the United States, improvements in existing programs and new program developments have occurred at a rapid rate, to the extent that the solution of almost any problem in the linear dynamics field can be accomplished. New developments are expected and needed to solve non-linear dynamics problems. ANSYS and MARC-CDC have addressed themselves to these problems. More work in this direction is indicated so that tools will be available to cope with non-linearities in material behavior, large displacements producing geometric non-linearities and non-linear boundary conditions, such as gaps. More work in this direction may also provide tools for dynamic stability analysis. The selection of a particular general purpose program for a specific job sometimes becomes one of personal preference. No general purpose program is suitable to be used under all situations. In the opinion of the Shock and Vibration Information Center, any institution where a significant amount of diverse analysis is done, should be using more than one program for the most effective results.

Special Purpose Programs

Due to the large number of named special purpose computer programs listed in the excellent standard reference works (1,2,3,4,18,19) we will not list all of the special programs by name, with a few exceptions. For detailed information consult the subject indexes or table of contents of the above references. References 1, 2, 3, 4 and 18 especially contain extensive reviews and summaries; for each program the summary lists its capabilities, solution methods, language (FORTRAN, etc.), hardware on which program runs, usage, the program developer, availability and ordering information as well as general comments.

For information on software dissemination centers in the U.S. and foreign countries consult Ref. (1) Part II and Ref. (20). Also of general interest is a bibliography of literature on computer graphics; it contains over 1,000 references covering the years 1950-1974 (21).

Each section* that follows will begin with a reference to a subject area which is contained in one of the standard special purpose computer reference works (1,2,3,4,18). Following the general references, brief descriptions of new programs will be given.

Numerical Methods

Laplace transform theory and the formulation of transfer functions comprise an important technique for the representation and analysis of linear, lumped parameter, multi-degree-of-freedom, vibrational systems. Bowens, et. al. (2) have written a general review of this subject with available computer programs.

*The general subject indexes of Ref. 1, 2, 4, 18 contain both U.S. and non-U.S. programs. For the purposes of this report the subjects will only be listed under the U.S. section.

K. K. Gupta has developed an efficient eigenvalue problem solution algorithm and applied it to a discrete damped structure (22) and a panel flutter problem (23). Eigenvalue and eigenvector extraction routines have been reviewed (2). Subroutines SEIGEN and NEIGEN are available for finding eigenvalues and eigenvectors of non-normal matrices (24). Improved numerical integration methods have been developed for time integration algorithms in structural dynamics (25) and linear equations of motion.

Modal Analysis

Two new programs have been developed for modal analysis. SCAMP (Stiffness Coupling Approach Modal Synthesis Program) is a computer program used to perform modal synthesis of structures by stiffness coupling (27). COUPL is a modal coupling program which computes vibration modes of a structural system by using fixed interface component modes (28).

Three basic algorithms have been developed: a two-cycle counting algorithm used in fatigue testing (29), an improved gradient algorithm for two point boundary value problem (30) and the PLU algorithm for determining eigenvalues of real Hessenberg matrices (31).

Computer Graphics -

What has become clear today is that for the efficient usage of finite element programs some form of computer graphics must be used. It is simply no longer rational for anyone to wade through stacks and stacks of printouts looking at columns of numbers. Graphics are no longer for the "computer gourmet;" they are for everyone.

Several reviews and summaries of computer graphics hardware and software are contained in Ref. (1). Potts (21) published a bibliography on computer graphics in 1974 which contains over 1,000 references covering the time period 1950-1974.

Buchanan, et.al. (32) have joined an interactive graphics package to a computer program for the transient response of rings. H. N. Christiansen, et. al. (33, 34) have created several graphics display systems for finite element models; their systems can be used to generate continuous tone images and animated displays or movies.

A recent paper (35) describes the latest version of the GIFTS system (Graphics Oriented Interactive Finite Element Package for Time-Sharing). GIFTS III's (released 1976) capabilities include automatic model and load generation, display of modes, etc. The paper gives applications of GIFTS III to structural engineering problems.

Material Mechanics

Reviews and summaries of computer programs related to the following subject areas are contained in Ref. (1): composites, weld problems, non-linear continua fracture mechanics, plastic analysis, thermal stress and creep, viscoelastic structures.

Yoshiaba Yamada (2) has reviewed programs which handle these time dependent material properties representable by the Boltzmann super position law or the Duhamel integral.

Two new programs have been developed for non-linear analysis. Mondbar, et. al. (36) have developed a new general purpose non-linear computer code. DYPLAS is a new finite element program developed by Zudans, et. al. (37) which computes the response history of general three-dimensional structures subjected to transient mechanical loadings. DYPLAS will handle elastic-plastic and large deformations.

Aeroelasticity

A general review of computer programs available to the general user for aeroelastic calculations has been published by Haviland, et. al.in Ref. (1).

Two programs have been developed by NASA-Langley Research Center for flutter analysis (38,39). Other aircraft analysis programs include the calculation of the unsteady aerodynamics of finite thickness wings (40) and the calculation of the stability and control characteristics of an elastic airplane (FLEXSTAB) (41). FCAP is a new computer program for the performance and structural analysis of complex aircraft with active control (42). Research on helicopter rotor blade dynamics is very active. Programs have been developed for the modal analysis (43,44) and aerodynamic loads prediction of rotor blades (45).

An STOL Aerodynamic Methods Computer Program has been developed for predicting the aerodynamic, stability and control characteristics of Short Takeoff and Landing (STOL) aircraft (46). An improved program has been developed for the control and analysis of cable mounted wind tunnel models in the Lewis Research Center 5 meter wind tunnel (47).

Optimization

The boundaries between computer aided design and optimization are ill-defined. A portion of much computer-aided design work involved minimum weight calculations, etc., which fall within the category of design optimization. Having said this, we will discuss mostly optimization in this section, with little on design.

A general review and analysis of readily available computer programs in structural optimization is in (1). Reviews and summaries of computer programs for the optimum design of mechanical systems, the kinematic design of mechanisms and the [optimum] design to performance of structural systems have been published (2).

Measurements on truck and rail shock and vibration environments have been in a project for the optimum design of a truck (48). ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is a new computer program based on sparse matrix and stiff integrated numerical algorithms (49). It has been used in design studies of the suspension of a 1973 Chevrolet Malibu and a Boeing 747 landing gear. An algorithm has been developed to design the unequal blade spacing of a face milling cutter to minimize total vibration.

Stability

General reviews and summaries of available computer programs for the analysis of structural stability and dynamic buckling of structures have been published (1,2).

SATANS-2 is a computer program for the geometrically non-linear analysis of a totally arbitrarily loaded shell of revolution. SATANS II-A is a modified version which can more accurately account for conditions at the poles of shells. SATANS II-A has been used to compute the static and dynamic buckling of shallow spherical shells subjected to step-pressure loads (50). A new code is under development which will be used for the dynamic buckling and post-buckling behavior of submerged structures under transient loading (51). The SABOR/DRASTIC 6 code has been used to analyze the dynamic buckling motion beyond strain rate reversal in cylindrical shells under radial impulse (52).

Modifications have been made to the VIPASA code (Vibration and Instability of Plate-Assemblies including Shear and Anisotropy); a procedure for stress analysis and options for graphical display of output have been added (53). SINGER is a program used to predict the geometrically non-linear response, including element failures and structural collapse, of skeletal reinforced concrete and steel structures to static and dynamic loads (54,55).

Fluids

General reviews and summaries of computer programs are available for fluid-structure interaction calculations and liquid propellant dynamic analysis (2).

Two programs are available for the acoustic and vibration analysis of aircraft hydraulic systems. HYTRAN is a Hydraulic Transient Analysis program which can be used to simulate the response of a hydraulic system to sudden changes in flow demanded by the system loads (56, 57). Its companion program is HSFR which stands for Hydraulic System Frequency Response (58,59); HSFR was developed to simulate the dynamic response of a hydraulic system to the acoustic noise generated by the pump.

Seismic

Seismic analysis has become big business in the U.S. and most countries. Large general purpose finite element programs are used extensively for this purpose. U.S. earthquake-prone areas like California have strict building codes and have been a watershed of activity in earthquake resistant building design. The Earthquake Engineering Research Center, University of CA, Berkeley, is a true international center for the dissemination of seismic technology.

Reviews and summaries of programs available for seismic analysis are available (2).

A computer program has been developed which can be used to match the response spectrum of a structure by adding together a train of appropriately spaced and sized square topped pulses (60). This method has been used to match the responses which would be produced by a real earthquake accelerogram. The modal seismic analysis of a Nuclear Power Plant using NASTRAN has been compared with an analysis using SAP 4 (61). SAKE (62) is a special purpose program developed to analyze an inelastic reinforced concrete plane frame structure subjected to an intense earthquake motion in one horizontal direction.

Two programs, LUSH (63) and FLUSH (64) have been developed for seismic soil-structure interaction analysis. LUSH is 2D and FLUSH is 3D.

Shock

Reviews and summaries of computer programs are available for computing shock wave propagation in solids (1) and mechanical and thermal shock analysis (2). Derby has written a review of shock and vibration isolation computer programs (65). SWAP-9, now available is an improved version of SWAP-7; it can be used for solving stress wave problems (66).

Many codes have been developed and/or used for the calculation of blast wave propagation and its interaction with structures. Four programs among those which have been used for blast wave calculations are BAAL, DEPROP, NOVA-2, and DYNFA. There are others.

BAAL is a 3D, transient hydrodynamics code developed by the Los Alamos Scientific Laboratory (67). DEPROP determines the dynamic, elastic-plastic, large displacement response of cylindrical and flat panels to arbitrary blast loadings (68). NOVA-2 is an updated version of NOVA (Nuclear Overpressure Vulnerability Analysis) for calculating the response of individual structural elements of aircraft to the transient pressure loading associated with the blast wave from a nuclear explosion (69,70). DYNFA (Dynamic Nonlinear Frame Analysis) has been developed to calculate the responses of frame structures to blast loadings (71). DYNFA was developed to aid in the design of blast resistant frame structures found in explosive manufacturing facilities.

Transient Analysis

Reviews and summaries of available computer programs for linear and nonlinear transient analysis have been published (1,2). Most of the transient analysis of structures can be handled by general purpose programs, so specific special purpose programs are limited in number. DYNGEN is a new program for calculating the steady-state and transient performance of turbojet and turbofan engines (72).

Shells

Reviews and summaries of the computer programs available for the analysis of both thin and thick shells have been published (1,2). D. Bushnell (73) has written a computer program for shell analysis in which finite differences are used for the thin shell segments and discrete finite elements are used for the thick shell segments.

Cables

Reviews and summaries of computer programs for the analysis of cable systems have been published (2). H. T. Wang (74, 75) of the Naval Ship Research and Development Center has written a computer program called CABUOY. This program is for the time domain analysis of general buoy-cable-body systems.

Piping Systems

Reviews and summaries of computer programs for the analysis of piping systems have been published (1,2). HYTRAN is a new computer code developed to analyze the transient pressures produced in piping by strong motions resulting from a nuclear detonation or earthquake (76).

Components

Computer programs used for the analysis of structural members and mechanical elements have been surveyed in Ref. (1). This includes programs dealing with extension members, springs, torsional systems, beams, rectangular plates, disks and cross section properties. In Ref. (2) reviews of computer programs dealing with the specific subject areas, grillages, beams and frames are given.

Bridges

Detailed reviews and summaries of bridge analysis computer programs have been published for the following subject areas: bridge and girder systems (1), curved girder bridge systems (4) and bridge rating systems (18). Kabir, et. al. (77) have developed a computer program for the analysis of curved bridges on flexible bents.

Fothergill, et. al. have developed a system of computer programs which are used for the calculation of stresses and stress ranges in a bridge resulting from highway traffic crossing the bridge. BRGSTRS (78) is the stress analysis program and BRIGLDI (79) is the traffic loading generation program for the above system.

Computer-Aided Design

Computers are being used today to aid designers of Engineering and Architectural structures, ships, aerospace vehicles and especially buildings. In an exhaustive study by the U.S. General Accounting Office the status of computer aided design in the U.S. and foreign countries is discussed (20). Goel, et. al. review the computer programs available for building design in Ref. (4). In the same book is a related section on floor analysis and design (4). In Vol. II of the structural mechanics software series (18) there is a section on computer programs for cantilever wall design and finite element programs for pressure vessels.

Lo, et. al. (80) have developed a computer program for the design and analysis of steel transmission towers or general trusses. Successive iterations between analysis and design are performed within the program to achieve convergence to the final solution.

Various vehicle suspension system designs today are analyzed using computer simulation. The program ADAMS (Automatic Dynamic Analysis of Mechanical Systems) was used by Orlandea and Chace (81) to simulate the motion of a 1973 Chevrolet Malibu.

Sea Systems

Reviews and summaries of computer programs available for the design and analysis of ships have been published (1). Offshore oil exploration today is of great interest which makes the design and analysis of offshore structures of importance. Computer programs for offshore structure analysis has been reviewed (2).

A computer program has been developed to assess the stability of floating platforms (82). GBRP is a General purpose Bending Response Program used for ship vibration analysis. A new capability for calculating the transient response of non-uniform beam spring models has been added to GBRP (83). A computer program has been developed which can predict loads on cavitating hydrofoils (84).

Rail

Frequency domain computer programs developed or acquired by the Transportation Systems Center, Cambridge, MA, for the analysis of rail vehicle dynamics appear in two volumes (85,86). Complete details of algorithms and program capabilities are given in Vol. I (85); programs FULL, FLEX, LATERAL and HALF are presented. Volume 2 (86) contains the programs listings. Recent improvements have been made to DYNALIST II - a computer program for stability and dynamic response analysis of rail vehicle systems (87,88,89). DYMOL is a program which was originally written to calculate the dynamic forces applied normal to a rigid surface by moving traffic. Recent revisions allow the use of the latest version of DYMOL for the computation of dynamic loads at grade crossings (90).

Crash Simulation

Recent trends in the U.S. towards lighter cars plus the new codes for energy absorbing bumper systems have caused heavy activity amongst automobile manufacturers in the area of crash simulation. Occupant safety and vehicle crashworthiness are today's watchwords. Computer programs exist for computing the gross motion of the victim (4) and vehicle crushing dynamics (91) [Program UMUCS-1]. A summary of available 3D crash victim simulator programs has been published (4). An improved 3D crash victim simulator has been developed (92). The Highway Safety Research Institute (HSRI) has developed many computer programs for crash victim motion, impact data analysis, etc. A recent report describes all software available at the HSRI (93).

Other publications contain reviews and summaries of computer programs for crash simulation, the simulation of human body response to crash loads and highway vehicle handling simulation (2). MVMA (Version 3) is a 2D crash victim simulator program developed at the HSRI (94).

CRASH (95,96,97) is an accident investigation computer program designed to compute estimates of impact speeds and speed changes from physical evidence taken from the accident scene.

Lastly we have Barrier VII (98), a computer program for evaluation of automobile bumper systems.

Spacecraft

Reviews and summaries of computer programs available for the analysis and design of spacecraft structures (2) and solid rocket nozzles (18) are available. RETSCP is a new computer program for the analysis of rocket engine thermal strains with cyclic plasticity (99).

Rotary Systems

Reviews and summaries of computer programs available for handling rotor-bearing systems (1) rotating machinery (2) and torsional systems (2) have been published. DYMAC (100) (Dynamic analysis of Machinery) is a program which finds displacements, velocities and accelerations in planar machinery subjected to general force systems.

Noise Prediction

Reviews and summaries of computer programs available for aircraft noise prediction and highway noise prediction have been published in Ref. (2). T. Harris (101) of AFFDL, Wright Patterson AFB, OH has developed a computer program which will predict the acoustically-induced vibration in transport aircraft. The National Bureau of Standards has developed a mini computer-based system for the measurement and analysis of community noise (102). An algorithm has been developed which will produce isograms of sound levels from noise measurements made in an industrial facility (103).

A computer program (104) for predicting noise levels inside large enclosures due to one or more noise sources has been developed recently. Glatt, et. al. (105, 106) developed a program for the prediction of sonic boom from experimental near field overpressure data. Zakkay and Ting (107) have developed a CDC 6600 compatible nonlinear sonic boom analysis code. Noise prediction programs exist for a linear array of turbojet engines (108) and helicopter rotors (109). Computer programs have been developed for noise reduction of a particular aircraft (110,111) and for calculating noise during takeoff and approach (112,113,114,115,116). The Boeing airplane noise/performance program calculates takeoff and approach profiles, including noise abatement procedures as a function of several variables such as speed, thrust, etc. (117,118). Output includes predictions of noise under the flight path.

NOISEMAP (119,120) is a computer program which predicts community noise exposure resulting from aircraft operations.

Test Data Reduction & Processing

Reviews and summaries of programs available for the reduction/processing of data have been published (2). The mini-computer and cheap Fast Fourier Transform modules have changed most data taking and analysis to a digital format. The usage of a mini-computer to manage data for input/output to a narrow band real time analyzer has been published (121). A mini-computer based data gathering system for a shock laboratory has been implemented (122). An algorithm for computing optimum parameters of a transient sweep to match specified shock spectra has been developed (123). A computer program has been developed for the data reduction and evaluation of hearing test data (124).

Multiple Energy Domain Systems

Computer programs for multiple energy domain systems have been reviewed (2); this includes programs using bond graphs.

Symbolic & Algebraic Manipulation

Reviews and summaries of computer programs for symbolic and algebraic manipulation languages and their application in mechanics have been published (4).

Miscellaneous

A computer program for analyzing the dynamics and stability of parachutes has been developed (125).

AUSTRALIA NEW ZEALAND

Special Purpose Programs

OMEGA 2 is a finite element program which was developed by Dr. H. Nolle of Monash University (2). It calculates critical speeds and natural beam mode frequencies and mode shapes of shafts without damping. Provisions for including shear deflection, rotary inertia, shaft elasticity and support stiffness are included.

UNITED KINGDOM

General Purpose Programs

ASAS is a g.p. finite element code developed by Atkins R&D, Surrey, England. It consists of the programs ASAS-G, ASAS-HEAT, ASDIS and several pre- and post-processors. It is a well developed program which can solve linear elastostatic isotropic problems (18). It is a good program for linear analysis; the documentation is good and substructuring is available on one level now.

BERSAFE is a g.p. finite element code which has been under development since 1967 (18). It consists of BERSAFE, BERDYNE and various pre- and post-processors. The system is used at over 40 outside computer sites as well as by numerous users at the central site in London.

BERSAFE will analyze linear and nonlinear isotropic and anisotropic elastic-plastic structures; some large displacement analysis is also available. It has heat transfer routines and special rock behavior properties routines. BERSAFE seems to be a versatile program for both linear and nonlinear analysis. Substructuring isn't available now but will be added soon.

PAFEC is another g.p. finite element program which is a fully integrated system (18). It is well documented and a user's group exists. PAFEC can handle linear elastic isotropic and anisotropic structures. It will also handle nonlinear elastic and elastic-plastic materials.

A notable item about PAFEC is that it is easy to modify for engineering and research purposes. In fact, in-house users are encouraged to do this to solve special problems.

GENESYS is a general engineering system of computer programs for structural and civil engineering (1,4,20). It consists of a master program and a library of programs called subsystems. It is most similar to the MIT-ICES system (1,20). The GENESYS system has been marketed internationally, although its penetration into the U.S. market has been limited. However, its contribution to the applications of computers to building design is recognized as significant.

Special Purpose Programs

Material Mechanics

TF0747 (1S,-5S,-41) is a series of fracture mechanics programs developed by the C.A. Parsons Co., Great Britain (1). It has been applied to various stress analysis problems that occur in turbogenerators.

TESS is a thermal stress and creep analysis program developed by the Central Electricity Generating Board (CEGB), Berkeley, Great Britain (1). It is very similar to the program CREEP-PLAST which was developed under contract to the Oak Ridge National Lab, U.S.A. (1).

CANADA

Special Purpose Programs

Piping Systems

DYNAL is a program which was developed at Ontario Hydro, Toronto, Canada. It has been used for analyzing piping systems (1). It is not to be confused with STRUDAL II (DYNAL) (1).

Torsional Analysis

TOFA (TOrsional Frequency Analysis) is designed for studying torsional vibrations of a mechanical system consisting of a set of connecting shafts with disks concentrated along the lengths of these shafts (1). It is designed to handle systems of not more than 50 stages, where a stage consists of a disk and a shaft. It was developed by the Atomic Energy of Canada, Ltd., Chalk River Nuclear Lab., Ontario.

Computer-Aided Design

Reviews and summaries of programs available for building design and curved girder bridge systems are available in Reference (4). Five of these programs were developed in Canada, namely AMECO (building design), BR200 (bridge analysis and curved gird), CISC (column design), CUBCAN (curved gird bridge design) and DAPS (building design). Reference (4) contains detailed descriptions of these programs.

FRANCE

General Purpose Programs

TITUS is a finite element program which will handle 1-D, 2-D and 3-D problems (1). It will do statics and temperature fields. TITUS was developed by Vouillon-Citra, Velizy.

Special Purpose Programs

Damping

ASTRE is available from the Institut National des Sciences Appliquees, Laboratoire de Mecanique des Structures, Villeurbanne. It accepts a complex stiffness matrix and the solution is found by modal superposition. It has been successfully used to solve the response of thick structures damped by visco-elastic layers and subjected to harmonic forcing. The loss factor and storage modulus can be functions of frequency (2).

Symbolic and Algebraic Manipulation

SCHOONSCHIP is a symbolic manipulation program designed more than ten years ago by M. Veltman at CERN (4). It is intended for doing long - but in principle straightforward - analytic calculations. Its major applications are in the fields of high-energy physics, but it is sufficiently general to have a broader field of applications. SCHOONSCHIP is written almost entirely in CDC 6000/7000 machine code.

ISRAEL

Special Purpose Programs

M. Ziv (126) has developed a computer program which calculates the transient response of an elastic half space to an embedded cylindrical load by a two-spatial characteristics computer code.

ITALY AND GREECE

General Purpose Programs

EURDYN (127) is a finite element computer program that was developed in Italy to analyze transient dynamic problems stemming from fast reactor safety. This program handles problems with material nonlinearities, small strains and large linear or angular displacements that frequently occur in fast reactor engineering.

PAS is a general purpose finite element program which can be used for analyzing linear elastic isotropic and anisotropic structures (18). It is a small program with few elements and no substructuring capabilities. However, it is relatively new (started in 1973) and only 2 man years of development time have been spent on it so far. A users group does exist and chances are the program will probably develop into a far more useful one in the future.

Special Purpose Programs

Creep Analysis

GOLIA was developed at the EURATOM Joint Nuclear Research Center, Ispra, Italy, and is designed to solve creep problems in plane stress, plane strain, generalized plane strain, and axisymmetric structures (1).

Computer-Aided Design

MEDES is a mechanism design program developed by Bona, Galleti & Lucifredi of Olivetti and University of Genoa, Italy (2). Its capabilities include planar mechanisms analysis and synthesis, numerical optimization and analysis of general mechanisms. It will also do cam and gear design. It interfaces with a drawing management system and N/C machines

Offshore Structures

DISMAR/CARGON is a finite element program which interacts with NASTRAN. D/C is used for time history analysis, substructure analysis, etc., of floating or fixed-based platforms (2).

JAPAN

In terms of number of computers in use, Japan is second to the United States. Their greatest usage of engineering programs are the large finite element codes, for the most part U.S. developed codes. Japan, being earthquake prone has made many advances in the application of large structural programs to the design and analysis of earthquake resistant structures. Their automotive industry has been using programs to improve vehicle crashworthiness. Similar to the situation in the U.S., computer-aided design of buildings has been somewhat less exploited due in part to the attitude of architects towards computers. It is a fairly well established fact that the Japanese use of computer-aided design in shipbuilding is far superior to the United States and well developed.

General Purpose Programs

ISTRAN/S - This general purpose finite element program was developed by Ishikawajima-Harima Res. Inst., Tokyo (1). Its capabilities include small and large deflections, bifunction buckling, modal analysis. It uses the displacement method, it has 1D, 2D and 2D-curved elements. It will handle isotropic and non-linear elastic materials. It has a pre-processor and plot routines. It is distributed by its developer, I HI.

Special Purpose Programs

Numerical Methods

SUBCHEB is a routine which will calculate the smallest eigenvalues and eigenvectors for the general eigenvalue problem (2). Its algorithm is a modification of Bathe's subspace method [routine SSPACE in Ref. 2]. Acceleration procedures are applied to the initial subspace iteration and Sturm sequence checks. Computation time is reduced by 75%. Available from the Computer Center University of Tokyo.

Frames

FRAME is a proprietary program for frame analysis available only on a computing service basis from Nippon Univac Co., Tokyo (2). Its capabilities include static analysis, mode and frequencies, and transient displacement by mode superposition and direct integration of linearly elastic frames.

Components

SASP (Structural Analysis of Stiffened Plate) can perform the stress analysis of a reinforced rectangular plate under later loads (1). It is easy to use and is quick. It operates on IBM 370 system and is used mainly for ship structures. It was developed by M. Higuchi, Ship Res. Section, Nippon Kokan KK Keihin Works, Kawasaki, Japan.

VASP (Vibration Analysis of Stiffened Plate) is a companion program to SASP but for dynamic analysis (1). It is used primarily for ship structures and is available from the same developer as SASP (1).

Computer-Aided Design

Japan is putting an intensive effort into optimization of the design of machine tools, e.g., to eliminate chatter, etc. Many computer programs have been developed in all parts of the world which simulate the dynamic characteristics of machine tools in the design stage. A good review of these programs is given by Cowley (128). Yoshimura describes an optimization technique that utilizes lumped-parameter, distributed mass and finite element methods together (129).

The system of programs optimizes with respect to the static and dynamic characteristics of the machine structures (129). Optimization is based on the energy balance principle. The program is new in that it combines the advantages of lumped mass, distributed mass and finite element modeling in one system.

Ship Structures

Many design and analysis programs have been developed by Japan's powerful ship building industry. Some of the programs are as follows:

BCSTAP - A finite element program which performs structural analysis of hold parts (1).

CONDESS (CONtainer Ship DESign System) - This program determines structural arrangement and member scantling. The 3D structural analysis is based on frame theory (1).

PASSAGE (Program for Analysis of Ship Structures with Automatically Generated Elements) - This program performs a linear elastic membrane analysis of a total ship structure (1).

TSHULGDR is a program which calculates the fluctuating normal stresses in the hull girder caused by the ship motions and dynamic wave loads in the seaway for a given probability of occurrence (1).

ZPLATE performs stress analysis of large 3D structures which can be modeled by plain or orthotropic plates. It is a finite element program (1).

X1 Z058 performs a frame analysis of tankers by the stiffness and transfer matrix methods (1).

Z1 Z072 determines bending and torsional strength of ships having large hatch openings (1).

Reactors

Takemori et. al. (130) have developed a computer program for calculating the non-linear dynamic response of a reactor containment structure.

NETHERLANDS AND BELGIUM

Special Purpose Programs

Bond Graph Technique

In the Netherlands they have written a computer program using the THTSIM language which runs on the PDP-11 minicomputer for the interactive simulation of non-linear bond graphs (131).

SWEDEN, NORWAY, DENMARK

General Purpose Programs

SESAM-69 was developed by Det Norske Veritas, Oslo, Norway (1). It has a good element library and is oriented to the extensive use of super elements. Although the program was developed primarily for ship applications, it has capabilities that make it really a general purpose finite element program. It operates on all major computer systems and is proprietary.

SAMBA is a general purpose finite element program developed by H. Jareland of SAAB-Scania AB, Sweden (1). It has 1D and 2D capabilities. It includes static analysis and stationary temperature fields. It will handle isotropic, anistropic and layered media.

Special Purpose Programs

Frames

PFVIBAT is a computer program for plane frame analysis which was developed by B. Abesson and H. Tagnfors, Chalmers University of Technology, Sweden (2). It will compute modes, frequencies and responses to harmonic excitation for linearly elastic plane frames. A recent publication by Akesson describes its current capabilities (132).

Fracture Mechanics

NV344 is based on the multi-level super element technique and can only be used in combination with the large-scale program SEASAM-69 (1). It performs fracture analysis based on the strain energy release rate. Fatigue propagation analysis is carried out based on computed stress intensity factor. Information on NV 344 is available through B. Aamodt, University of Trondheim, Norway.

FEMWC, FEMWC. ANIS is a fracture mechanics program developed by E. Byskov, Technical University of Denmark (1). It calculates stress intensity factors using the finite element method. It has a special cracked element with a square root stress singularity. Automatic mesh generation is included for rectangular plates with edge cracks.

Aeroelasticity

V.J.E. Stark (133) of SAAB-Scania, Linboping Sweden has developed a program for the calculation of aerodynamic forces on oscillating wings by using polar integration variables.

Offshore Structures

CONVIB (134) is a computer program for the dynamic analysis of offshore structures including soil-structure interaction and wave forces. It is based on a linear structural model consisting of beam elements.

SWITZERLAND

Special Purpose Programs

Transient Analysis

TUGSIM-10 (135) is a program which was developed for the transient analysis of nuclear gas turbines in a power plant under both operational and accidental conditions. In (135) DuPont, et. al. discuss the use of TUGSIM-10 to analyze a depressurization accident. Also, emergency shut down calculations for a 30 MW (c) fossil fuel plant are compared with measurements.

Symbolic and Algebraic Manipulation

SYMBAL is a symbolic manipulation program which was developed originally in 1965 by M. E. Engeli, FIDES Trust Co., Zurick (4). Its syntax is similar to ALGOL. Ref. (4) contains detailed information on SYMBAL.

WEST GERMANY

General Purpose Programs

Germany has several general purpose finite element programs including ASKA-II (2), COSA (2), TOPAS (18) and TPS 10 (18).

ASKA was started in 1965 and is Europe's answer to NASTRAN (18). It consists of the parts, ASKA-I, ASKA-II, ASKA-III-1, ASKA-III-2 and a number of pre- and post-processor programs. ASKA can handle linear elastic isotropic and anisotropic structures. It will handle non-linear material properties, elastic-plastic and creep. It is a powerful program which enables the experienced user to analyze a great variety of problems. For the less experienced users there exist rigid formats. System support and maintenance is good.

DYNAN, as the dynamic part of ASKA is called, was developed much later than the static part and is not nearly as versatile. ASKA is one of the few packages developed in Europe which is being used in the U.S., although it is not offered by any major computer network in the U.S. (2).

COSA, developed by Dornier GmbH, is a linear finite element program with a good library (2). DYNAME is the name of the part of COSA which performs dynamic analysis.

TPS-10 was developed by T Programm GmbH (18) starting in 1971. It consists of four different versions relating to program size. Full details are given in (18). It was developed for linear elastostatic isotropic and anisotropic structures. It can also handle limited nonlinear elastic structures. One of its most notable features is a powerful method for introducing complex boundary conditions via functions. TPS-10 is well suited for small to medium sized problems.

PRAKSI is a medium sized finite element program developed by Rechen-und Entwicklungsinstitut fur EDV in Bauwesen, Stuttgart (1). It will do 1 and 2D static problems both isotropic and anisotropic materials.

Special Purpose Programs

Components

K. Hain (136) has developed a computer program for examining curvatures and accelerations of rectangular link-connecting points.

Torsional Analysis

A series of computer programs have been developed in West Germany for analyzing the dynamics of torsional systems. Programs have been developed for the calculation of flexural vibration of turbomachinery shafts (137) and for general torsional vibration problems (138).

BEIGE (139) is a computer program for analyzing the torsional dynamics of machine tool drives, especially spur gear drives. BEIGE requires as input only data taken from construction drawings.

Computer-Aided Design

West Germany is a world leader in the utilization of computers in design. The West German Government has established a national technological policy and is financially supporting computer-aided design development (20).

Traditionally, strong support of technology has been an integral part of the total policy of the West German Government. Gesellschaft fur Kernforschung (GFK), located at the Karlsruhe Nuclear Research Center, is the West German Government's project manager for computer-aided design (20). In June 1976, GFK was supporting 100 projects relating to civil engineering. The project selection process is cumbersome but is designed to prevent reinventing the wheel and to insure that the research and development will be completely practical in nature. This program doesn't support 'science for science's sake;' the end result must be an application for use in industry (20).

A. Kanarachos (140) has published a review of all available optimization methods of interest to designers. The optimization methods which are well established in other areas (e.g., control theory, machine tool dynamics, space flight, etc.) are today being applied to the construction field. Research on machine tool design, especially with regard to the systems dynamics, is being actively funded. The Laboratorium fur Werkzeugmaschinen und Betriebslehre (WZL) of the Rheinisch-Westfalischer Technischen Hochschule, Achen is actively developing computer-aided design techniques; especially of numerically controlled machine tools. D. Wunsch and A. Seeliger (141)have applied computer-aided design optimization techniques to reduce vibration in machines. They give three examples in their article. Frolich (142) has published a compression spring design optimization program for a desk calculator.

Chapter 3

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Chapter 4

ENVIRONMENTS

INTRODUCTION

This section is concerned with work or programs related to the understanding and definition of dynamic environments that produce the loads and stresses affecting equipment, structures and humans. It might be said that these environments are the roots of all other problems in our technology. Our design approaches, analytical tools, isolation and damping methodology, and performance specifications all are influenced by an understanding of these environments and their effects. The definition of these environments is not simply a matter of numbers representing amplitudes and frequencies. It also involves an understanding of the nature of the sources and the factors which might play a part in modifying those sources, either at the source or in the transmission path to the object of concern. For ease of discussion, six basic environmental categories have been selected.

UNITED STATES

Acoustic

Acoustic environments and noise are presently of great concern in the United States. Until several years ago, the major concern was with noise of sufficient high intensity to cause structural or physical damage. The vibration engineer was and is well aware of the excitations that can be induced in his structure and equipment by high-level sound. The biodynamicist is aware of the potential damage to humans from extreme noise environments. More recently we have become concerned with long-term physiological and psychological effects of noise, with basic comfort in the community, or working environment, and with effects on safety and efficiency. In this section work relating to noise sources, transmission and definition will be discussed. Problems related to potentially-damaging vibration induced by high-intensity sound is covered in other parts of this report.

Aircraft Noise

In the world today one of the most significant noise producers is the aircraft. Of the several classes of aircraft, the military or commercial jet and the helicopter create the most noise-related problems. In the case of the jet aircraft, considerable work has been done to understand the basic noise-producing mechanisms (1, 2, 3, 4, 5). Extensive monitoring of aircraft noise has been accomplished and the validity of the data has been examined (6, 7, 8). Similarly, helicopter noise sources have been measured or examined (9, 10, 11, 12). To be sure, the techniques for measurement and prediction of aircraft noise levels have advanced in recent years. As valid data is gathered it is applied to the design of aircraft structures and equipment both in the interest of increased reliability of aircraft systems and in the reduction of noise in the vicinity of airports.

Sonic Boom

Until the beginning of operations of the British/French SST, the sonic boom was a problem created only by military aircraft. The shock wave produced as an aircraft enters supersonic velocity could have deleterious effects in populated areas. Numerous regulations in the United States prohibit supersonic activity but the effects have been examined (13, 14).

Construction Noise

Equipment used in various construction activities produce noise. An outstanding example is the piledriver (15). The Army Engineers have examined this area (16) with a view to noise control.

Machinery Noise

Machinery used in various industrial operations produce undesirable noise in the working or community environments. Studies on the nature (17), method of prediction (18, 19) and measurement (20) of these environments have been conducted in the United States.

Engine Noise

Both diesel and gasoline-driven engines are noise producers. The effects of operating parameters (21), engine components (22) and exhaust systems (23) on noise levels has been examined.

Vehicle Noise

Aside from noise produced on highways by motor vehicles, the basic noise producing mechanisms on these vehicles have been examined (24, 25, 26, 27, 28). The U.S. Army, in particular, is interested in vehicle noise from the standpoint of potential detectability during combat conditions.

Highway Noise

The impact of highway noise on communities has become increasingly important. Highway noise environments are defined in statistical terms (29, 30, 31). Methods for predicting, evaluating and alleviating traffic-generated noise have been proposed (32).

Community Noise

Community noise may originate from a number of sources. The environment is difficult to describe (33, 34) and the realistic effects are difficult to assess (35). Studies have been made on a number of modifying parameters such as tall buildings (36) and highway expansion (37).

Industrial Noise

Federal law requires that industrial noise be kept below certain levels. Common sense dictates that an employee's hearing must be protected. Advancements have been made in modeling the problem (38) and defining the characteristics of the environment (39). Proposals have been made (40) for solving the problem.

General

Acoustic environments are extremely difficult to define. There are many sources, many transmission paths, and many different effects depending upon the specific problem being faced. In the United States progress has been very good, but there is still a long way to go. Many interim solutions to acoustic problems are based in part on technological achievements and in part on someone's best judgement. In spite of this, our progress in understanding sound propagation, transmission through materials, reflection, scattering, and attenuation has been significant.

Periodic

Periodic or steady-state vibration is characterized by defining the frequency and amplitude. When periodic functions occur in the real world, they seldom occur as simple sinusoids. When they do occur, the methods of measuring and defining such functions are straightforward. The single most important use of periodic excitation is in the test laboratory, usually during the design development phase of a component or a system.

Random

Random environments are defined in terms of stochastic data which consists of any data sample, regardless of its origin, which cannot be represented by explicit mathematical relationships. It can be described in terms of probability statements and statistical averages. This type of data occurs routinely in a number of application areas related to noise and vibration. Rocket or jet engine noise, aerodynamic noise and the structural vibration that may be induced therefrom are examples of random environments. Indeed, even seismic and transportation environments may be described in stochastic terms. These environments can be measured and presented in the form of statistical distributions usually in terms of power spectral density. An excellent treatment of how this is done is given in (41). The usefulness of the measured data depends upon the specific application which governs the methods of data analysis and presentation. These topics are more properly covered elsewhere in this report.

Seismic

The principal source of seismic environments is earthquakes. Strong motion accelerations are also produced by nuclear explosions and by such activities as quarry blasting. The environments produced by these events are similar, yet different. For purposes of this report the greatest advances in technology have been related to earthquakes and nuclear ground shock. An excellent semi-technical discussion of this area is given by Bolt (42). One of the best works on the application of earthquake data is offered by Newmark (43). Earthquake environments are usually described in terms of response spectra. As might be expected, because of the great variations in the nature of the earth's surface, these spectra vary at different sites. This problem has been examined (44, 45) and guidelines for application of earthquake data under different conditions have been prepared (46). The relationship of the environment to the distance from the epicenter for an earthquake of a given magnitude has been studied (47, 48, 49). In the United States, California is a high-risk earthquake area and has been the focal point for many studies. Typical of these are the experimental (50) and analytical (51) studies of the seismic environments produced by the San Fernando earthquake in 1971.

Violent earthquakes may have serious effects on structures such as dams, bridges, buildings, and conventional and nuclear power plants. The methods used to solve specific problems of this nature will be discussed in the appropriate place. It is proper to mention here that the complete definition of earthquake input extends from the ground into the structure. To do this it was necessary to develop an understanding of soil-structure interaction (52) and structural response (53). That the study of earthquakes is important in the United States is emphasized by the fact that earthquakes of magnitudes greater than 3.0 on the Richter Scale occur at the rate of more than 80 per year. Studies continue to develop methods of reducing loss of life and property during catastrophic events.

Shock

Mechanical shock environments have been defined as sudden changes in velocity or as transient, or special cases of, vibration. Shock is a transient, as opposed to a steady-state, phenomenon. It is measured in terms of a time history of the event. This time history may be presented as motion (acceleration, velocity or displacement) or loading (force, torque, pressure or stress). The method used to characterize the environment depends upon the source of the shock and the ultimate use to which the measured data will be put. In general, all shock environments are produced either from explosions, impact or natural phenomena. It is with special cases of each of these phenomena that our technology is primarily concerned. Explosions, for example, may be conventional or nuclear, occurring in the air, underwater or underground. The firing of a gun or launching of a missile produces explosive environments. Impact occurs during vehicle crashes, aerial delivery operations, handling and dropping during transportation and manufacturing, rail car coupling and other events. Earthquakes are the major natural phenomena producing shock. Seismic environments were treated in the previous section.

Explosive Shock

The major concern of the United States Navy with respect to shock is with the shock produced by non-contact underwater explosions. The environment is usually defined in terms of a step velocity change produced in a ship's structure and equipment. This is a wartime environment and much of the input data is classified and will not be discussed here. The best single reference on this subject is by Cole (54). The most important single characteristic of shocks produced by underwater explosions is their variety. They cannot be defined exactly. The methods of testing to assure survival in this environment will be discussed later in this report.

Baker (55) has written an excellent text dealing with the phenomenon of explosions in air. The environment of concern to above-surface structures or equipment is the air blast, a shock front described in terms of overpressure. Blast produced by the firing of arms is of concern for sensitive equipment in the vicinity of the gun. Of major concern, however, is the air blast produced by actual or simulated nuclear explosions. Measurement technology has advanced (56, 57) in an effort to define the environment in more precise terms and to understand the loading mechanisms for design purposes (58). It is known that airblast induces ground shock and attempts have been made to understand this mechanism (59) and the extent of its effect (60). The Defense Nuclear Agency maintains a collection of nuclear blast and shock data and has sponsored a master file of such data from high-explosive events (61, 62). In the civilian world the problem of the effects of industrial blasting operations has been studied (63).

In the aerospace field, the separation of stages of a missile or launch vehicle or the blowing of a shroud is usually accomplished by an explosive device. The shock produced, normally called a pyrotechnic shock, is characterized by very large amplitudes and extremely short duration. Significant work has been done (64, 65, 66) to understand these environments and define them. Methods of simulation, reduction, specification, and design with respect to these environments will be discussed later.

Impact Shock

Impact is a process involving the collision of two moving bodies or a moving body and a fixed body. Such impacts may be broadly defined in terms of the effective impact velocity. The shock environment produced by impact is a function of the characteristics of the impacting bodies, therefore discussion of the analysis of response or effects is better left for more appropriate sections in this report. It is appropriate, however, to mention some of the more important areas of research related to impact.

Crash research involving aircraft, automobiles and trucks is at a high level of activity in the United States. The goal is first to minimize loss of life and injuries and, second, to lower property damage. At least some efforts (67) have been made to estimate the impact loads. Transportation and manufacturing handling shock, along with railcar coupling, are important areas, but very little new has been contributed to the technology in recent years. Impact during aerial delivery has been of concern for a number of years. In at least one case (68) modern methods of analysis have been applied to this problem. It should be noted that impact is frequently used as a tool to determine structural or material properties, as illustrated by a report on concrete (69).

Other Shock Environments

Discussion would not be complete if it were not mentioned that there are other shock environments which do not fit precisely under the category of explosions or impact. Parachute opening shock, water entry shock and certain manufacturing processes, such as magnaforming, fall into this category. Work on parachute opening shock was concentrated in an earlier time period, although some recent contributions (70) have been made. Water entry shock is of concern for items such as mines laid from the air (71) or, in the case of the Space Shuttle, the recoverable external tanks. Magnaforming, for example, was used to seal the fuselage of the TOW missile and produced an undesirable shock for the interior components.

The shock environment can create a lot of different problems, whether it causes catastrophic failure or performance malfunction. The problems caused are usually major and difficult to handle. It is particularly troublesome when a shock problem occurs in the presence of a vibration environment, causing a conflict in the methods of solution.

Transportation

Transportation dynamic environments, as considered in this report, are those environments which have effects on either humans or cargo. For humans, the concern is with the effects on safety, health, or comfort. For cargo the effect to be avoided is damage. Shock or impact environments related to transportation were discussed in the previous section. This discussion will be concerned only with the broader-based environments defined above.

Considerable work was done in the 1950-1960 time frame with respect to defining transportation environments for cargo. Results of this work can be found in the earlier publications of the Shock and Vibration Information Center and will not be referenced here. Recent publications (72, 73), although sparse, contribute to increased understanding of these environments. The Department of Defense has developed a different approach for the description of shock environments for highway vehicles (74). Special studies have defined the dynamic environment of landing craft (75) and forklift trucks (76).

Most of the health and safety consideration for humans (aside from motion sickness) are related to acoustics or shock, both covered earlier. Those environments related to comfort are also commonly defined as ride quality. This area was exhaustively addressed at a symposium in 1975 co-sponsored by the National Aeronautic and Space Administration and the Department of Transportation (77). Papers published addressed the technology needs (78), design criteria (79), simulation (80) and many other areas. All modes of transportation were covered. There was even a paper on ride quality in high speed ships (hydrofoils) (81). This indicates a significant trend, since on-going research on new transportation media, such as tracked-air-cushion vehicles, considers ride quality to be a part of the design phase.

ENVIRONMENTS

AUSTRALIA AND NEW ZEALAND

Acoustic

Acoustic environments and noise are also of concern in Australia. In addition to studies of underwater sound propagation they are interested in traffic noise, machinery noise, and sonic boom.

Traffic Noise

Traffic noise levels were measured on a commercial main street and the study not only revealed a need for urban planning it also revealed that uncontrolled vehicle use in commercial districts could be a health hazard.

An apparent weakness in techniques for studying sound propagation in streets is their inability to adequately consider the effects of sound scattering from objects. A technique for analyzing the sound field in terms of its propagating modes was developed which allows the effect of scattering to be calculated, using a simplified model of the scattering surface (82). The mechanism of tire noise has also been studied since it is a major contributor to traffic noise (83).

Sonic Boom

Sonic boom propagation depends on atmospheric and flight conditions. A study was performed to determine the factors affecting vertical reversal of sonic boom ray paths and sonic boom ray path curvature (84).

Machinery Noise

The noise radiation characteristics of punch presses as a function of capacity and load have been investigated (85). Studies of sound radiated from colliding spheres have also been performed and although they are of a more fundamental nature they might be useful in understanding the mechanism of sound radiated from colliding surfaces. The noise radiated by diesel driven front end loaders has also been investigated to determine the significant noise levels and their sources (86).

Seismic

Interest in the seismic environments includes ground motion due to both the natural causes, earthquakes, and man-made causes, surface or underground blasts. In the latter case studies have been performed to determine the significant factors that effect response of nearby objects to explosions as well as blasting techniques that can be used to minimize damage and meet established response criteria (87, 88). Seismologists in New Zealand are interested in predicting when and where earthquakes will occur. Several New Zealand seismologists visited the Peoples Republic of China a few months after the February 1975 Haicheng earthquake to learn about their successful earthquake prediction methods (89).

UNITED KINGDOM

Acoustic

General

Noise pollution is a serious concern in Great Britain as well as in other countries. One study was carried out to define future targets for noise reduction and future noise levels that need to be imposed to reduce noise pollution (90). A second study also addressed the noise pollution issue in terms of the trends in airplane noise near airports and traffic noise on highways (91). Another study described the development of an index predicting the annoyance due to both aircraft noise and road traffic noise (92). Two surveys on noise legislation have been published. One concerns external industrial noise (93), the other concerns occupational noise exposure (94).

Aircraft Noise

Many studies have been undertaken to define the sources of jet engine noise which is a major contributor to aircraft noise and a compendium of sources has been drawn up (95). A study was undertaken to assess the impact of the growth of civil aviation on the noise measurement area. It described how the demands were met and future development that is needed (96). Another study was undertaken to determine the relationship between noise level and the number of flights (97).

Measurements of human response to aircraft noise almost always result in a wide variability of measurements. A task was undertaken to eliminate some of the causes of the variability of measurements of human response to aircraft noise (98). One study was undertaken to study the sources of internal noise for general aviation aircraft and to determine the noise transmission paths (99). Helicopters are another and a growing aircraft noise source in Great Britain. A study was undertaken to determine the feasibility of rating helicopter noise (100).

Sonic Booms

The development of the SST has generated a significant interest in Great Britain in the response of structures to sonic booms. One study was undertaken to assess the response of the lead framework in leaded light windows to repeated sonic booms to determine the threshold of damage (101).

Airport Noise

The noise in the vicinity of commercial and military airports is also a major concern in Great Britain.

In one study of airport noise a noise burden factor for rating the noise nuisance value of an airport was proposed (102).

The problem of predicting noise levels in the vicinity of airports was also studied. A preliminary design guide was drawn up to assist planners in assessing an airport's noise nuisance with respect to city centers (103). A scheme for predicting airport noise that required a minimum amount of information on aircraft movement was developed. A standard case relating to a fully developed regional airport was defined (104).

Noise exposure criteria in the vicinity of civilian airports have been formulated in Great Britain. The noise level from aircraft in the vicinity of military airfields was measured and compared to the noise level criteria for civilian airports. The object of this study was to develop noise criteria in the vicinity of military air bases (105).

Traffic Noise

Next to aircraft noise traffic noise in Great Britain is a major concern and many studies were undertaken to define the nuisance and develop techniques for predicting the noise intensity.

A laboratory study was performed to measure the traffic noise levels that interfere with speech and communication both inside homes and outside (106). The noise nuisance caused by traffic in residential areas was studied. A social survey was performed and noise levels were measured in the vicinity of dwellings (107, 108). In addition a community survey was undertaken to determine the reactions freely flowing and congested flowing traffic on a nearby expressway. Another purpose of this particular study was to test existing noise indices to determine if they could be used to predict community dissatisfaction to traffic noise (109).

Several studies were carried out in Great Britain to develop techniques for predicting road traffic noise. One study led to an improved procedure for predicting noise levels and it has been incorporated in noise insulation regulations in England (110). Another noise predictive scheme was developed from a combination of analytical considerations and a noise peak level statistical model derived from published data (111). Studies have also been undertaken to develop techniques for predicting noise levels due to the interrupted flow of street traffic. An equation was developed from measurements in one city and it was validated by comparing predicted noise levels against measured values in two cities (112). A mathematical model for traffic noise was developed that goes beyond the noise produced by stationary sources (113).

Traffic noise measurements have been made on hilly roads under steady vehicle flow conditions to determine how the noise intensity varies with traffic flow, the amount of grade, and the passage of heavy or light vehicles (114).

Vehicle Interior Noise

Interest in noise levels inside of passenger vehicles exists in England. Noise measurements were made inside of a wide variety of vehicles to obtain data to set criteria for acceptable noise levels (115).

Miscellaneous Noise Sources

Noise data were collected from a variety of commonly used household appliances over which the user has no control of the noise levels (116). Noise levels were measured around refineries to develop techniques for predicting noise levels in the vicinity of the plant (117).

Acoustic Studies

Many studies of sound propagation have been made in England to develop techniques for predicting the noise intensity at locations that are remote from the source.

A review of the literature on the effects of various types of ground cover on the attenuation of sound was written. It pointed out the need for further research to develop accurate predictive schemes that consider the noise attenuation effects of ground cover (118).

Effects of the atmosphere in attenuating aircraft noise at various heights of flyover and for various atmospheric conditions were experimentally determined. The data were obtained to assess the standard atmospheric attentuation coefficients currently in use (119).

CANADA

Acoustic

Aircraft Noise

High interest in aircraft noise exists in Canada; the interest is in both external noise and internal or crew station noise. Noise measurements were made on a four engine STOL turboprop aircraft and the results showed that a 95 PHdB noise level requirement at 500 ft sideline at takeoff could be met (120). This indicates that it is possible to build a quiet STOL transport aircraft. Internal noise measurements were made in two helicopters to determine the crew station and cargo/passenger area noise environments and the adequacy of hearing protection measures for occupants in these areas (121). A noise survey was also conducted in the cockpit area of a modified aircraft to determine the effectiveness of the floor and mufflers in reducing cockpit air conditioner noise.

Sonic Boom

Measurements of the sonic boom pressure distribution were made inside of a plaster and wood construction room to determine the effect of window size and window orientation with respect to the sonic boom wave on the onset of cracking.

Community Noise

Several studies have been performed that relate to the community noise problem. A study of noise pollution sources and methods of controlling noise was performed (122). A study of the ability to predict the subjective reaction to road traffic noise was undertaken to determine if the data that were obtained meet the assumptions of a regression model that was established for predicting the community response to traffic noise. Two studies of outdoor sound propagation were undertaken. In one case the sound measurements over grass covered surfaces at ranges of 1 to 1000 feet were made to determine the effects of ground cover on horizontal sound propagation (123). Another study was undertaken to determine the effects of sound propagation in a temperature inversion and ground reflection on the sound pressure level at a receiver large horizontal distances from the source (124). Both of these studies would be very useful in predicting sound pressure levels at locations remote from unwanted noise sources such as airports, quarries, noisy industrial plants and the like. These techniques might also be useful in making more accurate predictions of noise levels either in surrounding communities or even at locations that are remote from activities such as explosive testing or rocket firing.

Vehicle Noise

Criteria for wayside noise limits of trains were developed in terms of energy equivalent sound level for speech interference or community annoyance, or hearing hazard. Existing knowledge of the previously mentioned factors and sleep disturbance were previously reviewed; since no criterion for sleep disturbance was found it was not included in the noise limit criteria (125).

FRANCE

Acoustic

Aircraft Noise

The Advisory Group for Aerospace Research and Development (AGARD) has published a lecture series. One of these lecture series publications is on aircraft noise generation, emission and reduction (126). The physical properties of aircraft noise are summarized. In a similar AGARD lecture series publication an up-to-date account and authoritative appraisal of aerodynamic noise concepts including theory and experiments is presented (127).

Sonic Boom

A. Dancer and R. Franke have studied the response of guinea pigs' inner ears to N-shaped waves simulating the sonic boom (128).

Industrial Noise

The impact of the 11 April 1972 French decree on noise control has been analyzed from the manufacturer's standpoint (129). The noise reduction of four-wheel drive loaders is presented as an example of the application of the decree.

Highway Noise

ONR London has studied the control of road traffic noise in France and has issued a report on the subject (130).

Random

The roughness of runways can be described in statistical terms. It causes a 'random' excitation of the aircraft on takeoff. J. Drevet has studied the effects of runway roughness on the dynamics of an aircraft during takeoff (131). Aerodynamic random excitations of aircraft have also been studied (132).

Shock

B. Duperray has studied the kinetic energy absorption of shocks by composite materials (133). This is a final report which also contains a list of laboratories in France dealing with composite materials. C. Lalanne has published a two volume work on the simulation of shock environments (134, 135). Different analysis methods are also discussed in the two volumes.

Blast due to an explosion, landing shock and projectile impact shock on an aircraft are all discussed by C. Petiau in a paper which was presented at an AGARD specialists meeting on impact of structures (136).

INDIA

Acoustic

Sonic Boom

The response of a curved bridge deck to sonic boom has been studied (137). The response of the bridge to pulses of various durations and shapes is computed using the normal mode method.

Random

R. N. Iyengar has developed a method for calculating the response of a second order nonlinear elastic system to random excitation (138). Using this method Iyengar finds good comparison between the predicted and the exact steady state probability distribution of a Duffing oscillator under a white noise input.

Shock

H. R. Srirangarajan and P. Srinivasan have computed the response of a nonlinear single d.o.f. system to a pulse excitation. The method was applied to a Duffing oscillator subjected to various pulses (139). The shock response of real single d.o.f. systems can be calculated using this method.

ISRAEL

Acoustic

Highway Noise

V. F. Ollendorff has developed a theory which predicts the sound field in road tunnels as a function of the size, acoustic properties of the tunnel and traffic flow density (140).

Random

E. Ghandour has developed a method for calculating the propagation of waves in a 1-dimensional random medium (141). Expressions are given for the statistical properties of the reflected and transmitted waves.

ITALY

Acoustic

Acoustic Studies

Underwater acoustic environments are studied extensively in Italy. Typical studies include predicting and measuring acoustical reverberation intensity (142), developing models of sea roughness (143), prediction of underwater sound propagation (144), and scattering of sound waves by immersed rigid bodies (145).

An interesting application of acoustics in Italy is the use of sonar arrays for medical diagnostics. Frequency spectra data for a resonant ceramic element were collected to provide design information (146).

JAPAN

Acoustic

Machinery Noise

Nishibe and Kaneko (147) have developed design criteria for the construction of low-noise high-voltage induction motors.

Studies of the noise sources in fans are in progress in Japan. Fukano, et al (148,149) have determined that wake width is one of the factors controlling turbulent noise in low pressure axial flow fans. Wake width is defined as the sum of the blade thickness and the displacement thickness of the boundary layer at the trailing edge of the blade.

Susuki and Ugai (150) have made experimental measurements on the effects of tongue clearance and mouth ring clearance on the noise emitted by high specific speed airfoil fans.

Engine Noise

Murayama, et al (151,152) have made studies of the noise sources in diesel engines. In one study (151) they separate combustion noise from engine noise. In the second study (152), the problem of similating diesel engine combustion noise was tackled.

Vehicle Noise

Noise reduction studies have been made for small vehicles (153) and high-speed railways (154).

Highway Noise

Z. Maekawa (155) has reviewed the methods available for shielding highway noise. He also presents new results of experimental studies and introduces some theoretical approaches.

Random

M. Ohta and some associates (156,157,158) have developed new theoretical methods for random processes which have application to random noise sources. Kameda (159) has developed methods for estimating the maximum response of structures to nonstationary random earthquake motion (159).

Seismic

Being an area of high earthquake activity Japan has developed a strong national program for earthquake resistant design. The Earthquake Resistant Structure Research Center (ERS), Institute of Industrial Science, University of Tokyo publishes an annual Bulletin of ERS which is an excellent source of information on seismic design.

In a recent article in the Bulletin of ERS, K. Kubo reviews the history of earthquake engineering in Japan from the earliest times to the present (160). Kubo's review contains an overview of the earthquake resistant design technology available today and recommendations for future research.

Worldwide the state-of-the-art of earthquake resistant design methods can best be seen in "Earthquake Resistant Regulations--A World List - 1973" compiled by the International Association for Earthquake Engineering. This list contains earthquake resistant regulations of 28 countries.

Shock

In a recent paper Y. Matsuzaki has reviewed the shock response spectrum (SRS) (161). The principal developments of the SRS are outlined with emphasis on analytical work; both linear and nonlinear systems are treated.

NETHERLANDS AND BELGIUM

Acoustic

Activity in noise control and acoustics is high in the Netherlands and Belgium. Of special note are activities in urban noise surveys, rail, air and traffic noise and various studies and applications related to noise control/reduction.

Acoustic Studies

The more fundamental studies in acoustics continue and are well represented in the various acoustical society journals in the Netherlands and Belgium. Recent work includes a hydrodynamic mathematical model of the inner ear (162). Two studies on plates have been completed, one on the radiation from plates (163), and one on the influence of an unbounded elastic plate on the radiation of sound from a point source (164). In a study related to noise reduction the broad band noise generation mechanisms in both radial and axial compressors were studied (165). The shielding effect of aircraft wings on engine noise has been studied (166).

A new single number rating system for airborne sound insulation material has been proposed in the Netherlands (167).

Community Noise

The Laboratorium voor Akoestiek en Warmtegeleiding, Katholiebe Univ. Leuven in Belgium has been making a series of field noise measurements for years. Among the measurements made by the Lab. was a large scale traffic noise survey in Antwerp and Brussels (168, 169, 170). A preliminary small scale study similar to the above was made in Leuven (171). In another work the Lab. made measurements around nine motorcycle cross-country circuits, a few cross-country car races and a motorcycle speed race (172). The object of the race course measurements was to determine the real distance required to eliminate the noise inconvenience to local residents.

Based on noise data from a community noise survey of Cincinnati, Ohio two reports have been published by Louvain University in Brussels. The first is the results of the Cincinnati survey (173) and the second is an urban noise model which is compared with noise data in the previous report (174).

Machine Noise

The advent of the minicomputer and cheap Fast Fourier Transform modules has led to the development of the instrumed hammer technique of extracting mode shapes, frequencies and damping values from structures in place with portable equipment. The general theory of this method has been described (175). In Belgium they have used this method for the vibration analysis of machine tools (lathes, milling machines) (176).

Shock

Experiments have been performed at the von Karman Institute, Belgium which were designed to closely simulate the aerodynamic environment experienced by a re-entry vehicle (177). Heat transfer and pressure distributions were measured in the complicated two-shock steady flow system which surrounds the three axisymmetric concave conic shapes. The data may be useful to designers of re-entry vehicles.

SWEDEN, NORWAY & DENMARK

Acoustic

Sweden has adopted a strong national policy for noise control, especially in industrial areas. In the recent INTER-NOISE 78 meeting, May 8-10, 1978 held in San Francisco, there were two complete sessions devoted to Sweden's approach to noise control and Swedish advances in noise control technology. Some of the subjects discussed in the proceedings by Swedish author's were about industrial noise control, noise control in the graphic arts industry, noise control in the ship building industry and several papers on structure borne sound source data.

Sweden's new approach to noise control in industry resulted in the publication of the "ASF" Handbook (178). ASF ((Arbetarskyddsfonden) is the Swedish Work Environment Fund. For its 1977 anti-noise campaign in factories and other working environments ASF needed a handbook. The purpose of the handbook would be to acquaint those involved in the campaign with the fundamentals concerning the behavior of sound so that they could better understand what can be done to reduce noise in industry. Stig Ingemansson of Ingemansson Acoustics, Gothenberg Sweden has published a paper describing the ASF Handbook in detail (179). Some of the more interesting guidelines in the handbook were that no formulas or mathematics should be used; everyday language should be used rather than technical jargon; the illustrations should be dominant; the written material should be held to a minimum; and the illustrations should be asociated with everyday experience. It is a unique approach to information transfer and this approach could be used by other countries which have noisy industrial environments such as shipyards and manufacturing plants.

So far as the ASF Handbook is only available in the Swedish language but the U.S. Government is planning to have it translated into English.

Sonic Boom

Drougge (180) has developed a wind-tunnel measurement technique in Sweden which permits determination of the sonic boom strength from measureements taken fairly close to a slender body.

Aircraft Noise

Sweden has developed a program for using automated equipment for monitoring the noise level of aircraft at takeoff (181).

Vehicle Noise

Rylanden, et al. (182) at the Dept. of Envioronmental Hygiene, Univ. of Gothenburg, Sweden have developed methods for performing social surveys of subjects exposed to highway noise. Reactions of persons exposed to tramway noise were also recorded (183).

Machinery Noise

M. White of the Akustik Laboratorium, Norway, (184) has developed analytical methods for estimating the sound level radiated from the skin of double skin integral panels. The methods were developed for reducing the noise radiation from machines. Roland Nilsson (185) has reported on recent advances in a noise control program at the Arendal shipyard. Audiometric measurements of the shipyard workers showed that noise-induced hearing loss among the shipyard workers was common; only 42% of those tested had normal hearing. In addition, shipyard noise, with its superimposed impulses was determined to be more harmful than that allowed by Swedish emission standards. A program was begun to reduce noise exposure by acoustical treatment of buildings and by modification of the working process. The reverberation times in the welding shops and assembly halls was very high because of the hard concrete and steel surfaces, especially steel ship plates. In their first attempts at noise reduction 80% of the ceilings and walls of the main assembly hall were covered with acoustic absorbers. Results showed that only workers in the far reverberation fields benefited from this treatment, which costs over $50,000. For this reason later efforts concentrated on noise sources. In a shipyard environment hand-tools of different kinds constitute the dominating noise sources, e.g. grinding machines, nut tighteners, pneumatic hammers. The striking not tightener was replaced by silent hydraulic methods. The pneumatic hammer is in frequent use in the shipyard and its radiated sound energy is in the most sensitive range of the human ear; it is probably one of the major contributors to noise-induced hearing loss at the yard. In an experiment a total of 221 pneumatic hammers were taken away from the workers. These hammers are most commonly used by welders for slag removal. Instead they used the same hand hammers they used in welding school. Results showed that everyone receives a lower noise exposure. The welders noise-dose was decreased by 6 dBA; the noise in the reverberation field was reduced 5-9 dBA. The expected production loss did not take place. By employment of improved welding electrodes, more careful welding techniques, and in some cases, modification of welding methods (automatic welding) the problems were solved. Final conclusions were that an acoustical treatment of buildings in expensive and may not be very effective, whereas elimination of the noise sources may be very effective.

Structure-Borne Sound

Fundamental studies on structure-borne sound have been made in all countries with strong shipbuilding industries such as Sweden and Norway.

Tor Kihlman of Chalmers Univ., Goteborg, Sweden has pointed out the urgent need for structure-borne sound source data for machinery (186). Manufacturers can usually provide useful air-borne noise data. However, the situation is quite different as far as structure-borne sound source data. In a recent inquiry by the Swedish Ship Research Foundation, manufacturers of diesel engines, compresors, pumps, etc., were asked to supply structure-borne sound source data. Practically no useful information was obtained. This forces the buyer of this equipment to either measure the structure-borne noise or guess what it is. This situation causes high noise levels because the precautions undertaken to eliminate structure-borne sound source data are either inadequate or over-dimensioned. Kihlman (186) points out that one main goal is to get standards for measurements and specifications. This would lead to machines with less structure-borne sound which are easier to isolate. Much more data is needed. Actual impedance of source footings as a function of frequeny is needed. Also needed is better information on source strength and better data on isolators other than their stiffness. In order to achieve this, Kihlman recommends that practical test methods should be developed and brought into use. It would be very useful to have methods for estimating source impednce from the mechanical design. The final step would be to introudce these methods into the design of fans, compressors, washing machines, buildings, merchant ships, etc.

SWITZERLAND

Acoustic

Aircraft Noise

Rylander, et. al. (187) have reanalyzed the relation between annoyance due to aircraft noise and noise exposure expressed as the dBA peak value. Data from a Dutch, German and Japanese study are re-examined.

Vehicle Noise

Rathe (188) has studied the propagation of railway noise and means for its attenuaton and control.

Machinery Noise

An interesting study of aerodynamic noise in medium-sized fans has been made by Ploner (189). In this paper the author goes through the basic principles of noise control with illustrations of each technique.

WEST GERMANY

Acoustic

Germany has tougher noise control laws and standards than the U.S. Their regulations distinguish between those for rating the noise to which a person is exposed - called NOISE IMMISSION - and for rating the acoustical output of a machine - called NOISE EMISSION. Although emission and immission are separate concepts, reducing machine emission will, of course, result in reduced immission levels of noise exposure.

G. Hubner and K.K. Woehrle (190) discuss current efforts in West Germany which are aimed at enforcement of their countries occupational noise standards by limitation of noise emission and immission. R. Martin (191) has published the results of an annual survey of the current status in West Germany with respect to noise measurement and noise ratings. Martins' survey contains 90 references. Books, standards, guidelines, noise measurements, instrumentation and characterizations of noise immissions are listed.

Aircraft Noise

Aircraft noise measurement and the effect of noise regulations on aircraft design are two areas of interest in West Germany. H.O. Finke, et. al. have investigated the noise immission around airports (192) and the psychological and physological impact of aircraft noise on man (193). Franzmeyer (194) has studied the effect of noise limit regulations upon the technical design of civil aircraft.

Vehicle Noise

The location and definition of noise sources on commercial vehicles is being actively studied. Gaub and Jakel has developed methods for predicting the increase in the noise produced by components due to wear (195). These same principles could be used to predict the degradation of the "quietness" of any mechanical components.

Machinery Noise

The noise produced by office machines are of fundamental interest to planners who are attempting to comply with noise control regulations. For this reason the survey by R. Martin (196) of the noise produced by 117 different office machines should be useful information.

Seismic

E. Keintzel has adapted Holzer's method, using a small computer, for the calculation of the coupled torsional and shear vibrations of tall asymmetrical buildings subjected to earthquakes (197).

Shock

In addition to the normal shock tube research in West Germany some of the recent work has been on the strength of adhesives under impact (198). Hahn (199) has developed test methods using a photodiode, optics, a hammer and a pendulum ram testing device for determining the impact strength of several commercial adhesive bonding materials applied to metals. This information should be useful because of the increased usage of adhesives and composites.

A more exotic area of shock research is in magnetohydrodynamic shock waves. N. Natter of the University of Stuttgart has developed methods for calculating maximum flow deflection by magnetohydrodynamic shock waves (200). Natter has relied on the evolutionary conditions of Akhiezer, Lyubarskiy and Polovin.

Transportation

Mitschke and Helms have surveyed the vibration levels in the vehicles of major German vehicle manufacturers (201). Their results show that it is safer and more comfortable to drive at top speeds on good roads than at 100Km/hr. on average roughness country roads.

Chapter 4

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Chapter 5

PHENOMENOLOGY

INTRODUCTION

In any indexing scheme, the word "phenomenology" would be a forbidden term. Literally it would be the science or study of phenomena. For this report, a special meaning has been assigned. It includes those sets of information on subjects related to materials or to properties of materials and structures, with broad applications in the shock and vibration technology. Fundamental work in damping and fatigue falls into that category. Whether a material is elastic or plastic, or somewhere in between is relevant to material selection for design purposes. Indeed, perhaps a viscoelastic material is required to solve a problem, or perhaps thermoelastic properties are of concern.

Composites are a class of materials with broad design application. Fluid dynamics touches on many shock and vibration problems that occur in either water or air. Soil dynamics plays a similar role for that medium. In the future, such important materials as ceramics for structures or closely related areas like Tribology may find their place in this category. For the present, discussion is limited to six subject areas.

UNITED STATES

Damping

The term "damping" as used in this report refers to the energy-dissipation properties of a material or system under cyclic stress. Energy-transfer devices such as dynamic absorbers are also considered in this section. Ungar (1) provides an outstanding single-page summary of the state of damping technology. His opening sentences provide an appropriate background for further discussion.

> "Friction has been studied for centuries, and vibrations of damped systems have been investigated for many decades. It is only within the present decade that the term 'damping' has been accepted as applying only to processes that involve energy dissipation; earlier usage applied this term to any vibration reduction method, including isolation and dynamic absorption devices (e.g. 'tuned dampers')".

As Ungar implied, friction or Coulomb damping has been studied a long time, thus a minimum number of current studies (2) on this subject have occurred.

An excellent text on damping was provided by Lazan (3), and published after his death. Subsequent discussions in this section will be divided into appropriate subject areas related to the overall topic.

Structural Damping

This subject deals with the energy-dissipation properties of structural materials and those damping mechanisms produced by construction (e.g. "joints"). An excellent treatment of this area is provided by Goodman (4). Birchak (5) has reviewed work on the damping capacity of structural materials and Nelson (6) has looked at tehcniques for design of highly damped structures, with considerations for joints and interfaces. An additional paper by Nelson and a colleague (7) deals only with damping in joints. Other studies (8) in this area have been made. Modification of structural materials or development of special alloys (9) has been used to increase damping for such applications as ship silencing (10, 11). External factors, such as high temperatures, present special problems with respect to damping. Jones (12) conducted a survey of the high temperature problem and found the technology somewhat lacking.

> "It seems clear, therefore, that the technology of high temperature damping has reached a critical point: many technical obstacles have been identified, possible approaches toward overcoming them have been derived, and technical problems in industry have become sufficiently grave to warrant a concerted systematic effort to develop the technology."

Parts of Jones survey are relevant to other subject areas discussed in this section.

Damping Treatments

Damping in structures may be enhanced by properly selected additive treatments using materials with high damping characteristics. This may take the form of bonding or painting a material on a surface, or by using damping materials as integral parts of structural elements in constrained layers. An instructive discussion of damping treatments is provided by Plunkett (13). Applications of coatings (14) and constrained layer treatments (15, 16) are abundant. The impact resistance of brittle materials like ceramics (17) may be improved by damping treatments. The special problems associated with extreme temperatures also applies to these damping methods (18).

New damping materials are constantly being developed. Since the properties of these materials depend strongly on frequency and temperature, it is important to obtain complete specifications on performance. Manufacturers are happy to provide these. The references cited herein provide guidance on the use of such materials in design.

Rotor Damping

Rotor systems and related problems such as balancing are discussed in other parts of this report. Here a few of the damping techniques for vibration reduction in rotating systems will be mentioned. One method employs oil squeeze-film damper bearings (19, 20, 21) which are designed based on short bearing lubrication theory. The squeeze-film concept has even been studied for application to buildings subject to seismic disturbances (22). The significance of bearing dampers on vibration reduction in turbomachinery was shown in a study for NASA (23) in 1974. Other damping methods have been tried. For example, an invention originally developed as a damper for linear motion was adapted as a torsion damper (24). Damping of torsional oscillators is important, as illustrated by a recent Ph.D. thesis (25).

Response of Damped Systems

Damping, in any form, has marked effects on system response. Understandably, there is a large body of work devoted to understanding these effects. The following citations are illustrative of the kinds of studies that are conducted: damping effects on high-order normal modes (26); effects of mass modifications (27); application of damping in computer programs (28); response using discrete dampers (29); and effect of damping on stability in linear systems (30).

Vibration Absorbers

This class of devices always involves auxiliary masses attached to a vibrating system for the purpose of reducing the vibration levels. If the system is vibrating at a constant frequency or if the vibration is a constant multiple of some rotating speed, it is possible to tune a spring-mass system to this frequency. This device possesses as little damping as possible and is called a "dynamic absorber." If it is difficult to incorporate damping into a vibrating system, an auxiliary mass-spring system with damping may be attached to the structure and thus provide the damping. Such a device may be called a "damped absorber" or an "auxiliary mass damper." An excellent treatment of all aspects of vibration absorbers is offered by Reed (31). Applications for these devices have been somewhat limited in recent years. Among the work that has been done, a tunable nonlinear absorber (32) has been developed and applications have been made in jet engines (33) and buildings (34).

Damping Determination

The basic techniques for measuring damping are well-known and contained in standard texts. However, damping measurement or estimation has been one of the most difficult problems associated with the dynamic analysis of complex systems or structures. It is to be expected, therefore, that much of the recent research on damping pertains to these problems. Examples of recent work done include the development of a technique for determining optimum damping values and locations in complicated multi-degree-of-freedom systems (35) and methods for damping determination from substructure test data (36, 37). The use of the logarithmic damping decrement has been extended to non-linear oscillations (38) and a technique called random decrement has been developed for the measurement of damping and the detection of damage in structures (39).

General (Damping)

Work progresses on the development of new damping materials and the evaluation of material damping characteristics. Research needs to be continued on methods for predicting damping of complex structural systems. The application of damping technology in the design of structural systems, particularly with respect to joints and interfaces, needs to be extended. Extreme temperature damping technology needs to be assessed further, including the techniques for measuring damping properties of materials for those applications and the characterization of these properties in accordance with useful mathematical and physical models.

Fatigue

Fatigue, as a property of materials related to shock and vibration, may be simply defined as cumulative damage by cyclic stress. The ability of a material to withstand repeated applications of stress is called its endurance strength or fatigue strength. There are a number of methods and machines to measure this property, usually based on the concept that the percentage of fatigue damage is a linear function of the number of stress cycles. This concept is called Miner's Hypothesis (40) which for a number of years has been used as the basis for estimating cumulative fatigue damage.

Fatigue is a highly variable process involving the generation and propagation of a crack to the point that function is impaired or structural integrity is destroyed. Crack growth models are sometimes substituted for Miner's Rule. As dynamic loads and the structures they affect have become more complex, considerable controversy has arisen over the best methods to predict fatigue life. It is from this controversy and from the need for more accuracy in fatigue life predicitons that most of the recent studies on fatigue have arisen.

Fatigue behavior of alloys and metals at low temperature (41) has been studied. Prior-to-failure crack propagation has been investigated (42) so that the ultimate fracture point can be anticipated. Fatigue studies have been conducted on airport pavements (43), aircraft carrier propellers (44), railroad cars (45), and automobiles (46). New methods such as acoustic emissions (47) have been developed to detect flaw growth. Methods of predicting fatigue life have been compared with test results (48) to determine accuracy. Fatigue properties of newer materials, such as composites (49), have become important. In the aerospace industry, the fatigue effects of random vibration have been examined extensively (50, 51, 52).

Precise prediction of the fatigue life of a structure remains somewhat of a mystery. As suggested by Morrow (53), lifetimes are erratic at constant peak-stress and very sensitive to stress level. Furthermore, dynamic stress is seldom known in advance, particularly in view of the complexity of dynamic loadings currently of concern.

Elasticity

Numerous texts have been written on elasticity and plasticity. Elasticity is that property of a material by which it tends to return to its original size and shape after being subjected to deforming forces. Plasticity is the property that enables a material to be deformed continuously and permanently without rupture during the application of a force that exceeds the yield value. Aside from these simple definitions no further discussion of the theory of elasticity will be given here. What is of concern for this report is the effect of the elastic properties of a system or structure on its response when it is subjected to dynamic loads. This area of study has been called elastodynamics.

In recent years the increase in elastodynamic literature is overwhelming. A two-part review by Scott (54, 55) cites a total of 717 references. One of the reasons for the immense amount of research on elastic wave propagation is that such research is conducted on both homogeneous and non-homogeneous media, continuous or discrete, and on every conceivable structural shape. This, of course, also means that this extensive research is not just for the sake of advancing knowledge about elastic systems, but that most studies are undertaken to solve some specific shock and vibration problems. The fallout benefits are obvious.

The reader is referred to four additional reviews to complete the summary of research efforts on dynamics of elastic solids. In the first summary, Rechfield (56) looked at developments on linear and non-linear effects on vibration of elastic structures. Then McNiven (57) reviewed approximate theories on wave propagation in elastic rods. About the same time the use of finite element analysis for shock and acceleration waves in non-linearity elastic solids was examined (58). Finally, Holzer (59) studies investigations on the stability of equilibrium of elastic imperfection-sensitive shells subject to finite periodic excitations. In the area of dynamic response of structures two reviews should be mentioned. Baker (60) reviewed techniques which yield approximate predictions of dynamic structural deformations. Jones (61) conducted a somewhat broader study of research on dynamic plastic response and came up with 97 references. The literature is abundant with references on the dynamics of elastic systems, as well as inelastic and thermoelastic phenomena. It is impractical to cite additional references here. When such research advances the technology in specific applications, it may be mentioned elsewhere in this report.

Viscoelasticity

Viscoelasticity is the mechanical behavior of a material which exhibits viscous and delayed elastic response to stress in addition to instantaneous elasticity. Viscoelastic materials have well-defined stress-strain curves and, when excited dynamically, exhibit internal damping roughly proportional to velocity. Such materials have broad application in the solution of shock and vibration isolation problems. This section deals with basic studies regarding the dynamics of these materials.

Two reviews are of interest. Robertson (62) surveyed methods of dynamic analysis of viscoelastic structures. The general method of attack for the approaches surveyed allows the solution of many problems that would normally be intractable mathematically. Certain limiting assumptions make the techniques most useful for modal type analyses of discrete structures that behave in a linear veloelastic way. A state-of-the-art review on the dynamic behavior of elastomeric materials was conducted by Hobaica and Sweet (63). The material of particular concern in this survey is rubber. Among other subjects, the review covers molecular structure of polymers and its effect on dynamic mechanical behavior, application of the time-temperature syperposition technique, and test methods for determining dynamic response. The article contains 70 references.

Some specific examples of recent work should be mentioned. Sandia Laboratories developed two transient experimental techniques for determining viscoelastic properties (64). Reddy (65) constructed variational principals for the linear coupled dynamic theory of viscoelasticity. The effect of time dependent compressibility on wave progation (66) was studied. The dynamic stability of one-dimensional non-linearly viscoelastic bodies was the subject of a Ph.D. thesis (67). Viscoelastic theory was used to develop a dynamic absorber for machine tool application (68). Even with the approximations required because of limitations in analytical capabilties, significant progress has been made on the practical applications of viscoelastic materials. At the same time, these constraints make this area fruitful for future research.

Composites

Broadly, composite materials are made up of two or more different materials in some structural configuration. Such materials may filament-reinforced (steel-reinforced concrete is an early example), layered (laminated), or sandwich (honey-comb) construction. There is a definitive book on sandwich construction (69)), although it treats primarily static aspects. Probably the most useful book on the mechanics of filamentary composites is by Jones (70). The requirements for high-performance materials has led to extensive research on composites in recent years. Almost endless combinations have been studied including fiberglass-epoxy, graphite-epoxy and boron-aluminum. Vapor-deposited and bonded laminates, as well as various combinations for honeycomb panels have been investigated. As indicated by Davis (71), research on these materials is receiving significant current emphasis in the Department of Defense, particularly in the area of the new metal-metal composites.

The behavior of these materials under dynamic loading is significantly different from that of homogeneous materials, so that new studies relate to impact, wave propagation, fracture and general structural response characteristics (72). Broad studies (73) have been conducted on bending. Research on methods of establishing properties is evident (74, 75, 76). Literature reviews have examined research on thermomechanical response of composites, (77) on fiber-reinforced viscoelastic materials (78), and on impact or foreign object damage (FOD) (79). Sandia Laboratories has investigated the dynamic properties of viscoelastic composites (80). Ross and Sierakowski (81) did an excellent review of research on wave propagation in 1975. Since then, certain typical studies (82, 83) illustrate extensions of this research. Studies on impact properties (84), particularly as related to fracture (85) and delamination (86) have been evident.

Research reviews (87, 88, 89) have illustrated the importance of studies on mechanical properties such as damping and stiffness. A large number of analytical investigations have been conducted in connection with various aspects of the structural response of composites to dynamic loads. Selected references (90, 91, 92, 93, 94) are indicative of the progress that has been made. Many of the analysis techniques already developed will be applicable to studies of new material combinations. Requirements for high-performance, low-weight materials are expected to continue to increase. Technological developments in composites are expected to stay abreast of these requirements.

Fluids

Fluid Dynamics is a science in its own right, broad in scope and with its own growth pattern. It would not only be impractical, but inapproapriate, to attempt to discuss general advancements in such a science in this report. What is of concern are four areas which are of particular interest to the shock and vibration community and for which advancements are made at least partially from developments in fluid dynamics technology. These four areas are:

*Fluid-Structure Interaction

*Flow-Induced Vibration

*Dynamics of Contained Fluids (Sloshing)

*Aerodynamics or Wind-Induced Oscillations

Fluid-Structure Interaction

Fluid-structure interaction encompasses a broad spectrum of technical areas of interest in engineering applications. Of special interest are underwater problems such as sound radiation and scattering (ship silencing), hydrodynamic divergence and flutter (e.g. propeller induced noise), structural vibration and shock response (ship vibration, response to underwater explosions), and hydrodynamic loads on off-shore structures. Chen and Pierucci (95) conducted a comprehensive four-part review of research on several of the topics mentioned above, along with some others. Their review was in terms of the nature of the applied forces-either mechanical, acoustical or hydrodynamic. The article focuses on the fluid-structure boundary (interface), specifically, upon the way in which the physically coupled phenomenon is being treated in engineering analysis. In this respect the survey is quite complete, however non-linear theory is not included.

Selected references are chosen to indicate progress with respect to fluid-structure interaction. Clark (96) defined time domains for radiation damping and added mass effects. King (97) compared theory with experiment with respect to determining flow-induced vibration of sonar domes. Velocity correlation in the wake of vibrating cables (98) has been studied. Hydrodynamic noise from submerged hydrofoils has been measured in a water tunnel. Research on off-shore structures include methods for determining response of floating platforms (99, 100), the prediction of the response of piles to ocean waves (101), and the calculation of wave forces on models of submerged structures (102).

Flow-Induced Vibration

Flow-induced vibration results when an elastic structure or component member is subjected to a flowing fluid. Wambsganss (103, 104) has written a superb two-part paper designed to promote the understanding of this phenomenon. As he points out, flow-induced vibrations are experienced in numerous fields including the aerospace industry, power generation/transmission (turbine glades, heat exchanger tubes, nuclear reactor components), civil engineering (bridges, buildings, smoke stacks), and undersea technology. Typically, problems can range from a mere nuisance (noise from pipes) to failure due to fatigue. The article by Wambsganss gives an indication of the state-of-the-art in this area, at least with respect to present understanding and characterization of the problems.

Flow-induced vibrations related to wind and certain undersea problems are discussed separately. For this part, three references have been selected as typical of current research efforts on fluid flow through lines, ducts and pipes. High-pressure hydraulic lines present significant problems, particularly in large space systems. Sewall and others (105) have studied hydraulic line resonance and developed methods of attenuation. The propagation of higher-order acoustic modes (upstream and downstream) into a moving fluid in a duct has been investigated. The second reference (106) describes a method of predicting flow-induced vibration in U-Bend regions of heat exchangers. Finally, the effect of fluid viscosity on coupled tube/fluid vibrations was studied (107).

Dynamics of Contained Fluids

Fluid-filled containers have been used as models to study such things as the behavior of oil tankers, blood flow, and head and eye injury. It is obviously not a new problem since Rayleigh studied it in the 19th century (108). The topic received the greatest emphasis in the 1960's primarily because of the space program and the large liquid propellant tanks for launch vehicles. During that period "fuel sloshing" was studied intensively; a comprehensive collection of the technology applicable to the problem was completed by Abramson and others (109) in 1966.

Two reviews in this area should be mentioned. DiMaggio (110) has surveyed work on steady-state and transient response of fluid-filled shells. His review is of published analytical investigations for spherical, spheriodal, and circular cylindrical gemoetries. A review by Engin (111) on the large-deformation theory of fluid-filled shells of revolution, is concerned with thin-membranes and is applicable largely in the area of biodynamics. Recent work by DiMaggio (112) has broken new ground with respect to the response of a containment vessel to fluid pressure pulses. New developments have emerged with respect to the determination of propellant effective mass (113) and the use of finite element analysis on fuel tanks.

Aerodynamic/Wind-Induced Oscillations

The flow-induced vibration and noise on aircraft in flight and the excitation of structures by wind will be briefly covered in this section. The flow of air past aircraft structures during high-speed flight produces a boundary layer due to the frictional forces between the air and the structure. Boundary layer theory is well-known. The fluctuating pressures in a turbulent boundary layer is an acoustic environment that can induce vibration of the aircraft structure. A paper by Landahl (114) discusses some recent advances in this area. Lang (115) addressed the dynamics of a separating and reattaching flow field, a problem that can cause stall. The Army has conducted dynamic stall experiments (116). Boundary layer separation has been studied (117) and the environment produced by flow past cavities has been measured (118). Additional advances in this area will be covered in the discussion on aircraft.

Vibration is induced by wind on a variety of structures such as buildings, towers, bridges, transmission lines, and chimneys. The Tacoma Narrows bridge is an often-cited example of catastrophic wind-induced fatigue failure. The phenomenon is aptly treated by Davenport and Novak (119). Various mechanisms exist for wind-excited behavior of structures. These include vortex shedding, galloping, stall, flutter, classical flutter, and divergence. In addition, oscillations may result from a turbulent wake from another structure upstream of natural turbulence in the airflow.

Three citations are indicative of research related wind-induced oscillations. Experiments have been conducted in a wind tunnel (120) to gain a better understanding of the excitation mechanisms. Wind loading on a structure has been simulated on a digital computer (121). A coupled dynamic analysis of wind energy systems (122) is of particular interest in view of the world energy situation. The large amount of activity in this area of research is indicated by the fact that there have been international conferences on wind engineering every four years since 1963. Two U.S. conferences in wind engineering have been held (123, 124). Although considerable information exists about the mechanisms of wind-induced excitation, much remains to be done. In particular, the theoretical formulation of data for design purposes is required. Dampers and other remedial techniques, for vibration reduction need to be developed.

Soil

Soil Mechanics, like Fluid Dynamics, is a broad science. Probably the greatest interest in soils by shock and vibration engineers is in those properties of soils that affect the response of buildings and other structures to seismic, nuclear or other explosive events. This is commonly called soil-structure interaction. The techniques developed thus far for analyzing soil-structure interaction problems usually involve either the continuum approach or the finite element method. Lee (125) has reviewed the continuum approach which, in contrast to the finite element method, uses a half-space continuum to simulate the foundation medium of the system. Lee's review clearly defines the state-of-the-art in this area with 71 references. The two approaches have been compared (126), with respect to their present capabilities, to address the significant factors of the problem. The finite element method has been applied to many structures, including underground structures (127). Calculations using the finite element method have been compared with measured data (128). The non-linear behavior in soil-structure interaction has been studied (129). Analysis techniques have been applied to such diverse structures as piles (130) and bridges (131).

A review of the current state-of-the-art of ground vibration propagation has been done (132), including theoretical models of vibration attenuation. Other applications of soil dynamic properties are to building vibration (133) and off-road vehicles (134).

AUSTRALIA AND NEW ZEALAND

Damping

Structural Damping

Most of the work in damping in Australia concerns damping inherent in structures by exploiting friction in lap joints, rotary joints or friction grip bolt joints. Predictions of energy dissipation have been made for modifier lap joints and for friction grip bolt joints with four different cover plate surfaces. Further experimental efforts are needed to assess the theory more definitely (135, 136). Friction damping should be exploited wherever possible in designing structures for noise or vibration control treatments.

Damping Determination

The characteristics of materials with a combination of a high elastic modulus and high internal damping were investigated. The properties of viscoelastic materials have also been studied.

Fatigue

Leads and soldered joints in electronics equipment are prone to fatigue failure. Work was undertaken to find a method for predicting fatigue life and detecting the factors that affect the fatigue life of leads and soldered joints (137).

The growth rate of edge cracks in acoustically-excited panels has also been studied. A single panel modeled as a flat plate was considered and fracture mechanics principles were used to predict the crack growth rates associated with the first two modes of vibration of a cracked panel.

UNITED KINGDOM

Damping

Research on the subject of damping is significant in England. The areas of interest can be divided into friction damping, material damping, and damping treatments.

Structural Damping

The author of a review article pointed out that friction damping in joints is a major contributor to structural damping (138) and the fear of fretting corrosion in the joint inhibits its use. However, studies of interface preparation techniques have been made and several are available for dissipating energy due to interfacial slip while minimizing fretting (139). Rotational slip in joints is another form of friction damping that has been studied in England. In this case the joint is fastened to prevent translational slip but to permit rotational slip. The structure can be analyzed by using a general dynamic analysis computer program with a sub-program to model the friction in the joint (140).

Response of Damped Systems

The damping capacity of three materials that were subjected to sinusoidal strain with randomly varying amplitudes was studied to establish a relationship between the energy dissipated and the rms value of the strain history (141).

Damping Treatments

In Great Britain damping treatments have been applied to control the vibration of many types of structures. Some of the more interesting studies concern damping treatments that were applied to control the wind-induced vibrations of tall structures. In one case passive dampers were investigated (142); in the other case an active damper was used (143).

Fatigue

A significant number of fatigue studies have been made in Great Britain, but most of the studies involve specific applications. However, one study was undertaken to understand the effect of periodic-random loading on fatigue crack growth (144).

England roads and structures are not immune to fatigue failures; in particular, "pot holes" in roads occur because of fatigue failure of asphalt. An investigation of the fatigue damage of asphalt was undertaken to arrive at a method for predicting its life under compound loading (145). An investigation of an experimental bridge deck panel was undertaken to find the cause of cracking in the connections (146).

An investigation was carried out to determine the effect of the type of loading, i.e. sinusoidal vs. random, on the fretting fatigue strength of an aluminum alloy (147). A similar study was undertaken to determine the fatigue crack propagation characteristics of a null steel under random loading (148).

Composites

Among the studies on composite materials in England, the effects of fiber orientation on the propagation of stress waves through a carbon fiber reinforced plastic have been investigated. In addition, acoustic emission is being used to identify fatigue failures in carbon fiber-reinforced plastics (149).

Fluids

With respect to fluid dynamics in Great Britain, the areas of study can be divided into fluid-structure interaction, dynamics of contained fluids, and sound generation and propagation.

Fluid-Structure Interaction

Fluid-structure interaction studies vary considerably. A study of locking on of vortex shedding about an oscillation circular cylinder was investigated for the case where the stream velocity in shear flow varied with spanwise distance (150). Studies have also been conducted on the effects of submerged cylinders on surface waves (151,152) and submerged spheres on surface waves (153). A study of the transmission or reflection of surface waves in presence of parallel object was studied. The objects contained gaps and the results of the study could be used to design breakwaters (154). The stability of a rectangular surface in subsonic uniform flow was also studied. Both surfaces supported on all edges and those with partial support were investigated (155). The stability of flow between two converter cylinders has also been investigated. In this case the inner cylinder was vibrating while the outer cylinder was at rest (156).

Dynamics of Contained Fluids

Studies of the dynamics of confined fluids have included the coupling between the sloshing modes and the structural modes of a system consisting of a two-degree-of-freedom structure with a partially-filled rigid container (157). A study was performed to extend the phenomenon of energy transfer between near resonant oscillations at greatly differing frequencies to the general case. The vibration of a liquid-filled beaker in one of its bell modes was investigated with this method (158).

Aerodynamic/Wind-Induced Oscillation

Several studies concerning fluids and sound were performed. These include the acoustic vibration of structures in liquids (159), the scattering of sound as it is propagated through a turbulent fluid (160) and the effect of steady fluid flow on the generation of sound by aerodynamic sources located near a scattering body (161).

CANADA

Damping

The effects of two types of damping on a tubular cantilever conveying fluid were investigated. Empirical hysteretic damping and two parameter viscoelastic damping were modeled (164).

Fatigue

A method was developed for improving the fatigue resistance of sheet material with loaded holes. The material is initially dimpled at the location of the hole and this ultimately results in a residual compressive stress that in turn results in an increase of the fatigue strength of a loaded hole for a prescribed number of cycles to failure (163). This technique might be applied to the production of many different sheet metal parts with holes. A study of the importance of various factors that affect the fatigue behavior in notches was undertaken to arrive at a better model of the fatigue process.

Significant interest exists in Canada in techniques for predicting fatigue life and several studies have been performed. A computer-based fatigue analyses model was developed to include the effects of local stress and strain at stress concentrators in predicting the fatigue life of randomly-loaded notched components (164).

A Monte Carlo simulation method for fatigue failure was developed to predict the statistical characteristics of fatigue life under random and constant amplitude cyclic loads (165). The advantage of this method lies in the reduction in the amount of experimental data that are required to establish the fatigue life of the test item.

Miner's rule is often used to predict the fatigue life of a material subject to different strain level for both a deterministic and stochastic loading. In the latter case, Miner's rule is often unfairly blamed for the unsatisfactory prediction of fatigue life. Miner's rule was proven to be valid in the probabalistic sense and a method for accurately predicting the fatigue life of a material using Miner's rule was developed (166).

Elasticity

Studies in elasticity in Canada include an investigation of high frequency cylindrical and spherical wave propagation in an inhomogeneous elastic half-spaces (167), the determination of the wave propagation velocity in an inhomogeneous medium from the reflection coefficient (168), and the propagation of Rayleigh type waves in anisotropic materials (169).

Composites

The propagation of one-dimensional longitudinal pulses in non-linear elastic and viscoelastic composite materials was investigated to determine the amplitude and the frequency response of the various layered media (170). The results of these studies might be useful in determining the integrity of composite armor.

Acoustic resonances in composite cavities were investigated (171). The results of this study were used to develop a technique for evaluating the reflection coefficient of the bond interface of composite cavities. This same technique might be applied to determining the integrity of bonds in many other composite structures.

Fluids

Studies of fluid-induced excitation are of continuing interest in Canada. The aeroelastic response to two different turbulence intensities was investigated for square and "H" structural shapes (172). The results showed a need for further work to explain the aeroelastic behavior of both structural shapes.

Flow-induced structural vibrations involving flow instability have been studied. The range of flow conditions where such vibrations occur can be predicted by a kinematic analysis based on a combination of experimental data and stability theory (173).

Soils

Studies of dynamic properties of soil are of interest in Canada. These include wave motions in rockfill (174), the dynamic response of horizontal saturated sand deposits to earthquake motions with vertically propagating sphere waves (175), and the dynamic behavior of soft clays.

FRANCE

Damping

Most of the current damping work in France is related to their space programs. M. Poizat, et al. (176) used a viscoelastic damping coating as a remedy for 'Pogo' effects on the DIAMANT Satellite Launch vehicle.

Damping Determination

The temperature dependent properties of damping materials continue to be developed. R. H. Blanc and F. P. Champomien (177) have developed a wave front method for determining the dynamic properties of high damping materials. The properties are deduced from the development of a stress pulse wave-front propagation through a bar of the material. J. Moriceau (178) has also made measurements of the dynamic characterisitcs of viscoelastic materials; the results of the study are to be a catalog of viscoelastic materials to be used in shock or vibration damping systems. D. I. G. Jones has written a paper on the high temperature damping of dynamic systems (179).

Fatigue

The fatigue properties of materials for aircraft construction continue to be studied. Low-cycle high-temperature fatigue resistance problems typical of aircraft engine environments have been studied (180, 181). Part III of a series on acoustic fatigue design data is now available (182).

Fluids

Flow-Induced Vibration

Flow-induced vibration in reactors continues to be a problem which must be dealt with by designers. M. Dubourg, et al (183) have made model test and numerical analyses of reactors. Of fundamental importance to the understanding of flow-induced vibration is the concept of vortex shedding. E. Szechenyi (184) has developed a mathematical model of the vibration induced in a cylinder by vortex shedding and compared the results to a wind tunnel test on a flexible cylinder.

Dynamics of Contained Fluids

Fuel sloshing is still a very tough problem to model or solve. The influence of sloshing of fuel in aircraft wing tip tanks on the natural modes of an aircraft has been studied (185). A general method for predicting POGO has been developed by R. Valid, et al. (186). The method is one of finite elements which combines structural and fluid elements.

INDIA

Damping

B. C. Nakru of the Indian Institute of Technology (187) has written a review of methods available for vibration control with viscoelastic materials. In other works, Nakru and his colleagues have investigated the effects of viscoelastic damping layers on structures subjected to vibration (188, 189) and shock excitation (190).

M. P. Chandrasekharan and A. Ghosh (191) have developed a composite shaft with an elastic-viscoelastic core. They have also developed equations which accurately model the shaft dynamics, including damping.

Fatigue

A. R. Rao (192) has reviewed the current experimental methods used today in fatigue life estimation of randomly loaded structures. Rao discusses the accuracy of these methods.

Composites

R. Chandra (193) has developed analytical methods for calculating the large deflection vibration response of composite plates. The frequency response turns out to be non-linear. Calculations are shown for isotropic, glass-epoxy, graphite-epoxy and boron-epoxy plates.

Fluids

Flow-Induced Vibration

Results of both experimental and theoretical studies of the wind excited vibration of a square section cantilever beam in smooth flow are available (194). Discrepancies between theory and experiment were attributed to slight irregularities in the cross-sectional shape of the beam.

Dynamics of Contained Fluids

The dynamics of a reservoir-foundation system has been studied in which the reservoir is modeled as a compressible fluid and the foundation as a system of linear springs with inertia (195). It is found that natural frequencies decrease monotonically with foundation depth and the influence of free-surface waves is neglibible for most constructions.

ISRAEL

Fatigue

M. Korbin (196) has developed a technique for equating the fatigue caused by constant amplitude loading with that caused by variable amplitude loading. Constant and variable amplitude conditions are considered equivalent if they produce the same extent of damage on the structural part under load after equal durations of service.

Elasticity

Y. Benveniste, et al. (197,198) have developed methods for predicting the propagation of waves in viscoelastics. They have used the technique successfully to predict the build-up of shock waves in non-linear material (199).

Composites

Work on composites in Israel has been on the propagation of waves in fiber-reinforced elastomers (200), testing of impact strength of angle-ply fiber-reinforced material (201), and predicting the response of an incompressible composite sphere to a radial pressure pulse (202).

ITALY AND GREECE

Elasticity

In Italy a model of elastic energy dissipation was developed and it was applied to the problem of determining the response spectrum at the surface of a layer when a spectrum is given at the bottom (203).

Soils

Considerable interest has been shown in Greece in using vibration for compacting soils. However, the best soil compaction is obtained by the proper combination of the operating frequency and the amplitude of the compacting device itself. A laser device has been developed to measure these properties for the compacting device when it is compacting various types of soils. This in turn will make it easier to predict the compacting force that is necessary to obtain the desired soil density (204, 205).

JAPAN

Damping

Most of the recent works on damping in Japan are related to machine tools. Higashimoto, et al. (206) have developed methods for measuring the damping in guide ways of machine tools. Okada (207) has applied an electro-magnetic servo damper to improve the modal damping of a machine tool structure. Seto and Tominari (208) have developed a variable stiffness-type dynamic damper for use on machine tools with a long overhung ram. Okamun and Suzuki (209) have developed optimum designed sound damping rings for gears. Experimental techniques have been developed for the measurement of the damping in welded (210) and bolted (211, 212) joints. Kunieda and Sakurai (213) have developed a technique for the application of oil dampers to the bottom of spherical tanks to minimize the effects of earthquakes. They applied optimum sized dampers to a 200,000 M^3 gas tank and made vibration measurements before and after. They proved that the dampers were very effective in increasing the earthquake resistance of the structure.

Fatigue

Metallurgical research, especially experimental, is very advanced in Japan, due partly to their use of large quantities of steel in Japan's shipbuilding industry. Many studies of crack initiation and propagation exist (214, 215). Nakagawa, et al. (216) have used electron microscopes to study the fatigue properties of metals. Kawamoto, et al. (217) have modified a mechanical type of random fatigue testing machine so that random loads with arbitrary overall means can be applied.

Elasticity

Several studies have been made in Japan on the propagation of waves in elastic (218) and viscoelastic (219) rods.

Composites

Toda and Fukuoka (220) have developed methods for the analysis of wave motion in a composite circular rod which has a circular matrix rod and a circular sheath tube made of different materials.

Fluids

Flow-Induced Excitation

Several studies have been published on the flow-induced excitation of pipes (221, 222, 223). Nakamura and Mizota have made wind tunnel tests on the flow-induced vibration of rectangular elastic prisms (224, 225).

Dynamics of Contained Fluids

K. Sogabe, et al., have developed aseismic designs of liquid storage systems. A summary of their analytical and experimental work has been published (226). K. Shiraki (227) of Mitsubishi Heavy Industries has studied the seismic response of self-supported thin cylindrical liquid storage tanks.

Aerodynamic/Wind-Induced Oscillations

K. Shirabi has published reports on the response of tower-like structures to strong winds (228) and the vibration of bridges due to wind (229). H. Kunieda has developed methods for the analysis of wind-flexible structure interaction system (230, 231, 232).

Soils

Inoue, et al. (223) have developed expressions for calculating the dynamic response of non-linear soil-structure systems. Numerical results to a white random excitation are given.

NETHERLANDS-BELGIUM

Damping

Vibration Absorbers

An exhaustive study was made by the Royal Netherlands Aircraft Factories Fokker, Space Division on dampers for the bobbing up-and-down motion of spinning rigid bodies. Passive nutation dampers were analyzed for single spin satellites. The first volume of a three volume report contains the results of a literature survey and preliminary selection of damper types for further study (234). Vol. 2 contains the selection and dimensions procedure for the 4 types of dampers studied which were: pendulum with eddy current damping, tube with end pots damper, partly filled annular damper and mass-spring dashpot (235). Vol. 3 is an Appendix which contains a literature matrix and mathematical details of the damper models (236).

SWEDEN, NORWAY, AND DENMARK

Damping

B.A. Akesson of Chalmers University, Gothenburg, Sweden has investigated methods for damping wind-excited structures (237). Akesson has developed methods for calculating the effects of installing a small damped vibration absorber on a structure with wind-induced stochastic vibrations.

Fluids

Some studies have been made in Norway of the liquid sloshing in Liquified Natural Gas (LNG) tanks. Olsen and Hysing (238) have developed methods for computing the dynamic loads caused by LNG sloshing for various tank configurations, fill depths, excitation amplitudes and frequencies.

SWITZERLAND

Damping

A survey (239) of damping mechanisms has been published in Switzerland. Mathematical modeling of mechanical vibrations and impacts (240, 241) have been made in which special attention was given to damping.

Fluids

Flow-induced Vibration

Guide-vane vibrations caused by vortex shedding has been studied (242, 243) in Switzerland.

Aerodynamic/Wind-Induced Oscillations

A summary of various analytical, experimental and numerical buckling analyses of large hyperbolic cooling towers has been published (244). Wind-induced excitations of these towers is examined.

WEST GERMANY

Damping

Several interesting studies have been performed recently in West Germany with damping as a common theme. The systems to be damped range from hydraulic fluid lines to bearings.

Hoffmann (245) has developed techniques for damping fluid vibrations in hydraulic lines. Rules for selection and proper installation of the damper are provided. Vibration damping in satellites is a well-known problem for the spacecraft designer. K. Popp (246) has compared active and passive vibration damping of gravitationally stabilized satellites. He has developed methods for the optimal design of the passive (linear spring and viscous damper) or active (linear regulator with servomotor) types.

In an experimental work on rotors and bearings, Glienicke and Stanski (247) have demonstrated that the vibration of rotors in friction and roller bearings may be reduced by proper external damping.

Fatigue

In addition to general analytical efforts aimed at modeling the fatigue life of materials under cyclic stress, other efforts in West Germany have centered on the fatigue life of notched structures, crack propagation and the use of digital computers in structural fatigue research.

Several researchers in West Germany (248, 249) have applied Neuber's theory of macro- and micro-supporting effects to the life prediction of oscillating notched structural members. W. Doll (250) has developed experimental techniques for measuring the speed of propagation of fast running cracks in a range of quasi-brittle materials. The method is based on an energy balance principle and involves measuring the heat output associated with the plastic work at the propagating crack tip. Buxbaum and Haibach (251) have developed computer methods for fatigue research. Their efforts include the use of digital computers to generate a stationary Gaussian random process, simulating roadway roughness, for input to a vibratory load for a fatigue test on automobile components. Also, they have used a digital computer for the stepping and superposition of stress collectives for fatigue life calculations using cumulative damage hypotheses.

Elasticity

Viscoplasticity

H. Liertz (252) of Technische Universitaet Munich in his Ph.D. thesis has developed a description of the mechanical behavior of polyethylenes using linear differential equations. In Liertz's study, he considers oscillations, creep, tensile stress at both constant tension and constant elongation velocity, and relaxation.

Composites

An interesting application of composites is the fibrous absorber. F.P. Mechel has developed analytical models of the absorber which consists of a bundle of parallel fibers (253, 254). Of particular interest is the propagation of sound waves in the bundle. In addition to the usual acoustic compressional waves Mechel's model predicts viscous waves and thermal waves. As with any absorber device, this one should be useful for vibration and noise reduction applications.

Fluids

Aerodynamic/Wind-Induced Oscillations

Some research is being done in West Germany on the vortex-induced vibrations of bluff bodies. R. Landl (255) has developed a mathematical model of vortex-excited vibration which is a two equation model containing a non-linear aerodynamic damping term of the fifth order. The model in its present form can be used to explain different experimental results and observe their common features. Kluwick and Sockel (256) have shown in a series of experiments that the Scruton spiral is the most effective measure for aerodynamic damping of vortex-induced vibrations.

IRAN

Fatigue

In Iran the random loading of structural members has been investigated by Abu-Akeel (257). He has developed a method which allows for the accurate estimation of the cumulative fatigue damage incurred in a randomly-loaded structural element when loading is given in the form of spectral density load or stress plots.

Soil

In Iran, as in other countries, engineers are concerned with efficient methods for sinking piles into the ground. M.A. Satter (258) has developed a mathematical model incorporating "pile-soil interaction" for the analysis of resonant pile driving. The author has introduced simplifications into the solution method to minimize computational effort while retaining good accuracy.

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Chapter 6

EXPERIMENTATION

INTRODUCTION

Experimental problems related to shock and vibration may be classified in a number of ways. For this report four topics have been selected: Measurement and Analysis; Dynamic Testing; Diagnostics; and Scaling and Modeling. The equipment and techniques for measuring dynamic environments, either in the field or in the laboratory, and for analyzing and presenting the measured data in usable form are covered under the first topic. Dynamic testing involves the philosophy and techniques, facilities, test control methods and procedures for simulating dynamic environments in the laboratory. The third topic covers a special class of measurement and analysis problems related to the prediction of impending failure in mechanical equipment; sometimes the process is called "machinery health monitoring", sometimes "diagnostics". Large structures or equipment are often not easily tested because of cost of the item involved. Work related to the use of physical scale models and the scaling of test parameters is treated under the last topic.

Not so many years ago the separation of discussions of measurement and data analysis from dynamic testing would have been quite straightforward. With the rapid advances in recent years on the use of minicomputers for digital test control and on-line analysis, these distinctions are not so clearly drawn. The reader is advised that the inclusion of discussions of technological advancements under Measurement and Analysis or Dynamic Testing may be somewhat arbitrary based upon the judgment of the authors.

UNITED STATES

Measurement and Analysis

The measurement and analysis of shock and vibration data is an extremely important area for those concerned with almost any aspect of the technology. Almost one fourth of the definitive handbook by Harris and Crede (1) is devoted to this subject. This material provides most of the basic information required, from a description of sensing elements (transducers) and how they work to the standard methods of processing shock or vibration data. Also included in this handbook is an excellent chapter on measurement techniques. Two reviews provide excellent summaries in the area of shock and vibration instrumentation. Plunkett (2) points out that the basic principles of transducers and techniques for their use have remained the same for the last several years. The big advances have been related to electronics for signal processing, particularly in the areas of high-gain operational amplifiers, integrated circuits, wide-range logarithmic amplifiers, and hard-wired digital minicomputers. The use of computers in the area of shock and vibration measurements is expected to continue to be one of the more rapidly expanding segments of the technology. Mitchell (3), in his review of accelerometers, agrees that most advancements related to these transducers are related to refinements rather than new developments. There are more types and sizes. Miniature accelerometers are now widely available. Capabilities for measurement at extreme temperatures have expanded. Both frequency and amplitude ranges have been extended and reliability has improved.

It is appropriate to point out that, in many cases, transducers with substantially the same basic designs are used for both vibration and shock measurements. In the succeeding sections developments related to each of the dynamic environments are discussed.

Shock Instrumentation

Except for the refinements discussed earlier, most of the recent advances in shock instrumentation are related to special application areas, such as the measurement of seismic events. In this connection, Pauly (4) discussed developments on seismic instrumentation of nuclear power plants, specifically related to how these developments are influenced by NRC regulations. Instrumentation for blast-induced ground shock continues to be a difficult problem. The development and evaluation of four types of transducers for measuring blast-induced motions in buried structures is described by Pickett (5). Agbabian Associates (6) analytically studied velocity gauge emplacement for the measurement of ground shock. The investigations covered a wide range of borehole/free-field impedances under a variety of interface conditions.

Automotive crash research provided the impetus for the development of a solid-state digital crash recorder (7). The recorder is self-contained and automatically triggered to capture the crash severity-time event on ten separate data channels. In the packaging area, an instrumentation system has been developed to measure dynamic characteristics of cushioning materials during drop-weight or impact testing (8). In a related area, Venetos (9) described the design of a miniature recorder/analyzer system developed primarily for the measurement of the environment experienced by packaged items during handling, shipment and storage. Underwater shock technology has been advanced by the development of a water particle velocity meter (10) for use in applications where computations of particle velocity are unreliable.

Shock Data Analysis

Developments in shock data analysis relate in large part to new equipment developments. Smallwood (11) reviewed available analog and digital methods for matching shock spectra with oscillating transients. An excellent discussion by Ramsey (12) illustrates the impact of digital Fourier analyzers on structural dynamics testing. He describes several techniques for measuring structural transfer functions and introduces digital techniques for identifying closely-coupled modes. Kao and others (13) have used transfer function measurement techniques to predict the shock environments of equipment on isolated platforms produced by inputs at the base of the system.

Because of its high frequency, high amplitude characteristics, the analysis of pyrotechnic shock data presents difficult problems. Albers (14) conducted an investigation which shed some new light on data reduction for this environment. Holography is becoming an important tool in the analysis of shock as well as other dynamic environments. Laser holographic interferometry was used in the detection of shock patterns in the outer span regions of high tip transonic rotors (15). Holographic techniques were also used to visualize compressor blade/wake interaction (16). The management of data from a specific area of the technology may have great influence on its usefulness and application. Malthan (17) described a sophisticated shock data base, developed for the Defense Nuclear Agency involving data storage, analysis, retrieval and display.

Vibration Instrumentation

Earlier in this report references have been cited relating to basic vibration measurements. It is appropriate to mention two additional efforts designed to promote greater understanding in this area. A five-part paper by Jackson (18) offers valuable insights into the measurement of machinery vibrations. Lang (19) reviewed the measurement, presentation and interpretation of the six classical transfer functions relating to vibration. The effects of other environments, such as thermal transients (20), on the performance of vibration transducers is also important.

In the vibration area, new developments in instrumentation are again related to special problems. The interest in infrasonic vibrations spurred the development of a low-frequency vibration calibration system (21). Propeller blade vibration flight and ground testing required special instrumentation (22). Unique flight instrumentation/data reduction techniques had to be employed on the Viking dynamic simulator (23). New devices for remote sensing (24) and other detection (25) of vibration are in the patent process. A light-scattering heterodyne interferometer for vibration measurements in auditory organs has been developed (26). The problem of measuring low-frequency components of track-induced railcar accelerations has been solved by the use of a limited-range, high-resolution, servo-accelerometer (27).

Vibration Data Analysis

In the interest of cost, sometimes a simpler approach in an area like vibration data analysis is significant. The Army (28) has built an analysis system around a programmable calculator and peripheral equipment. A special mobile data acquisition system has been developed for motor vehicle testing (29). Special analysis techniques had to be employed to develop specifications for electronic equipment in remotely piloted aircraft (30). New developments in hardware and software make all these things possible. For example, the capabilities for the analysis of data from modal vibration tests (31,32) have advanced significantly. Along this line, Targoff (33) has attacked the problem of orthogonality checks and corrections of measured modes.

Holographic vibrational analysis has been employed to locate nonbonds in a ceramic/fiberglass composite (34). Nonbonds, undetectable by other methods, are made clearly visible by this technique. Hung et al (35) have used a time-averaged shadow-moire method to determine the amplitude distribution of a vibrating plate. Pearson and Thaller (36) conducted an innovative investigation of vibration-induced doppler effects on an airborne communication system.

Acoustic Instrumentation

"Throughout the past decade instrumentation has become far more complex in its capabilities, higher reliability, smaller in size, and, in general, more expensive." So says Kamperman (37) in a concise review of sound and vibration instrumentation. The basic transducer for sound measurement is the microphone. Convenience is added by using sound level meters allowing direct dial readings. Dosimeters combine sound level with exposure time yielding a noise exposure index relating to humans. These instruments and others are described in a comprehensive review of instrumentation hardware published in Sound and Vibration (37, 38). The state-of-the-art of noise measurement has been reviewed by Schneider

(39). Applications for acoustic measurements include aircraft flyover noise (40), highway noise (41), special vehicle noise (42), and many others. Noise measurements are particuarly important in facilities such as reverberation chambers (43) and wind tunnels (44).

Further developments in microprocessors are already having the effect of lowering costs of measurements and analysis. Developments are on the horizon relating to the incorporation of portable calculators into measuring systems. Such instruments could perform complex measurement tasks simply and inexpensively. For all new developments, the major emphasis will be on simplicity, increased performance, and reduced cost.

Acoustic Data Analysis

Other than increased emphasis on combining measurement and analysis capabilities, as mentioned earlier, a few specific efforts on noise analysis should be mentioned. A special recording system has been developed for the measurement of blast noise produced by mining operations (45). A special computerized system has evolved for use in handling noise data from an outdoor, full-scale fan noise facility (46). Techniques for spectral analysis of truck tire noise have been applied (47). Acoustical holography techniques were used by Watson and King (48) to locate sound sources on complex structures. Finally, the Naval Research Laboratory has developed an electronic system whereby the relative velocity and attenuation of an acoustic wave can be measured simply, dynamically, automatically, and simultaneously (49). This system applies best to certain phase transition experiments.

Special Dynamic Measurements

The literature contains many references on work not specifically attuned to shock, vibration or acoustics, or perhaps applicable to some aspect of all of them. One such area is mechanical impedance (mobility). There are equipment and techniques available for measuring mobility and the information related to this is readily available. However, both experimental and analytical developments in mobility are applications-oriented and thus more appropriately discussed with respect to the component or system involved. In this section only a few of the many references on special measurements will be mentioned, selected because of uniqueness or the special impact on the technology.

An unusual challenge was met by Buckley (50) when he developed instrumentation to obtain aerodynamic (pitching moment and lift) information for automobiles during road tests. A special transducer was developed to measure dynamic loads in metal cables (51). A transducer capable of simultaneously measuring the dynamic forces and moments acting on the wheel of an automobile has been described (52). Surface roughness (profile) causes dynamic loads on vehicles; a non-contact profile measuring system was developed by Joyce (53). An advancement in material damping measurement for specimens undergoing forced flexural vibration is offered by Gibson and Plunkett (54). Various recent techniques, such as acoustic emission (55), acoustical holography (56), advanced optical (57) and interactive computer graphics (58) are being applied to a broad range of measurement and analysis problems.

Dynamic Testing

Laboratory tests to simulate shock, vibration, acoustic noise, or other induced environments provide the means by which components or systems may be examined to gain reasonable confidence in their operational or functional reliability. Tests are used for qualification to a pre-determined set of requirements, as quality assurance mechanisms for operational acceptance, or as useful tools during the design/development phase of a system. Pusey (59) reviewed developments in the field of dynamic testing over the past thirty years. C. T. Morrow devoted portions of two chapters of the Harris and Crede handbook (1) to the subject of testing. As the various types of dynamic tests are examined in this report, the discussion will relate in part to philosophy and techniques, in part to facilities, and in part to control and procedures.

Shock Tests

The various aspects of shock tests conducted using laboratory simulation devices is the principal topic for this section. However, there is another important mode of simulation that should be mentioned. With the ban on atmospheric nuclear testing, the use of conventional high explosives in large-scale field tests to simulate nuclear airblast, cratering and ground shock became an important test area. Sevin (60) provides an excellent overview of such testing, including some representative data and a discussion of the degree of simulation possible for the various nuclear shock effects.

In recent years there has been widespread use of electrodynamic vibrators (shakers) to synthesize shock inputs to test specimens. Keegan (61) investigated the capabilities of shakers for shock testing. Major progress in shaker shock synthesis came with the technological breakthrough of using digital minicomputers for control of dynamic tests. Smallwood (62) prepared a comprehensive paper related to digitally-controlled shock tests. More about digital control is included under Vibration Tests and Acoustic Tests. A complete description of other shock test machines is provided in Chapter 26 of Harris and Crede (1).

Pyrotechnic shock was described under ENVIRONMENTS. A number of approaches for the simulation of this environment have been used, including high-intensity shock machines (63), explosive charges (64), and bounded impact (65). Requirements for qualifying equipment to earthquake shock have steadily increased. Existing techniques for simulation of earthquake motion are discussed by Kao (66). An example of a broad capability seismic test facility is provided by Kana (67). A proposal to employ mechanical pulse generators for the seismic testing of structures is offered by Masri and Safford (68).

Blast is an explosively-induced shock environment. Facilities for the simulation of conventional (69) and nuclear (70) blast are available. A high-pressure actuator (71) was developed for system level simulation of airblast-induced ground motion. Structureborne gun blast shock has been reproduced on a electrohydraulic vibration exciter (72). Shock tubes are important facilities for the study of shock effects. This conclusion is supported by the extent of participation in the Ninth International Shock Tube Symposium as discussed by Bershader and Griffith (73). The proceedings, "Recent Developments in Shock Tube Research", published by Stanford University Press is 830 pages long. Crash-worthiness of either motor vehicles or aircraft must be verified by test. Robbins (74) reviewed the state-of-the-art of impact testing for automotive collision research. Vaughan and a colleague (75) describe a full-scale aircraft crash test facility.

The Navy has expanded its capability for simulation of underwater explosion shock by the development of a large floating shock platform (76). An exploding wire technique has also been used for this purpose (77). Special techniques for impact testing have been developed. Explosively propelled plates are impacted against the test item (78). The tangential velocity of a centrifuge is used to create the required impact environment (79). Finally, a variable angle rocket launcher (80) launches a test item at an impact target.

Vibration Tests

The various types of vibration test machines, including mechanical, electrodynamic and electrohydraulic, are described in Chapter 25 of Harris and Crede (1). A comparison of techniques and equipment for vibration testing is given by Tustin (81). An exceptionally useful monograph on vibration test selection and procedures was written by Curtis, et. al. (82). An informative monograph on the equivalence of different vibration tests is provided by Fackler (83). As with all testing, expenditures for vibration tests must be kept as low as possible. Young (84) performed a useful cost optimization study on spacecraft testing. To be useful, vibration test results should in some way be compared to failures in the field. Kana (85) has provided a method to do this for fatigue damage. New techniques are applied to testing as they are developed. Smallwood (86) has applied unloaded motion measurements and mechanical impedance to predict parameters related to test response.

Department of Defense requirements with respect to reliability testing (MIL-STD-781C) have changed to incorporate random vibration tests. Tustin (87) has examined inexpensive mechanical and pneumatic shakers for this purpose. Edgington (88) described a three-dimensional vibration system and Ryden (89) a dual shaker facility. The use of pneumatic vibrators for random vibration testing of missiles is proposed (90). Hieber (91) discusses the importance of fixtures and Lowenadler (92) addresses safety devices with respect to vibration testing.

The importance of developments in digital test control has been mentioned earlier. Because of the rapid advancements in this area, a special seminar on understanding digital control and analysis in vibration test systems was co-sponsored by NASA and the Shock and Vibration Information Center. The proceedings of this seminar provide the most definitive collection of papers available in this area. Chapman (93), a pioneer in digital control, gives a comprehensive overview of the subject. Keegan (94) discusses innovations in testing permitted by digital control. Mosely (95) treats extended measurement and test capability. Ratz (96) addresses digital control of sine-sweep tests. Norin (97) describes random vibration testing, and Stauffer (98) covers combinations of random and sine waves. The important modal analysis area is treated by Richardson (99) and safety of test articles during digitally-controlled tests is considered by Dorian (100). Digital control is now used on servo-hydraulic test systems (101). Refinements are continually being made (102) and it is expected that test capability will continue to be extended over the next several years.

Acoustic Tests

The sources for generating acoustic noise include sirens (discrete frequency and random), loud speakers and special noise sources such as unheated airjets or actual rocket or jet engines. The test chamber choices are progressive or standing wave tubes and reverberent chambers, or some combination of these. A comprehensive listing of acoustic test facilities was produced by the Institute of Environmental Sciences in 1975 (103). A comparative evaluation of acoustic noise generators has been made (104) and modifications in geometry of reverberent test chambers have been studied (105,106). A special chamber has been described (107) to be used for reverberent test in either air or water. Digital control of acoustic tests has been achieved (108).

The breadth of interest in acoustic testing is illustrated by a few developments. A special facility has been designed to test the techniques for jet aircraft noise reduction (109,110); techniques for the study of helicopter noise have been applied (111). A new test method for evaluating impact noise has been proposed (112). A special facility for determining the sound power emitted by appliances (113) is being used and an anechoic chamber has been adapted for fan noise testing (114).

Special Dynamic Tests

This report would be somewhat lacking if a few special test developments were not discussed. A lengthy report by NASA (115) discusses all aspects of flutter testing, including methodology and data analysis techniques for flight testing and on the ground. The development of testing techniques useful in airplane resonance testing, wind tunnel aeroelastic model testing, and airplane flight flutter testing was discussed by Jennings et al (116). Reed (117) described correlation with flight of some aeroelastic model studies. Houbolt (118) reviewed various procedures that might be used in evaluating systems response characteristics as involved in subcritical flight and wind tunnel flutter testing of aircraft.

Three selected examples of additional special tests include the use of a semi-anechoic room for small engine noise studies (119), a technique for the validation of vehicle models using a road simulator (120), and an automated dynamic load simulator to evaluate combustion engine cranking systems (121). It is the observation of the authors that test engineers are generally very innovative. Whenever there is a need for a special dynamic test, the methodology will be developed to perform it.

Diagnostics

Machinery during operation exhibits certain measurable effects which, when measured during efficient operation then monitored for trends away from the norm, can indicate conditions that may lead to operational failure. Various parameters could be used, for example, power and efficiency; oil, coolant and bearing temperatures; oil pressure and contamination; and vibration and noise measurements. This report is concerned only with vibration (mechanical) and acoustic signatures and their use in machinery diagnostics. Such techniques are widely used in the United States to predict impending failure in machinery.

> "The literature contained many references to the use of vibration signatures for monitoring the condition of machinery and its components. It is a viable technique since laboratory studies and field experience have shown that the amount of vibration in a machine or its components can be related to the presence of defects or the severity of wear."

The foregoing statement is the conclusion of Volin (122) in his comprehensive review of the state-of-the-art of mechanical signature analysis technology. The reader is referred to Volin's paper for more detail on advancements in this field. It should be added that acoustic signatures are also used for diagnostic purposes (123,124,125) and that acoustic emission technology is frequently used for flaw or failure detection (126,127).

Scaling and Modelng

The use of physical models of structures or equipment along with proper scaling of the test parameters can, in many cases, provide all the required test information, usually at greatly reduced cost. The most comprehensive text on the subject is by Baker et al (128). Baker also made a recent contribution by the introduction of a new scaling law for strong shocks (129). Scaling laws have been developed for highly nonlinear acoustic fields and ground winds related to a launch vehicle (130). Water impact data has been scaled in connection with model tests of the space shuttle solid rocket booster (131). Snell (132) conducted experiments with subscale Lexan plastic models to study the effects of pyrotechnic shock. Bannister (133) has reviewed the use of scaled plastic models to study the behavior of large structures. The static and dynamic collapse characteristics of corrugated scale models has been studied (134) and model testing has proved to be cost effective in automotive collision research (135). Even a foam rubber model of earthquake faulting has been used to generate dynamic displacement data (136). The cost effectiveness alone makes this an important area for further research in the United States.

AUSTRALIA AND NEW ZEALAND

Measurement and Analysis

Shock Instrumentation

A shock tube device was developed for calibrating pressure transducers. The device which consists of a straight diaphragm-bursting shock tube with a conical extension generates a weak triangular pressure pulse (137).

Vibration Instrumentation

Low transverse sensitivity of accelerometers is necessary for accurate acceleration measurements. A device was developed to measure the transverse sensitivity of accelerometers at any azimuth. The device consists of a vertical cantilever beam with a horizontal surface at its free end for mounting the accelerometer. The beam is driven in flexural vibration by two vibrators. This device allows the transverse sensitivity of an accelerometer and its azimuth to be measured directly (138). A device was also developed to restrain the lateral motion of an accelerometer undergoing calibration as well as that of the standard accelerometer used for back-to-back calibration (139).

Acoustic Instrumentation

Research is being carried out in measurement of infrasound in Australia. The performance of infrasonic transducers in an infrasonic sound field is being investigated theoretically and experimentally. The work in this area is still in progress.

The engineers of the State Electricity Commission of Victoria have developed techniques for continuously measuring and analyzing noise. These techniques might be useful for measuring noise emitted from airport operations or other applications where continuous noise measurement and analysis is required (140).

A technique more suited to quick roadside measurement of vehicle passage noise was developed. This is a method that could be used world wide by police to set up noise traps in the same manner as radar traps (141).

Dynamic Testing

Acoustic Tests

The use of two reverberation rooms was found to be a practical method for determining the transmission loss of large size apertures. The technique requires the measurement of sound power level differences and the absorption in each room. The apertures become partitions of zero transmission loss and they can be used to check the accuracy of any test procedure and test facility (142). Related to the previous effort is the use of an impedance tube and horn for the absolute calibration of a reverberant room for measuring the sound power in tones.

Time-averaged holography has been used to study sound radiated from vibrating surfaces. The plate response to acoustic excitation, for a particular mode of vibration, is measured using holography, and the radiated sound power is measured in a reverberant room with the plate mounted in one of the room walls (143). The theory of time-averaged holography was also extended to consider possible 3-dimensional surface motion (144).

Vibration Tests

Methods and instrumentation for the measurement of vibration of large structures are available in Australia. The measurement techniques were used to measure vibrations and mode shapes of a radio telescope, a solar observatory, an oil refinery structure, and a bulk cargo unloader (145). Large structures contain low frequency modes of vibration, thus the techniques that were used for measuring vibration of the previously-mentioned structures might be used for measuring the vibration of a wide variety of large structures in this country.

The National Association of Testing Authorities (NATA) is a body that accredits test laboratories in Australia in many disciplines of science and engineering; vibration and acoustic testing are two such disciplines. Registration or accreditation is voluntary and it means that a laboratory meets their standards of testing practice. No such test laboratory accreditation authority exists in any other country, although New Zealand, Sweden, and Denmark have adopted similar schemes. The United States is reported to be considering something that is based on this authority (146)

Diagnostics

Acoustic emission in the audio band has been used for monitoring concrete test specimens for impending failure (147).

Mechanical Signature Analysis is becoming more popular in Australia. Rotating machinery in Australia is also extensively monitored to determine its condition and predict when it should be shut down for maintenance. Rotating machinery is instrumented for continuous monitoring of vibration levels with provision for automatic shutdown if the vibration levels become excessive (148).

UNITED KINGDOM

Measurement and Analysis

Special Dynamic Measurements

An apparatus was developed in Great Britain for measuring the dynamic torsional modulus and aerodynamic damping of single carbon filaments (149).

Shock Instrumentation

Methods were developed in Great Britain for measuring the mounted resonance frequency of shock accelerometers. The effect of the mounting on the accelerometer's resonance frequency was considered; the applicability of this technique to accelerometers whose resonance frequency ranges from 50 kHz to 250 kHz was also considered (150).

Two interesting techniques are used to analyze shock data in Great Britain. A technique for processing shock data that eliminates interference effects and background noise was developed. It is based on a computer graphics system for signal editing with Fourier Transform filtering (151). Another data processing technique makes use of a series algorithm for extracting modal information from the responses of lightly damped structures (152).

Vibration Instrumentation

Instrumentation for vibration measurements is also important in Great Britain. Holographic interferometry is used to study the response of test articles to vibration. Time-averaged holography was combined with electronic speckle pattern methods of analysis in a single system, and the electronic speckle pattern method for detecting vibration modes of three dimensional objects was evaluated (153).

Several interesting techniques were developed for measuring vibrations in rotating machinery. A laser system was developed for measuring torsional vibrations of rotating shafts. The system only requires that a line of sight be available to the point of measurement (154). A light emitting diode (LED) telemetry system was developed to transmit signals from transducers on rotating machinery to signal conditioning apparatus and data acquisition equipment. It overcomes problems inherent in slip rings and telemetry systems (155).

Vibration Data Analysis

A method for extracting damping ratios and modal frequencies of a multi-degree-of-freedom linear system from the Fourier transform of the one-sided autocorrelogram of the system reponse to transient and random excitation has been developed in Great Britain (156). An evaluation was made of methods for analyzing non-stationary data analysis procedures from the viewpoints of computational efficiency and ease of interpretation (157).

Acoustic Instrumentation

In Great Britain, interest exists in instrumentation for measuring continuous noise levels. Reference (158) contains a discussion of the parameters to be measured in both continuous equivalent noise meters and noise close meters. The process of correlation has been applied to acoustic measurements. An analog correlator suitable for acoustical measurements involving long time delays was developed (159). In an effort to determine the sources of sounds in jet engines, an acoustic telescope was developed (160).

Acoustic Data Analysis

A technique for processing signals from target arrays to obtain increased resolution for target identification was extended to the location of sound sources in a jet engine. The technique is based on multiplicative signal processing and it may be used in the case where a target signal is strong in relation to extraneous noise (161).

Dynamic Testing

Shock Testing

Transient excitation is used as inputs for modal testing in Great Britain. Two applications were made of this technique and, in one of these, the results are compared with double pulse holography tests (162).

Vibration Tests

One noteworthy facet of vibration testing concerns random vibration environments. One study was undertaken to devise a method for simulating random vibration response by discrete frequency testing (163). Two studies of the simulation of road vehicle response to random vibration due to road surface inputs were also performed in Great Britain. The purpose of one of the investigations was to provide inputs for studies of human response to road vehicle vibration (164). The other study described a digital technique for simulating random environments and the results were applied to the simulation of the response of a road vehicle (165).

Ground vibration transmission is also of concern in Great Britain. An impact method was developed to measure the impedance of the ground and attenuation of vibration with distance from the source (166).

Another study of vibration testing concerned time domain averaging as a means for enhancing a signal in the presence of high levels of background noise (167).

A major area related to vibration testing in Great Britain is the measurement of mechanical impedance. An extensive study is being made of the techniques necessary for making accurate measurements of this property. Professor D.J. Ewins of Imperial College, London, is the prime mover in this undertaking.

Acoustic Tests

Acoustic testing in Great Britain is concerned with methods for measuring the acoustic properties of structures and materials. A method for directly measuring the sound radiation from room surface was developed to replace a technique that was unsuited for lightweight structures (168). The use of a sound level meter was investigated as a substitute for 1/3 octave band measurements of the airborne sound insulation of walls and floors subject to white or pink noise excitation (169).

A correlation technique was developed for measuring a materials absorption coefficient in place. By using this technique it is unnecessary to test an identical sample in the laboratory or to dismount the material and test it (170).

A method of comparing the sound transmission characteristics of various materials and their combinations was developed. A modified impedance tube technique was used which eliminates the need for testing in a reverberation room (171). A method was also developed for measuring the reverberation time of a closed space in a high ambient noise level (172).

The polar correlation technique was developed for noise source location in jet engines. The technique employs an array of far field microphones which are normally located on a polar arc centered on a jet nozzle (173).

Facilities

In Great Britain, many test facilities have been developed for special purposes. A survey of noise test facilities was prepared which provides a detailed description of jet engine noise test facilities as well as the design, construction and operation of the noise test facility at the National Gas Turbine Establishment (174).

Special test facilities that are needed for supporting research towards quieter aircraft are described as part of a recent paper that discussed the entire research effort on this problem in the U.K.

Test Equipment

A torsional pendulum was developed to investigate the damping mechanisms of metals and alloys over wide stress frequency and temperature ranges. This device also allows measurements to be made at extreme temperatures or in a vacuum (176).

Test laboratories are often faced with a requirement for calibrating angular transducers. A rotary vibrator, based on a printed circuit motor driven by a servo amplifier, was developed for this purpose (177).

Diagnostics

Techniques for monitoring the condition of rotating machinery is an area of high interest in Great Britain. A survey article (178) that reviews the state-of-the-art in monitoring techniques in Great Britain, and in the United States, through 1976 was published. The published literature also describes the application and limitation of sampling and averaging techniques that can be used with wave analysis for detecting faults in the inner and outer races of ball bearings (179). The problems in monitoring the condition of rotating machinery have been discussed (180). Case histories of vibration problems in rotating machinery both in the chemical industry (181) and in power plants (182) have been published. Both of these sources discussed the techniques that were used to find the cause of the vibration problems.

Machinery condition diagnostics requires an understanding of the dynamics of the machine as well as the forces and instabilities that excite the unwanted vibration. Two studies that address this issue were performed. The first presented case studies of vibration phenomena that resulted in malfunctions of various types in rotating machinery (183). The second study discussed methods for determining the dynamic characteristics of machinery components, as well as relating signals from a component within a machine to the exciting force with the aid of transfer functions (184).

Once data have been acquired, it is necessary to interpret them in terms of the condition of the machine as well as its life expectancy. Prediction of the future life expectancy of a machine is largely an empirical process, however, Collacott (185) has developed an analytical procedure for predicting future machine life based on measured data.

As pointed out earlier, most diagnostic techniques are based on vibration measurement, however some techniques that are based on acoustic measurements have been used in Great Britain. An investigation of the sonic response of cantilevered test specimens during a fatigue test revealed a pronounced change in the power spectral density with time during the test. The effects of the change in overtones and their significance needs to be investigated (186). An acoustic resonance technique was developed to find breaks in gas-filled pipes. Breaks as small as 2 mm can be detected (187).

CANADA

Measurement and Analysis

A multi-sensor array was developed for monitoring a high speed shock wave passage. A scaling method and fast sweep technique allow the results from a large number of stations to be recorded on the screen of a dual beam oscilloscope with no loss of information.

Dynamic Testing

A review of the world's literature on impedance analysis techniques was prepared in Canada (188). This survey covers current measurement and testing techniques, recent applications, and suggestions for future applications. Interest also exists in system identification by means of resonance testing.

Speical Dynamic Tests

There is interest in a wide variety of tests that cannot be classified as shock, vibration, or acoustic. An age-old problem concerns agreement between predicted resonance frequencies of beams, using either Bernoulli, Euler or Timoshenko beam theories, and the measured results. This problem was discussed in a critical assessment of theories of beams flexure in connection with measuring the dynamic modulus of elasticity of a material (189). Dynamic stability tests of aircraft models are of continuing interest. Several advances in testing techniques have been developed in Canada (190).

Facilities

Facilities and equipment for acoustic testing are being developed in Canada. A 1/12 scale model of an acoustic research facility was built and tested to assess the background noise levels in the anechoic measurement area and to develop an exhaust collector for jet conditions for the prototype facility (191). Test facilities have been built to support programs concerned with sonic boom problems. In one case, a portable sonic boom simulator that weighs less than 25 lb was developed for field tests (192).

Diagnostics

Several elements in Canada have expressed a keen interest in machinery health monitoring; the interest is continuing and perhaps it is more widespread than the published literature indicates. Case histories of and techniques used for monitoring gas turbines in the petro-chemical industry have been described (193). The same holds true for pump sets in a hydroelectric plant (194).

The Canadian Armed Forces have had extensive experience in machinery condition monitoring. Real time automated octave band analyzers have been installed on many of their ships to monitor the condition of main propulsion machinery and principal auxiliary equipment (195). Automated machinery condition monitoring techniques should be developed as necessary and applied to major ships in the United States fleet. This arrangement might also serve to acquire environmental shipboard vibration data during actual ship operation.

FRANCE

Measurement and Analysis

Vibration Instrumentation

Dynamic photoelastic analysis may now be performed with a new type of ellipsometer (196). Applications to shock and vibration tests have been made. A contactless interferometric sensor for structural vibration measurement has been developed (197). Experimental results are presented for blade and helicopter main gear box vibrations.

Acoustic Instrumentation

A finite-difference method was used to calculate the acoustic emission properties of a pseudo-interdigital surface wave transducer (198). A pseudo-interdigital Rayleigh-wave transducer consists of an ordinary grating deposited on a quartz crystal surface and a counter electrode separated from the grating by a dielectric layer.

The reference sound source -- a source of known acoustic power output -- was developed in the United States in the mid 1950's. Several new devices to simplify the determination of sound power have emerged since 1970; the standards for the characteristics, calibration, and usage of these instruments have now been developed (199).

Dynamic Testing

Vibration Tests

Comparisons among ground vibration test data, flight vibration data and responses predicted from finite element models have been made (200,201). Vibration testing techniques for non-linear structures have been developed (202).

Modal testing techniques continue to be developed, especially in those countries, such as France, that have a strong space program. Modal survey techniques have been developed which use single point excitation (203) or arbitrary excitation (204). M. Feix (205) has developed an iterative self-organizing method for determining modal characteristics. In this iterative method, starting with an arbitrarily applied force, at the end of each step the algorithm provides instructions for the execution of the next step, while a test shows if the number of degrees-of-freedom to be considered has been reached. X. T. Nguyen (206,207) has reviewed theoretical and experimental modal survey methods and proposed a new method.

Philosophy and Techniques

G. Hoffman (208) has developed techniques for the multi-variable control of an aircraft model in a wind tunnel. The controller stabilizes the elevation and the pitch angle, alleviates vertical gusts, and improves the damping of the first elastic mode.

Facilities

An explosively driven shock tube which can accommodate waves with 50 mbar overpressures has been constructed (209). It has a diameter of 300 mm and is 70 m long. It was constructed to investigate the detonation dynamics of an explosive charge in a tunnel.

J. Bongrand (210,211) has described the characteristics of the new A17 anechoic chamber at Centre de'Essais des Propulseurs, Saclay, France. An anechoic wind tunnel is soon to be constructed which will have characteristics similar to those of the A17. A recent study discusses the design problems related to the development of an anechoic wind tunnel (212). A complete review of research aimed at the design and operation of large wind tunnels has been published (213). This is the result of a meeting in which 132 research workers from nine countries participated.

INDIA

Measurement and Analysis

Acoustic Instrumentation

B. Yegnanarayana (214) has made experimental measurements of the sound decay rate in rectangular rooms (214) as a function of the boundary conditions on one wall. The coefficients derived from the initial decay rates do not correspond to either Sabine's or Eyring's theories. Explanations of the experimental results are offered by the author.

Dynamic Testing

Shock Tests

Experimental results are available for the response of a clamped circular plate to axisymmetric half-sine pulse load impacts (215). Experimental results were compared with numerical results. A shock tube has been used by A. Rajamani et al (216) to investigate the response of plates, with and without cut-outs, to blast loading. In a related analytical work S. A. Ramu and K. J. Iyengar (217) have analyzed the responses of circular plates to blast loadings.

Vibration Tests

The National Aeronautical Lab in Bangalore, India, has developed a multi-point excitation system for ground vibration testing (218). Their system contains sophisticated controls with six loops, one to control excitation frequency and five to control force levels (219).

ISRAEL

Measurement and Analysis

Vibration Instrumentation

S. Braun (220) has developed new methods for the extraction of periodic waveforms by time domain averaging and for the computation of variance from signals of unstable chracter (221).

Adelman, and others (222,223,224) have developed several analytical methods for the analysis of PZT-4 transducers of various shapes including cylinders and disks. They have applied their methods to the study of annular accelerometers operating in the radial-shear mode. They have used their methods to design efficient piezo-ceramic bandpass filters and other composite transducer devices.

Kaplan (225) has developed new transducers for measuring translations and vibrations of mechanical parts. The transducers are non-contacting; they sense with electromagnetic fields. Kaplan discusses three types: 1) One-sided capacitive transducers, 2) differential capacitive transducers and 3) microwave interferometric bridges. With the microwave bridge it is possible to record the movements of remote objects with amplitudes in the micrometer region from distances of several meters.

Braun (226) has developed simple analog and digital compensation systems for the minimization of possible dynamic errors caused when using seismic low-tuned transducers.

Shock Instrumentation

Segev, et al (227) have developed an experimental technique for measuring the shape of a shock emerging from a tube based on a shadowgraph technique.

Dynamic Testing

Facilities

Results of measurements of flow uniformity and noise in the 60 cm x 80 cm induction wind tunnel are available (228).

ITALY AND GREECE

Dynamic Testing

The special effect of sonic boom on the behavior of gas turbines is of concern in Italy. Sonic booms, or air blast waves, distort the inlet pressure to an operating gas turbine which in turn produces an unsteady mass flow through the engine, as well as possible responses of the inlet fan and compressor components. Various methods of simulating sonic booms have been studied, and an operating gas turbine has been subjected to simulated sonic booms to determine how its performance is affected. Particular attention was paid to propulsion system instability and the responses of the inlet fan and the compressor to the inlet flow distorted by the sonic boom (229).

JAPAN

Measurement and Analysis

Shock Instrumentation

Ikui, et al (230) have developed fast-acting valves for use in shock tubes to replace the usual breaking-diaphragm type.

Vibration Instrumentation

Yamada, et al (231) of the National Aerospace Laboratory, Chofu have developed a rotary drive vibratory output, two-degree-of-freedom gyroscope. This device formed the basis for the later development of a rotary-drive-vibratory-output accelerometer (232). Kagawa, et al (223) have developed a mapping technique using liquid crystals for the detection and visualization of ultrasonic fields.

Acoustic Instrumentation

Hatano and Mori (234) have developed a new method for the absolute calibration of acoustic emission transducers using a reciprocity technique in a Rayleigh-wave sound field.

Dynamic Testing

Control and Procedures

Hirai and Matsuzaki (235) have developed an experimental compensation technique which negates the influences of resonances in the test structure. The relative acceleration, velocity and displacement between the shaking table and the test structure is fed back with the proper gain rate. The method has been used successfully on an electro-hydraulic shaking machine with a 1-ton table.

Facilities

Mitsubishi Heavy Industries, Ltd., completed in April 1973 a large bi-axial shaking table for aseismic engineering and other vibration tests at the Takasago Technical Institute. It is designed in such a way that it may be developed into a tri-axial shaking table by adding a vertical actuator. It is a low frequency (0-50 Hz) electro-hydraulic system with a 6 x 6 table which will handle 100 tons in single axis, with a maximum exciting force of 100 tons.

Diagnostics

Dr. Takuso Sato, et al, have developed several applications of the "bispectral analysis" of random signals. Bispectral analysis is the analysis of the statistical parameter related to the coherence among three frequency components in a random signal. It gives useful information when applied to vibration analysis which cannot be obtained by conventional power spectral analysis. Bispectral analysis has been applied to holography (236), sonar (237), the contactless diagnosis of gear noise (238) and to laser doppler velocimetry (239).

Scaling and Modeling

Model tests are used frequently in Japan. Takei, et al (240) recently performed structural shock tests of a model of a prototype FBR "Monju" nuclear reactor using high explosives. The tests simulated the structural dynamic response of a LMFBR primary coolant boundary to a hypothetical core disruptive accident (HCDA). Mori and Kawakami (241) have studied the earthquake response of fill-type dams. Nakamura and Yoshimura (242) have used models of bridges in wind tunnels to study the binary flutter of suspension bridge decks. In another series of wind tests, Yoshida, et al (243) studied the dynamic performance of 1/10 scale models of vehicles passing through a cross-wind region.

NETHERLANDS

Measurement and Analysis

Acoustic Instrumentation

Members of the Institute of Applied Physics, TNO-TH Delft have published several works on experimental acoustic measurement techniques. Reciprocity type measurements have been made of acoustic source strength (244) and mechano-acoustical transfer functions (245). Interest is increasing in the Netherlands on the measurement of industrial noise emission, because a noise abatement bill has been introduced into Parliament which contains a zoning system for industrial areas. This was the main reason for the Inst. of App. Physics publishing a paper on measurement of the source strength of large industrial sources (246).

Much progress has been made, especially in Belgium, on the standardization of procedures for measuring acoustic absorption coefficients in reverberation rooms (247,248,249). Although nearly eight decades have passed since Sabine published his experimental formula, there is still an urgent need for a better knowledge of the sound absorption coefficient and for its precise measurement in reverberation rooms (250). Researchers still disagree about the regions of validity of Sabines formula and Eyrings formula.

Dynamic Testing

Acoustic Tests

Many round robin tests (R.R.T.) have been made in the Northern European countries. A report which contains a summary of these activities has been published (251). This series of tests were about how to measure acoustic absorption coefficients. Another international R.R.T. was conducted on the magnitude of auditory sensation (251). There was also an International R.R.T. on the subjective and objective measurements of the loudness level of impulsive noises (252).

Facilities

The European Space Research and Technology Center, (ESTEC) Noordwijk, Netherlands continues to upgrade their environmental test facilities. They have improved their ESTEC vibration test equipment (253). The ESTEC acoustic test facility has been described (254). Fuel-slosh rigs have been constructed to study the effects of fuel sloshing on spacecraft nutation damping (255).

SWEDEN, NORWAY AND DENMARK

Measurement and Analysis

Much experimental acoustic work is being done in Sweden, Norway and Denmark recently, especially measurements of the reverberation times of rooms.

Acoustic Instrumentation

Bodlund, (256), of the Lund Inst. of Technology, Lund Sweden, has developed techniques for measuring the statistical characteristics of the standard room acoustic parameters, such as sound pressure level, reverberation time, sound power level and transmission loss. Lund (257) has developed an improved experimental technique for measuring diffusion. This is an important acoustic parameter to measure correctly, because of the application of diffusion panels in reverberation rooms to diffuse the low frequency sound fields.

Vibran and Sorsdal (258) of the Norwegian Institute of Technology have made a comparison study of five commonly used methods for the automatic measurement of reverberation time. The measurements were made in two reverberation chambers. The authors (258) state that an automatic method should be recommended to supplement the "straight line" method outlined in existing standards. Hognestad and Bjor (259) of the Central Institute for Industrial Research, Blindern, Norway, have developed a new microphone multiplexer which allows one to use several microphones in the measurement of the space average of sound levels in rooms. Ulf Sandberg, et. al. of the Nat. Swedish Road and Traffic Res. Institute have made several experimental studies on pavement roughness (260) and its influence on tire noise (261).

Dynamic Testing

Shock Tests

The Norwegian Defense Construction Service has sponsored an extensive series of model tests on the air blast propagation in underground ammunition storage sites. The tests were designed to simulate accidental explosions. At least eleven reports are available which either describe the test themselves (262, 263, 264, 265, 266, 267, 268, 269) or related topics (270, 271, 272).

Skjeltorp, et. al. (265) in part one of a five part report on the test give a general description of the scope and purpose of the tests as well as a presentation of the principles of scaling. Also given in Part 1 (265) is a survey of the test program, instrumentation, and data reduction for the whole test series. In later reports Skjeltorp et. al. (266) discuss the chamber pressure time histories for various explosives (TNT, PETN, Dynamite,.) blast wave propagation in the tunnel system (267, 268) and the blast loads on doors (269). The tunnel models contained various branches and angles and ratios of tunnel diameters. The models ranged in scale from 1/100 to 1/40. The model test data compared favorably with one full scale test. Relatively simple scaling relationships were obtained from an analysis of the test data. One interesting result is that a large air blast will be attenuated by a rough walled tunnel (272). Also, a reinforced door was tested with gradually increasing air blast until reaching the maximum load required by NATO (271).

Bjorno and Levin (273) of the Technical Univ. of Denmark have developed experimental techniques for underwater explosion research using small amounts of chemical explosives. The authors have generated empirical expressions for the peak pressure, time constant, impulse and energy flux density as a function of charge weight and distance.

Vibration Tests

Helmut Wittmeyer, Consultant, SAAB-SCANIA AB, Linkoping, Sweden had developed a new model survey method (274). Wittmeyer's method determines the complex eigenmodes of a structure. Wittmeyer states that complex eigenmodes can be excited more easily than real eigenmodes produced during the classical ground resonance test. These are the modes the structure would have if it had no damping. His method requires the damping be small. Output of the procedure is the generalized stiffness and damping for each mode as a function of the amplitude of the mode. Wittmeyer feels his method has advantages over the methods in current use in both the United States and Europe.

Facilities

A new anechoic water tank has been constructed at the Technical University of Denmark, Lyngby (275). Bjorno and Kjeldgaard give detailed discussions of the physical properties of the proposed tank liners. The final liner chosen was a cork and aluminum powder-loaded butyl rubber lining backed by marine plywood. Measurements in the 10 kHz to 300 kHz region showed the tank to have excellent anechoic qualities.

SWITZERLAND

Dynamic Testing

The philosophy of overspeed testing of large turbines and generators at the Brown Boveri Group's test facilities has been discussed (276). The test facilities are also described.

WEST GERMANY

Measurement and Analysis

A considerable amount of experimental work in West Germany centers on acoustic measurements, i.e., transducer calibration, measurement of acoustic absorption coefficients in reverberation rooms, and techniques for accurate sound level measurements when the microphone is embedded in a flow region.

Vibration Instrumentation

Wittmann and Friedinger (277) have developed an instrument which measures the wind-induced vibration of tower-like structures. The instrument contains an inductive motion pickup which measures elongation and an especially-designed digital unit which resolves the longitudinal and lateral vibration components.

Acoustic Instrumentation

In a two part article, I. Veit has reviewed techniques for acoustic and vibration measurements in industry. The two part article contains a detailed review of acoustic transducers as well as methods and instrumentation for the analysis of the measured data. In Part 1, Veit (278) briefly introduces the concept of sound propagation in gaseous, liquid and solid media. He then describes the functions of the most common sound transducers, such as the condenser-microphones, hydrophone and accelerometer. In Part 2, Veit (279) discusses the most important measuring instruments and methods for sound-pressure level measurements as well as calibration methods and techniques for frequency analysis.

Brendel and Ludwig (280) have developed methods for measuring the diffraction loss for circular transducers in the Megahertz frequency range. Knowledge of this diffraction loss is crucial for the self-reciprocity method of calibrating acoustic transducers.

Several researchers have developed methods for sound measuremetns using microphones in flow regions such as ducts (281, 282) and in wind tunnels (283).

Efforts continue in West Germany towards more accurate measurements of sound absorption coefficients in reverberation rooms (284) and in polyhedral rooms with non-uniform absorption (285). In (285) Kuttruffi shows that Eyring's reverberation formula is not generally valid if the wall absorption is non-uniform. Kuttruffi also derives a correction term to the Eyring formula for use in rooms with non-uniform absorption.

Special Dynamic Measurements

Wiegand and Goldelius (286) have developed a fully automatic torsional oscillation testing instrument, connected to a process-control computer, which determines the shear modulus and mechanical loss factor of the sample. The system is especially useful for testing plastics and it offers considerable advantages over customary testing instruments.

Mehner and Peschel (287) have developed a test stand for the determination of the dynamic response of rotating elastic power transmission components, particularly couplings and v-belts.

Another torsional test device has been developed by Althof and Schlothauer (288). Their device is for the torsional vibration testing of adhesive-metal joints which have been exposed to climatic conditions for a long period. A novel linear displacement transducer has been developed by Bouts and Gast (289). The device is based on a vibrating string; the frequency of vibration of the string is related to the displacement. The principal is that, as the tension in the string increases, the frequency shifts upwards.

Dynamic Testing

In West Germany the emphasis with respect to dynamic testing has been on modal survey methods, development of wind tunnels testing techniques and facilities, and the application of holographic methods.

Shock Tests

Mahlin and Froboese (290) have developed an explosively-driven shock tube with a right-angled junction. Driven by firing bars of Hexolit, the device generates upstream overpressures of 12 to 40 k bar in the area shortly before the junction.

Vibration Tests

H.G. Natke (291) has surveyed the ground and flight vibration test methods used in practice in the European community since 1968. The survey contains a short description of the methods, comments on their application, and lessons learned. Natke notes that few methods consider non-linearities; most are based exclusively on estimation procedures, and background noise is the biggest headache. In a related work, Niedbal (292) has analyzed the state-of-the-art of modal survey test techniques. Besides the classical phase resonance method, some new modal survey test techniques are described (Angelini's, Natke's and Wittmeyer's methods). Niedbal used a three-degree-of-freedom mathematical model to test each method and to show that each new method should be checked systematically.

Kiessling (293) has developed methods for performing static vibration testing on V/STOL rotary wing aircraft. Predictions of the dynamics of the rotorcraft when the rotors are in motion can be made from these static test methods.

Facilities

A new acoustics center for noise investigations has been constructed in Cologne, Merkenich (294). The anechoic chamber is equipped with a built-in two-axle chassis dynamometer. The adjacent reverberation room serves to determine the sound power and to improve the noise characteristics of vehicle components such as engine, transmission, and fan. A special opening between the reverberation room, and a transmitter room with reverberation room characteristics, allows specific sound transmission loss investigations to be made on damping materials fitted to body parts, such as vehicle dash panel assemblies.

A new transonic and supersonic wind tunnel has been constructed at the Aerodynamic Institue (295). Present compressor installations restrict the use of the new wind tunnel to an intermittent operation schedule. Freytag (295) discusses the design and operational details of the wind tunnel, including the Laval nozzle, the free jet chamber, the diffusor and the transonic chamber.

Philosophy and Techniques

New testing techniques for the investigation of flutter characteristics and flutter suppression systems have been developed in West Germany. Hoenlinger and Sensburg (296) have demonstrated the method by applying it to an active flutter suppression system.

Special Dynamic Tests

Holographic testing and measurement methods continue to be applied in West Germany industry. In a recent report on holographic techniques Steinbichler and Rottenkolber (297) state that holography, as a non-destructive test method, is best used on materials where conventional test methods are difficult. These are materials like rubber, metal/rubber combinations, adhesive materials, reinforced plastics, and so forth. They state that the advantage of holographic testing is that nearly ideal stress is possible. Ideal stress can occur in one part of specimen even while another part is being destroyed. In an application of acoustical holography, King and Watson (298) have developed acoustic holographic methods for the location of sound sources on complex vibrating structures such as a three-bladed ventilator fan. In their report of the method, optical and computer sound source reconstructions are compared and analyzed.

Diagnostics

In West Germany, as in the U.S., much of the diagnostic work is centered on detecting the imminent failure of components on rotating equipment. Detection of bad bearings and blades in turbomachinery must be made early to avoid catastrophic failures and to allow for more orderly scheduling of shut-downs and overhauls.

Felske and Happe (299) have developed methods for the vibration analysis of structures, such as automobiles, using a giant pulse laser with 30 ns double pulses. A hologram is made using a camera especially constructed for making double-pulsed holograms.

Diagnostic techniques for the detection of faulty bearings using structure-borne sound have been developed in West Germany by Ullmann (300). Freidrich, et. al. (301) have developed improved methods for the recognition/detection of blade failure in turbomachines. The method employs pressure transducers, accelerometers, real-time analyzers and a mini-computer. Gudat (302) has discussed the application of acoustic pattern recognition techniques to modern industrial production. He expects the usage of acoustic pattern recognition techniques in industrial production to increase in the future for two reasons. The first reason is the present availability of efficient semi-conductor technology. The second reason for using pattern recognition techniques is to help with the automation of quality control. Pattern recognition techniques have been applied for the detection of impending failures in turbomachinery (303) by measurement of the emitted noise. The techniques have been used successfully in the laboratory and are now being applied to power plant turbines.

Scaling and Modeling

Acoustic models are being used in several experimental studies in West Germany. A free jet test stand has been constructed at the Institut Fuer Technische Akustik, Trauen, West Germany (304). The test stand will be used for aeroacoustic model experiments.

W. Neise (305) has performed experiments on two fans with impellers of 140mm and 280mm diameter. His results verify Weidmann's formulation of similarity laws. The results show that data from a model fan can be extrapolated to other geometrically similar fans of different size.

ROMANIA

Measurement and Analyses

Micrea Rades (306) has reviewed present (1976) methods for the analysis of structural frequency response measurement data (306). Rades review provides an introduction to the graphical analysis of frequency response data. Particular emphasis is placed on vector diagrams. Four excitation techniques are discussed: (1) steady-stata harmonic, (2) quasi-steady state, (3) transient, and (4) continuous random. For grounded systems the methods discussed are the peak-amplitude method, phase-angle method, in-phase component method, in-quadrature method, vector-diagram method, forces in quadrature and rotating unbalance method. Ungrounded and nonlinear systems are also discussed.

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Chapter 7

COMPONENTS

INTRODUCTION

A system may be electrical, mechanical, structural, or a combination thereof; it is conceived for some specific functional purpose and stands by itself. Every system is made up of a number of parts or elements, which for purposes of this report shall be called components. This category deals with shock and vibration research and development problems related to the design and successful function of these components. Only highlights are given to indicate trends. No attempt is made to include comprehensive literature citations.

UNITED STATES

Electrical

The literature is sparse with respect to dynamic studies of electrical components, except in those cases where work is done as part of a systems analysis. Perhaps this is symptomatic of a need to be filled. Electric motors, for example, seem more often subject to mechanical than electrical failure. Murray (1) offers some guidelines to avoid such failures. Power plants are known to be fraught with dynamics problems. Pigott (2) has looked at vibration effects on power plant condensers. Fischer and Daube (3) carried out an exhaustive analysis and test program on earthquake-resistant circuit breakers. Dynamic troubles in this are are not unique to ground systems, since the Navy has been plagued with shock-related circuit breaker problems for years. Two studies (4, 5) indicate methods of solving commonly-occurring vibration problems for printed-circuit boards. Dynamics studies have been conducted on control systems for flutter modes (6), propeller gust response (7) and feedback suppression of dynamic response in helicopter rotor blades (8).

Mechanical

Dynamic effects on mechanical components are the chief cause of system troubles. At best a faulty component can reduce the efficiency of the performance of a system; at worst it can cause catastrophic failure. The components discussed herein were selected to illustrate some cases in point.

Tires

The dynamic characteristics of vehicle tires have a marked effect on vehicle handling, as indicated in a report by Ervin et al (9). Barone (10) has studied the area of tire vibrations produced by impact and its effect on the harshness of vehicle operation.

Absorbers and Isolators

Absorbers and isolators are integrated in the design of a system to reduce the mechanical impacts to acceptable levels (see earlier discussion on damping). Chen and Adams (11), in a paper on parameter optimization, characterized a mechanical vibration absorber as having an inertia member coupled to a vibrating system through suitable linear coupling elements (usually a linear spring and viscous damper). Snowden (12) pioneered novel platelike vibration absorbers, which comprise either a circular or an annular damped plate that is loaded at its outer perimeter by a rigid annular mass. Snowden (13), in another important paper, discussed transmissibility across novel compound or two-stage mounting systems incorporating dynamic vibration absorbers. The practical application of absorbers is treated by Raynesford (14).

Automotive shock absorbers are important to almost every citizen. Jennings (15) produced an interesting paper on the damping of motorcycle shock absorbers. The important area of automotive collision research has produced a study (16) assessing the nature of the dynamic problem with a view to the use of crushable energy absorbing devices. Elastomeric foams are used as isolators for a number of applications including package cushioning. Sepcenko (17) describes an analytical and experimental study leading to a method for predicting the dynamic response of such materials to impact loading. A study by Schubert (18) illustrates the use of shock and vibration isolators for heavy machinery.

Blades

Blades are components in jet engines, blower or cooling fans, propellers, helicopter rotors, gas turbines and compressors, circular saws and so forth. A multitude of dynamics problems are associated with blading. High performance jet engines have brought forth the problem of transonic blade flutter. Platzen (19) has conducted a survey of this area. Optical techniques (20) are used to determine blade deflections. The use of composite blades has solved some of the problems related to impact of foreign objects (21) and vibration (22). Special design techniques have been employed to reduce fan blade noise (23, 24).

Factors influencing failure of aircraft propeller blades have been studied (25); flutter and damping characteristics of helicopter rotor blades have been investigated (26). Fertis (27) conducted a theoretical investigation of the dynamic response of nonuniform rotor blades. Gas turbine blades are subject to vibration and temperature problems. Jones et al (28) use tuned dampers incorporating high temperature vitreous enamels for energy dissipation. Special ceramic blades (29) have also been employed to solve the high temperature problem.

The reduction and control of circular saw vibration are essential to the improvement of wood surface quality and cutting accuracy, to the reduction of kerf losses and noise, and to the prolongation of tool life. Mote and a colleague (30) conducted a comprehensive review of research in this area with 123 references. The reviews concluded that progress is substantial but that much research remains to be done. As a special note on blading, soil excavation has been improved by deliberate oscillation of bulldozer blades (31) and communities will benefit from noise control techniques on lawn mowers (32).

Bearings

Worn or defective bearings produce vibration problems for rotating machinery (See Diagnostics). The rolling contact fatigue life for bearings in a contaminated lubricant can be predicted (33, 34). Torque noise in precision ball bearings used to support instrument platforms for spin-stabilized spacecraft creates alignment problems. Research in this area has been performed by the Aerospace Corporation (35). Gupta et al (36) have investigated the vibrational characteristics of ball bearings. A number of research studies have been conducted on gas lubricated journal bearings (37, 38, 39). Hybrid journal bearings have been studied (40) and a new type of tilting pad journal bearing (41) has been developed. Work on analyzing damping and stiffness for squeeze-film bearings has been extended (42).

Shafts

The use of drive shafts creates a special class of vibration problems. A definitive monograph (43) was written on this subject in 1969. Research related to transition through critical speeds (44) and the response of variable cross section shafts (45) has been accomplished. Techniques for identifying and correcting truck driveline vibrations have been developed (46).

Ducts

The concern about fluid flow in ducts is noise. For example, Jones (47) conducted a thorough study of grilles, registers and diffusers in connection with noise generation in air conditioning equipment. Work has been done to optimize acoustic liners for ducts associated with turbomachinery (48). Noise reduction for curved duct sections has been studied (49). Chestnutt and Feiler (50) have advanced inlet duct noise reduction concepts for aircraft. Nozzles, closely related components, have been studied with respect to lip noise generated by flow separation from the nozzle surface (51).

Linkages and Gears

Linkages are connector mechanisms in machinery systems. Couplings and cams fall into this category. Gears are a form of linkage. A review of research on the balancing of certain linkages was completed by Berko, et. al. (52). Dix (53) surveyed the latest computer-based methods for the dynamic analysis of rigid-link mechanisms. Chen (54) conducted a literature review of the dynamic aspects of cam mechanisms, including the kinematics of cam profiles, system modeling and analysis, system response and design methods. Chu and Pan (55) produced a useful paper on the dynamics of a high-speed slider-crank mechanism.

Some couplings require a seal to prevent leakage. Goodrich engineers (56) developed a torsional elastic seal for this purpose. Since zero shaft misalignment is impossible, couplings must have some flexibility. Johnstone (57) discusses flexible couplings and their functions beyond the compensation for misalignment. Milenkovic (58) describes a new constant velocity coupling for a specialized application, with specifications that are outside the range of any existing designs.

The dynamic behavior of gear systems is capably treated in an ASME publication (59). Warner and Wright (60) describe a high-performance vibration isolation system to isolate the marine gear from its foundation on the DD963 Class Navy ships. Forms of fasteners can also be considered as linkages. Vibration studies have been performed on both nails and bolts (61, 62).

Pipes and Valves

Dynamic considerations are very important in the design of pipes and piping systems. Shipboard piping is especially vulnerable to shock. Prause (63) produced a very useful review of work on the dynamic modeling of pressure vessels and piping systems. He provides a background for identifying current problems and limitations. He points out that computer programs for this purpose are relatively well developed. However, the modeling and subsequent analysis of specific structures still requires considerable engineering judgment and many assumptions and approximations that can be critical to the validity of the results. Modeling techniques need to be improved through further research.

Earthquake effects on above-ground oil pipelines have been studied (64), structural performance of buried PVC pipe has been assessed (65), and the dynamic characteristics of underwater pipeline has been analyzed (66). Sudden valve operation produces a sudden pressure and shock loading on pipes, commonly called the steamhammer problem. The dynamic response of piping to this environment has been described (67). Wachel and Bates (68) discuss techniques for controlling piping vibration and failures, while McQueen (69) treats the problem of wrapping and lagging noisy piping. A concept for reducing valve noise by optimizing valve jet size and spacing has been introduced by Reed (70). Vibration problems in heat exchanger tubes has been dealt with by several investigators (71, 72, 73).

Springs

Springs are used in isolation systems and in machinery mechanisms. Recent basic studies on springs have been related to fatigue (74), pulse propagation (75), and on the synthesis of spring parameters in planar mechanism design (76).

Structural

Structures are usually analyzed by looking at the combination of structural elements of which they are composed. Extensive mathematical research has been done on various structural elements, with the most abundant studies on beams, plates and shells. Although it is recognized that these mathematical exercises have greatly enhanced capabilities in structural analysis, it is not appropriate to treat such a broad area in any depth in this report. Discussion in this section will mostly be limited to applications-oriented studies in problems of current concern to United States interests. An example of this is a review article by Ross, et al (77) on experiments related to the effects of blast loading on simple structural elements.

Beams and Cables

A grid-work is defined as a structural system consisting of several sets of intersecting beams. Rao (78) has reviewed several mathematical techniques that have been used to analyze planar grid-works under dynamic loads. Numerical methods are used to determine differences between distributed versus lumped mass idealizations, torsional effects, boundary variations, spacing, and stiffness of beams. A practical example of a beam problem is related to the motion of ground vehicles over a bridge, as analyzed by Benedetti (79). The shock response of beams, a problem significantly related to Navy interests, has been a subject of interest at Pennsylvania State University (80, 81). A method has been developed (82) to produce a design curve for predicting the response of a beam to impact loading. Snowdon (83) uses mechanical four-pole parameters which enable the transverse vibration response of beams with discontinuities to be analyzed readily.

The dynamics of flow-excited struts in water, related to hydrofoils, has been studied by Blake and Maga (84). The dynamic analysis of shock struts on airplane landing gears has been accomplished at the Boeing Company (85). Wire ropes and cable systems have important Navy applications related to towing and salvaging. The dynamics of such systems have been studied extensively (86, 87, 88). Doll (89) has analyzed the response of flexible electrical cables to shock motion.

Cylinders

Much of the research related to cylinders deals with flow-induced oscillations. Chen's two-part review (90), also referenced under Fluids, discusses much of the current work in this area. Additional work should be mentioned concerning studies on cylinders related to floating structure applications (91, 92). Mahajan (93) provides a useful consolidation of information related to the design of tall stacks.

Columns

In this instance at least, columns are considered to be vertically-oriented beam structures for the purpose of supporting weight. An item of interest therefore is a report on the state-of-the-art of bearing capacity prediction for axially loaded piles (94). Columns that support loads such as tanks or overhead signs have been the subject of recent studies (95, 96). Gupta and Singh (97) offer a design procedure for columns used in earthquake-resistant structures.

Frames

Frames, as components of larger structures, significantly influence the response of the entire structure. Tall, unbraced frames are special cases, for example, and a subassemblage concept has been worked out to calculate collapse loads (98). Optical design procedures for frame-like structures have been developed by Sun, et. al. (99). The substitute structure method (100) extends the analysis capability for earthquake-resistant reinforced concrete frames to multi-degree-of-freedom structures. Belytschko (101) presents a formulation for the transient analysis of space frames in large displacement, small strain problems. NASA's Langley Research Center (102) has developed methods of determining dynamic characteristics of large tetrahedral space truss structures. This has important applications for analysis of extremely large, relatively flexible space structures. When a shallow arch is subjected to a symmetric dynamic load, this load becomes critical if a slight increase in the load magnitude leads to a sudden snap-through. Lo and Masur (103) have analyzed this dynamic buckling instability problem.

Membranes

Membranes have applications in transducers, such as microphones and loudspeakers, and certain musical instruments. The human eardrum is a membrane. Membranes are also extensively used in machine design for such items as pumps, compressors and pressure regulators, and in certain space applications. The principal problem in connection with a membrane is the investigation of its transverse vibration with a fixed boundary. Three research efforts (104, 105, 106) illustrate the nature of the problems that are investigated.

Panels

The only thorough review of work on the dynamics of composite and sandwich panels is by Bert (107), also referenced under damping. Geometrically, panels are like plates, but are usually called panels when they are applied to some structure. They may also have special structural characteristics. Carden (108) for example, determined the vibration characteristics of corrugated, flexibly supported heat shield panels. The impact behavior of stiffened and unstiffened aluminum panels under fixed boundary conditions was investigated by Furio and Gilbert (109). Panel flutter and acoustical effects in panel response have been studied in connection with applications on supersonic aircraft (110, 111). There was little known about the dynamic behavior of large precast panel buildings until a study by MIT (112). Of course, there are numerous studies of sound transmission through panels in connection with acoustic insulation problems.

Plates and Shells

Two important applications of plate analysis are in connection with wave propagation (113) and response to blast loading (114). The first easily relates to ship silencing problems; the second to explosive shock effects. Pertinent review articles on shell analysis are by Holzer (115), Klosner (116), and DiMaggio (117). Blast and shock are also important environments to consider in shell research. The dynamic response of shells to blast loads has been investigated by Ross and Strictland (118), while Chen and Symonds (119) have used a mode approximation technique to study impulsively loaded plates. Underwater shock interests are furthered in a study by Ranlet, et al (120) to determine the response of submerged shells with internally attached structures. This clearly represents a submarine. Nash (121) has analyzed shell response to random noise and a dynamic analysis of fiber-reinforced composite shells for missile structures was performed by Chung and Eidson (122). Lee (123) used a shell as a model to study axisymmetric vibrations of the head.

Rings

Among other applications, ring elements are used for containment of fragments in turbojet engine rotors and as reinforcements in missile and submarine structure. Four selected research efforts (124, 125, 126, 127) illustrate the range of investigations that are being conducted.

AUSTRALIA AND NEW ZEALAND

Mechanical

Absorbers

Two types of energy absorbers for protecting structures against earthquakes were developed. The first type of absorber is based on extruding lead through an orifice. The amount of energy absorbed is limited by the heat capacity of the lead. This energy absorption technique is not new, however the application to absorbing energy from earthquakes is novel (128). A lead rubber shear damper was also developed for use with base isolation systems for protecting bridges and buildings from earthquakes (129).

Bearings

Interest in the use of squeeze-film bearings exists in Australia. An investigation of the effect of pressurization of the oil film on the vibration isolation capability of squeeze-film bearings was made. The bearings were used to support a rigid rotor that was mounted in rolling element bearings. The analysis showed that supporting a rigid rotor in this manner provides vibration isolation and noise reduction (130).

Several techniques were developed that can be used to predict the effects of bearing properties or operating conditions on rotor-bearing systems. One technique used assumptions of short bearing approximation and constant lubrication properties to predict operating regions where external influences might excite regions of instability or undesirable vibrations. The technique also allows one to predict the effects of changing operating conditions, lubricant properties, and bearing geometry on the system operation (131). A computer program representing a shaft and rotor whirling in bearings was developed to calculate the timewise variation of the energy in translational motion that is supplied to the rotor by oil film forces (132).

A less costly approximate method, based on an overall energy balance, was developed for predicting the stability of rotating systems (133).

Valves

The Australians have made contributions to the use of bond graphs for modeling hydraulic control systems. As an example, the dynamic response of a proposed hydraulic control system was predicted using bond graph techniques for modeling the system (134).

Backlash in hydraulic control systems degrades the performance of some systems under some operating conditions. Noise emission is another undesirable effect of this phenomenon. A study was undertaken to determine the decay rate of hydraulic backlash for a particular system as well as its origins and remedies (135).

Structural

Cables

The theory of the static and dynamic behavior of a single suspended cable was extended to the dynamic behavior of cable trusses of several different geometries (136). Cable trusses have been used as a means of supporting long span roofs in buildings such as arenas and stadiums. Other interesting studies of cable dynamics include experimental studies of electrical transmission line vibration due to Vortex shedding excitation and the dynamics of cables that are sup‿rted at different levels.

There are many problems that must be solved before any technique for obtaining meaningful measurements of the mechanical properties of natural fibers can be made. A critical review of physical principles and experimental techniques was undertaken in Australia to find suitable techniques for measuring the dynamic properties of such fibers. An acoustic pulse propagation method was found to be the most suitable and associated small tools were devised for making the measurements (137). Cotton and other natural fibers have many uses and a knowledge of their dynamic mechanical properties would lead to the selection of those that would be the most wear resistant.

Membranes

Approximate expressions for the free vibration of a membrane have been developed. The theory of free vibrations of shallow membranes has been applied to large spans that are supported by cable trusses. A recent review of the world's literature concerning the vibration of membranes (138) reveals that designers of membranes are beginning to consider anisotropy and nonhomgeneity of the membrane. The reviewer also feels that the finite element technique will be important in the future design of membranes. However, more studies of nonlinear membranes, particularly with noncircular geometry, need to be performed. In addition more experimental work is needed to check theoretical results and to provide guidance for future studies.

Plates and Shells

A great deal of work in Australia is directed at the analysis of plates and shells. In some cases the analyses were aimed at a specific problem such as response to sonic boom. A simplified approach was developed for analyzing the response of flat plates to a far field sonic boom by using the concept of iso-amplitude contour lines on the surface of the plate. Plates having clamped or simply-supported boundary conditions were analyzed, with the results to be used to predict the response of window panes and wall panels to sonic booms (139).

A simplified approach to the analysis of large amplitude vibrations of plates, using constant deflection contour lines was developed (140). The method could also be extended to the large amplitude vibration of membranes.

The vibrations of triangular viscoelastic plates were also studied using the concept of constant deflection or iso-amplitude contour lines (141).

An experimental determination of the dynamic characteristics of plates was made using pseudo-random excitation and cross correlation analysis. This statistical technique allows the dynamic characteristics of plates to be determined in spite of the presence of background noise (142).

The method of iso-amplitude contour lines was extended to the analysis of vibration of shells. The method was applied to the transient vibration of an elliptical dome (143), and it might be useful for the dynamic analysis of end closures on pressure vessels.

An analysis of the steady-state response of an elastic cylindrical shell to a constant velocity ring load was performed (144). This type of analysis might be applicable to cylindrical shells that are engulfed in blast waves.

UNITED KINGDOM

Mechanical

Blades

Gas turbine blade vibration phenomena are complex. A series of investigations of blade vibrations have been undertaken to understand blade characteristics and predict their response to the operating environment. The studies used simplified but closely representative models of complete bladed disc assemblies (145).

Two studies have been performed in Great Britain on predicting the natural frequencies of shrouded bladed discs. The first study discussed means of extending mathematical models of complex shaped components for predicting the natural frequencies of a complete blade-disc-shroud assembly (146). A finite element analysis was performed on a blade-disc-shroud-assembly to determine the influence of weight ratios, flexural rigidity ratios and length ratios between blades and shrouds on the assembly natural frequencies (147).

Two studies of the vibration modes of mistuned blades and discs have been carried out in Great Britain to remove some of the uncertainties concerning the phenomenon (148, 149). Several studies have been carried out on the optimal design of turbine blades (150, 151). In addition, a review of the literature pertaining to the optimal control design of turbine blades was prepared in Great Britain (152).

In addition to mechanical excitation of blade-disc assemblies, aerodynamic excitation produces either maloperation or dangerous stress conditions. One study was undertaken to understand the phenomenon of supersonic flutter in blades of turbojet engines (153). Another investigation was carried out to assess the contributions of potential flow interaction and wake interaction to the total sound pressure level generated adjacent to the interacting blade rows (154). An analysis of the unsteady lift on a cascade of airfoils moving through circumferential inlet flow distortion was undertaken to develop the applicable prediction techniques (155).

The containment of blades failures within a jet engine is also a problem in Great Britain. Scale model firing tests were conducted to determine the failure mechanism at the point of impact of the containment structure. A theoretical analysis was also developed and good agreement was obtained between tests and theory (156).

Bearings

Interest in bearings in Great Britain can either be related to the determination of their condition or to their dynamic behavior. Only the latter topic will be treated here. The evaluation of bearing condition was discussed under Diagnostics.

Stability of operation is an important consideration in the design of bearings, and several studies were performed that address this topic. One study deals with the stability limits and the stabilizing capacity of bearings for flexible rotors that are subject to hysteretic forces (157). A method for predicting the pressure distribution in an air film of a porous thrust bearing was the subject of another study. The stable operating region of this type of bearing depends on the pressure distribution (158). Another study was performed to determine whether the interaction between surface roughness and the hydrodynamics of a bearing had any significant effect on the stability of the bearing (159).

Other studies of the dynamics of bearings have been undertaken to determine the movement of a shaft center in a roller bearing (160) and to determine the dynamic behavior of passively-compensated hydrostatic journal bearings with various numbers of recesses (161).

Ducts

For efforts relating to noise in ducts are numerous in Great Britain. Studies can be divided into two categories, sound propagation or generation and sound attenuation.

A study of the propagation of waves in elliptic ducts was undertaken to determine the effects of various eccentricities on the cutoff frequencies for the higher order circumferential modes. The specific application is in the use of elliptic ducts to reduce jet engine compressor noise (162). This technique might have application in the U.S.

Two studies of sound propagation in curved duct bends were performed in Great Britain. One study addressed the problem of higher mode sound propagation in rectangular cross section ducts (163); the other study considered the transmission of sound in both rectangular and circular section bends (164).

Sound transmission studies in straight duct sections have also been undertaken. In one case, the study addressed sound transmission in ducts with axial temperature gradients (165). In the other case, the problem of sound transmission through a double partition was studied (166). An experimental study was undertaken to understand the mechanism of self-induced sound generation due to flow past perforated liners in ducts. The liners consisted of honeycomb structures that were sandwiched between two flat perforated aluminum skins (167).

Predictions and measurements of the sound attenuation in ducts lined with porous sound materials and perforated facings were made. The study was conducted to obtain data for the design of flow-splitter type silencers (168). Studies of the attenuation of sound in rectangular ducts which were lined with a sound absorbing material on all four walls were also performed (169).

A method for estimating the normal incidence absorption coefficients and acoustic impedances of both fibrous materials (170) and single-layer perforated sheet liners (171) for gas turbine propulsion ducts has been developed. In addition, a paper by Lawson (172) discusses the design of duct liners and the tradeoffs that are required in a practical aircraft design.

Pipes and Tubes

Many studies of noise and vibration of pipes and tubes have been carried out in Great Britain and this is a subject of continuing interest. With the exception of the development of methods for optimizing the design of complex piping systems for turbomachinery or process plants, most of the studies were concerned with flow-induced noise and vibration in pipes. A group of studies concern the acoustic excitation of pipes and tubes in heat exchangers (173).

Three studies on the noise in pipes were performed. The noise radiated from fully-developed turbulent flows exhausting from straight pipes and bent pipes were measured (174). An experimental investigation of the sound attenuation in fully developed turbulent flow was undertaken (175). Transmission loss measurements of low frequency sound through pipe walls were made (176).

Studies of external flow-induced vibrations of pipes and tubes were conducted. One study concerned the effect of grid turbulence in the free stream flow on the vibration response of tubes in one-row and two-row arrays (177). A study was performed of the effects on the vibration of tube pitch-to-diameter ratios, depth of tube bank, and Reynolds number (178). Studies of the vibration of pipes conveying fluid were also undertaken. The linear stability of a system composed of a thin elastic tube, replacing a rigid pipe, conveying an inviscid compressible fluid was studied (179). An experimental investigation of the flow in an axially-moving pipe was undertaken to measure the flow velocities of pulsating water flow (180).

<u>Structural</u>

Beams, Strings, Rods and Bars

Many studies of the vibrations of beams have been performed in Great Britain. The following discussion will be limited to those that are applications-oriented.

Many structures are composed of periodically supported beams. An approximate method was developed to predict their average response by using the proper choice of an assumed mode of vibration that satisfies the boundary conditions on one periodic beam element (181).

Mobility data can be used to predict the vibration properties of coupled structures, and it is necessary to consider all significant directions of vibration at each coupling point. Both translational and rotational mobilities are required when beam-like structures are analyzed. An experimental technique for deriving rotational mobilities from measurements of the translational mobilities was developed (182). This technique might be explored for measuring the angular rotation of transversely-deflected beams.

Many structures, such as ship's hulls, exhibit coupled bending and twisting and, in some cases, the structure can be modeled as a non-uniform beam. A study was undertaken to develop an analysis technique to obtain the principle modes of a non-uniform beam that executes coupled bending and vibration (183). The vibration characteristics of a combined column-beam-mass system were studied. The system was used as a simplified model of a cockpit motion machine (184). Finite element techniques are being used for the study of stress distribution, stiffness and vibration characteristics of perforated beams. Perforations of various shapes and sizes have been considered and their influence on the behavior of the beam is being examined (185).

Many structures can be modeled as box beams. A method has been developed for predicting the mode shapes and the natural frequencies of box beams which were modeled as assemblages of thin plates (186). Many complicated structures such as chimneys or tower buildings can be modeled as an equivalent cantilever beam of limited stiffness. Techniques for determining the dynamic characteristics of these structures were developed (187).

Vibro-acoustic studies of beams were performed. One study concerned the sound radiated by a cylindrical beam in multimodal transverse vibration (188). The other study concerned the velocity response of a single circular beam to pure tone sound in a reverberation chamber. The variation of the response with position within the chamber and the effect of the proximity of other parallel beams was considered. One application of this analysis is the prediction of the fatigue life of heat exchanger tubes in nuclear reactors (189).

Cables

Cable dynamics is studied extensively in Great Britain. One area of interest lies in the control of aerodynamic instability of stranded cables, and a study was performed which showed this instability. The introduction of a viscoelastic material in the void between the cable strands increased the damping of the cable. It also reduced the effects of aerodynamic instability. Other control techniques that were studied included a combination of an auxiliary mass vibration damper and impact damper, and spacer dampers. An investigation of the behavior of a variety of cable booms was conducted to determine the influence of mechanical and thermal excitation and their suitability as supports for equipment sensors on the GEOS satellite (190).

Oscillation of overhead power transmission lines is an important research problem. One study concerns the growth of wind-induced oscillations in overhead power transmission lines (191). The wake-induced oscillations of the leeward conductor in twin bundled overhead transmission lines was also investigated (192). Two studies of the dynamics of overhead current collection lines were performed. In the first study, a wave solution was derived for the dynamic response of the overhead simple catenary system to a directly-applied time-dependent travelling concentrated load (193). A computational procedure for predicting the dynamic behavior of the wire-catenary system was derived in the second study (194). Both of the foregoing problems would be useful in dynamics studies in support of high speed electrified rail systems in this country. One possible area for further investigation might be the effects of the vehicle dynamics of the pantograph catenary sub-system.

Cylinders

Studies on the vibration of cylinders relate to their response to fluid-induced or air-induced excitations.

Three studies on fluid-induced excitation of cylindrical structures were performed. One study was concerned with wave forces in flexible cylinders and the ability of eddy shedding to excite flexible cylinders into motion (195). A second study concerned vortex-excited structural oscillations of a circular cylinder in flowing water. This study was used to derive design criteria for a hydroelastic model of a marine pile (196). The wake interaction between two flexible vertical circular cylinders in flowing water was investigated experimentally to determine their structural stability under vortex shedding excitation (197).

An experimental investigation of base pressure coefficients of circular cylinders oscillating transversely in a stream was undertaken to determine the variation in the drag coefficient (198). An investigation is being made into various structural methods of controlling wind-induced vibration of unsupported steel chimneys.

Plates and Shells

There is a strong interest in the vibration of plates and shells in Great Britain and many fine studies have been and are being conducted. Only those studies that pertain to specific applications will be discussed.

Plates are used in a wide variety of structures that could be subjected to explosive loadings. A technique was developed to predict the stress propagation through plates and the damage to plates due to the detonation of surface rings of explosives (199).

SPAN is a computer code that was developed by the Naval Construction Research Establishment in Dunfermline, Scotland for the static and dynamic analysis of flat plates and grillages. This code has a wide range of calculation capabilities (200).

A study of the flexural vibrations of line stiffener plates subjected to fluid load was undertaken. The techniques that might be used to solve the problem of wave propagation in these plates were examined in this study (201). The techniques in this study might be applied to the analysis of plate-like structures of ships and submarines of the U.S. Fleet.

Many stiffened-plate structures can be analyzed as periodic structures. Periodic structure theory and the theory of dampered force normal modes were combined to develop a technique for determining the loss factor and the resonance frequencies of damped periodic sandwich plates (202). This analysis technique might be considered for cases where integrally damped and stiffened plate sections are required to reduce the effects of noise and vibration in the design of aircraft or helicopter structures. In fact this technique might be used in the initial design stage.

Data have been prepared in graphical form for calculating the natural frequencies of isotropic rectangular plates in the 3,1 and the 1,3 modes. Free, simply supported, and damped edge conditions were treated (203).

A technique was developed for determining the variation of the resonant frequencies of plates with temperature. The technique is suitable for use with the finite element method and it applies to either loaded or unloaded plates (204).

Plate theory was used to design glass-reinforced sandwich radome panels for an antenna system on the top of the CN tower in Toronto, Ontario. The panels were designed to withstand static or dynamic loads and thermal stresses without undergoing large deflections or buckling (205).

A survey of the literature on the acoustic excitation of sandwich structures and a shallow shells was prepared. It covers modal densities of shallow shells and the use of the statistical energy analysis technique for structural analysis (206). A comprehensive study of the response of thin-walled cylinders to aerodynamic excitation was prepared in Great Britain (207, 208). It includes ground wind distributions for loading on full-scale structures, wind pressure forces on rigid cylinders and flexible shells, statistical methods available for response analyses, and a review of techniques for the analyses of thin shells. Some of the material that is contained in this study might be useful in the aerodynamic response analysis of structures that can be modeled as thin shells, such as chimneys, and some tanks.

Two studies on the buckling of cylindrical shells were conducted. One study considered the buckling of cylindrical shells subjected to non-uniform pressure loading (209). It is applicable to the analysis of many cylindrical structures that are subjected to wind or flowing water excitation. The other study considered the buckling of cylindrical shells due to non-uniform wind pressure. As a result of this study current British and American codes for the stability design of oil tanks were examined and their deficiencies were pointed out (210).

The response of a distorted cylindrical shell to acoustic excitation, below the acoustic cut-off frequency was studied. The results were used to predict the vibration response of a tube with small circumferential variations of wall thickness, radius and modulus of elasticity (211). The results of this study would be useful in the analysis of tubes in nuclear reactor heat exchangers.

The use of vibration absorbers for reducing the vibration of cylindrical shells due to a single radial harmonic force and a harmonic pressure distributed over the shell surface was studied (212). The free vibrations of cylindrical shells with various types of closures at one end were investigated (213). The results of this study could be applied to the analysis of pressure vessels and tanks.

CANADA

Mechanical

Absorbers and Isolators

Impact dampers have been developed in Canada. Impact dampers are containers confining masses that are free to roll and impact the ends of the containers. A parametric study was undertaken to determine, among other things, the effects of Coulomb friction on the performance of impact dampers with shorter than critical length containers (214).

A vibration absorber is another device to control vibration. A vibration absorber was developed to minimize transient vibrations of uniform thin plates following their release from an arbitrarily-deflected shape (215). Modal control techniques have been applied to the design of dynamic absorbers to control transient vibrations of thin beams (216).

Gears

A survey of dynamic effects on gears was prepared covering the dynamic effects on the gears themselves (tooth loads, wear and failure), as well as on the rest of the system (217). Another study concerns epicyclic gear vibrations to determine the natural frequencies of in-plane vibration of a single planetary gear stage.

The dynamic stability of a two-stage gear train was investigated to determine the effect of a variable meshing stiffness. A simple technique was developed to determine whether an operating gear train is in a stable or an unstable region of meshing (218).

Linkages

The PLANET II computer code was developed as a self formulating code that is used to simulate the dynamic response of mechanisms with clearances. The code is based on the vector network method which can generate the dynamic response of the mechanism from the mechanism description (219). This code might be used in the United States to analyze the dynamic response of linkages that are widely used on various machines in the textile industry. Textile machines have a wide variety of linkages, many of which are complex, and their operation is a major noise source in textile machines. Determining the dynamic response of the linkages is the first step towards noise reduction.

Pipes and Tubes

Canada has active research programs on the vibrations of pipes and tubes. Of particular interest are investigations of the stability of pipes conveying fluid. One study concerns the stability of pipes with either a constant flow velocity or a constant flow velocity with a small superposed harmonic content (220). In another study, the dynamics of beamlike motions of pipes with both ends clamped was investigated. Both beam theory and thin walled shell theory were used (221).

Numerical and experimental studies of the parametric resonances in pipes conveying a pulsating fluid flow were performed (222, 223). Studies of the stability of thin-walled tubes conveying fluid were performed to examine the effects of flattening. In this study, two simplified models were developed which represent a flattened tube as two parallel flat plates (224). The dynamics of pipes containing fluids was also described by means of Timoshenko beam theory. The results of this study were compared against the results obtained using Euler-Bernoulli beam theory (225).

A finite element analysis of the motions and baffle contact forces of a single heat exchanger tube was undertaken (226). Current work in this effort involves the effect of a squeeze-film in the clearance space between the tube and its support. The VIBIC code will be used to predict tube motions of and contact force in multi-span heat exchanger tubes. This will provide data for assessing the tube wear potential of shell and tube heat exchanger designs. Both in-plane and the coupled twist bending out-of-plane vibrations of an intermediately-supported U-Bend tube were investigated (227).

A method of direct frequency response conversion to transient response was applied to terminated pneumatic transmission lines (228). Other studies were on the seismic response of buried pipelines and methods of eliminating flow-induced vibrations of a hydraulic valve.

Structural

Beams

Many structures are modeled as beams with various boundary and support conditions. Investigations are continuing in Canada on the response of beam-type structures to underwater shock loading or air blast (229). The results of these studies are used to develop criteria and procedures for predicting the response of shipboard antennae to shock loads.

A comprehensive study of the vibration of beams with equally-spaced supports was performed and all possible end conditions were considered (230). In addition to the application to the design and development of boilers, as suggested by the author, the results might be useful in the analysis of guideways for futuristic air cushion vehicles, as well as in determining the response of any multiple-supported structure. A technique was also developed for analyzing the interaction between a flexible vehicle subjected to random input and a flexible guideway. This vehicle-guideway interaction must be considered in the design or analysis of any guideway transportation system. Methods for evaluating the probabilistic dynamic response of reinforced concrete beams are also of interest.

Rods

Judging by the numbers of studies in the published literature, there is a great deal of interest in the vibration of rods. One class of studies concerns curved rods. Investigations of wave propagation in curved rods were performed. In one case the rods were slightly curved and elementary theory was used (231). In the second study, uniform and nonuniform rods were considered (232). A third study considered the oscillations of naturally curved and pretwisted rods. Other studies include the dynamics of parametrically-excited rods that are used in mechanisms and boring bars (233) and the stability of rods that are subjected to nonconservative tangential follower forces (234).

Cables

One study on the dynamics of cables and strings involved the dynamics of a drifting buoy cable array. A perturbation analysis was used to obtain the frequencies of the lateral and longitudinal motion. The array is used to detect the presence of submarines (235). The small oscillations of a stiffened string has also been investigated.

Bars

Bar-type elements are used in many types of structures. Studies of the dynamics of bars in Canada concern wave propagation in inhomogeneous variable section viscoelastic bars (236) and an experimental study of the response of long aluminum bars to short duration impact (237).

Cylinders

Cylindrical sections, including discs and rings, are found in many types of structures and in machinery. A review article of the published literature on the vibration of cylinders was prepared in Canada by Gladwell (238). This survey reviewed the methods that are used to formulate the problems relating to the vibration of cylinders and the methods for predicting their response. In a separate but somewhat related work, the same author prepared a set of tables for the natural frequencies of the first five symmetric and anti-symmetric modes of hollow or solid circular cylinders (239).

Four commonly used finite element shell models were compared to determine their accuracy in predicting the natural frequencies and mode shapes of infinite and free-free finite length solid and hollow circular cylinders (240).

A study was performed to determine the stability of a leaward cylinder in the wake of a fixed windward cylinder (241). Examples of possible applications include power transmission cables or tubes in heat exchangers vibrating in the wake of one another. Another study on the stability of cylinders concerns the dynamic behavior of flexible cylinders in pulsed axial flow (242).

Rings

A recent development in the dynamic analysis of rings is described in a study of in-plane vibration of a thick circular ring, in which the effects of transverse shear and rotary inertia were considered (243).

Discs

The finite element method has been applied to the dynamic analysis and stress analysis of thin rotating discs. Annular finite elements were derived to describe the bending and stretching of the discs (244).

Panels

Acoustic effects on panels is of interest in Canada. One study was performed to determine the feasibility of an optimal acoustics design process for sandwich panels (245). Another study of importance concerns the response of a nearly-pure gypsum panel to sonic booms. The ultimate purpose of this effort was to determine the lifetime of plastic panels that are subjected to sonic booms (246).

Plates

A major emphasis has been placed on research relating to the vibration of plates and shells in Canada. The studies can be divided into three groups: applications, approximate techniques and general solution techniques.

Under the applications group, an experimental study was undertaken to determine the deformation of flat slab floors at their connections with columns, when they were subjected to static or dynamic horizontal forces (247). A second study concerned the vibration of two types of integrally rib-stiffened plates. The finite element method was used to predict their mode shapes and natural frequencies and real-time laser holography was used for experimental verification. The results of this study should be useful in connection with the vibration of floors or cargo decks of aircraft (248). A third applications-oriented study concerned the vibration of two-span rectangular plates resting on linear and torsional springs (249). This study might be useful in the analysis of isolated platforms for mounting sensitive equipment.

Examples of studies discussing approximate analytical techniques include an investigation of the use of the calculus of finite differences to obtain the natural frequencies of the finite strip model of a simply-supported rectangular plate (250), and a study of the inadequacy of beam vibration mode shapes when used with the Ritz method for obtaining the bending modes of plates (251).

Many techniques have been developed for solving plate vibration problems. These include free vibrations of cantilever plates by the method of superposition (252), vibration of rectangular plates with two opposite edges simply-supported (253), stability of elastic plates by Lyapunov's Second Method (254), elastic waves in plates (255), small strain nonlinear dynamics of plates (256), and large amplitude flexural vibrations of rectangular plates (257).

Shells

Ongoing studies on shells can also be divided into an applications-oriented group or into an analytical techniques group. Some examples of applications-oriented studies are as follows. The flexural-rotational coupled motion of three flexible cylinders, cantilevered to a central head, was investigated. Two types of in-plane motion were considered, one corresponding to the vibration of the cylinders without rotation of the central body. The other type involved the coupled motion of the entire array (258). The results might be applicable to sensors in the ocean that are excited by hydroelastic forces. The effects of internal and external turbulent flow on the vibrations of anisotropic cylindrical shells were investigated (259). This study would be applicable to flow-induced excitation of tubes in heat exchangers.

The dynamics of neutrally-buoyant inflated viscoelastic cantilevers used in a submarine detector system was investigated. Thin shell theory was used to account for the stresses arising from the internal pressure. The reduced shell equation was used (260).

Some example of investigations of analytical techniques follow. Two triangular mixed finite elements were used for both a linear and a nonlinear dynamic analysis of thin shallow shells (261). Techniques were developed to determine the transient torsional mode response of variable thickness shells (262). Other studies include wave propagation in elastic shells, free vibrations of isotropic layered spheres and vibrations of deep spherical sandwich shells.

FRANCE

Mechanical

Blades

Research is active in France on the design of better compressor blades for steam turbines and jet engines. R. Bignet (263) has developed experimental methods for the study of the vibratory behavior of steam turbine blades. P. Trompette, et. al. (264) have developed methods for the prediction of modal damping of jet engine stator vanes using finite element techniques. The use of the technique was demonstrated by analyzing the high-temperature enamel coating damping treatment of a jet engine vane. The advantage of this particular finite-element approach is that it is a low cost method for predicting the effects of many types of damping treatments on the dynamics of the structure. The same French group has also studied mode shapes and frequencies in jet engines for use in improving the design (265).

Bearings

M. N. Abdul-Wahed, et. al. (266) have studied fitted partial arc bearings and tilting-pad bearings. Their studies indicate that the static and dynamic performance of fitted tilting-pad bearings has advantages over the non-preloaded clearance-type tilting-pad bearings. The dynamics of a ball bearing with a fixed or moving internal ring has been investigated theoretically by Mommessin (267). The method was applied to miniature high-speed bearings; all frequencies of vibration from 0 to 2000 Hz were identified.

Pipes

D. Hure and M. Morysse (268) have made a comparison of two methods for the analysis of piping systems subjected to seismic motion. The response of a particular piping system was evaluated by the two methods. Of the methods evaluated, the modal approach appears to be cheaper, faster and more reliable.

INDIA

Mechanical

Blades

J. S. Rao (269) has published a review of the literature on blade excitation forces, vibration of blades with large aspect ratio, disk-blade interaction, vibration of blades with small aspect ratio and experimental methods.

Bearings

Many excellent studies of journal bearings have been made in India. Several studies of gas lubricated porous journal and thrust bearings have been made (270, 271, 272, 273). G. R. Kulkarni (274) has developed design charts for the analysis of dynamically-loaded journal bearings. These charts for commonly available bearings are used for determining the journal center cyclic path as a function of the loading cycle.

In a review of self-excited vibrations in oil film journal bearings, Jain and Srinivasan (275) have concluded that damping must be included to yield an accurate prediction of stability conditions. In one of the rare experimental reports from India on bearings, the force coefficients (spring and damping coefficients) of partial journal bearings were measured on a sophisticated test rig (276). Useful design data are given along with a theoretical comparison.

The effect of the non-Newtonian behavior of lubricants, resulting from the addition of polymers, on the performance of hydrodynamic journal bearings has been investigated (277, 278).

Disks

Mindlin's improved dynamic theory of plates which includes transverse shear and rotary inertia has been applied to the analysis of circular disks (279, 280). N. C. Ghosh (281) has studied the thermal effect on the transverse vibration of spinning disks. The results might be applied to the analysis of saw blades.

Linkages

A graphical method for the synthesis of function-generator linkages satisfying pre-selected precision conditions has been developed (282).

Gears

Modal analysis was used in a study of the dynamic loading of gear teeth (283).

Springs

A simple graphical method for the design of helical springs has been developed (284). With this method a maximum work helical spring with minimum volume of material can be designed.

Structural

Beams

A number of studies on beams, the most commonly encountered structural element, have been aimed at including the effects of shear deformation and rotary inertia. A review of the available literature on beams, with emphasis on the post 1973 era, has been published by Wagner and Ramamurti (285). Laminated beams have also been studied recently (286, 287).

Strings

K. K. Deb (288) has analyzed the dynamics of the impact of a hammer on a string. Expressions are found for the displacement of the struck point, the force of the string on the hammer during contact and the energy loss of the hammer. These results might possibly be of use in today's instrumental hammer techniques for modal analysis.

Arches

The response of fixed arches under seismic forces has been studied for a wide range of structural designs (289).

Panels

The flutter of panels has been studied using the finite element method (290) and by an analog computer (291). The non-linear response of sandwich panels during buckling (292) and under shock pulse excitation (293) has been studied.

Membranes

Approximate methods for determining the vibration modes of membranes have been reviewed by Sasadhar De (294).

Plates and Shells

India has produced a great number of studies on plates in recent years. Although it isn't appropriate, in this report, to list the extensive literature available some general comments will be made.

Arthur W. Leissa (295) published a book "Vibration of Plates," in 1969 which summarized all of the information available at that time. Leissa's chapters were written in order of increasing complexity. The first eight were based on classical plate theory and covered the basic shapes. The next three introduced the complications of anisotropy, in-plane forces and variable thickness. It is notable that in that publication 'large deflections' and the 'effects of shear deformation and rotary inertia' were listed under other considerations. Today the situation is quite different as represented by the work being done in India.

Solutions are still being worked out for different shapes of isotropic plates, circles, rectangles, skew shapes, etc. The emphasis today, however, has shifted to other areas as follows. Recent advances in composites has generated many studies of orthotropic plates (296, 297, 298). Other studies have focused on including the effects of shear deformation and rotary inertia (299, 300, 301). Large amplitude vibrations are being actively studied today (302). The main efforts today are aimed at applying the finite element method to plate problems (303, 304, 305) and applying new solution techniques such as Galerkin's method (306), Wegstein's iteration technique (307), Berger's approximation (308), finite difference methods (309) and Bolotin's asymptotic method (310). Increased capabilities in general purpose computer programs will allow for the easier solution of non-linear problems such as large-amplitude plate vibration or the vibration of orthotropic plates such as laminated cross-ply composites.

There are far fewer studies done on shells than on plates. Shell problems are tougher, there are fewer accurate, reliable solution techniques available and buckling is always a complicating factor. A few studies on shells in India have been made on orthotropic shells (311, 312) such as layered composites.

Different solution methods are being applied such as the finite element method (313) and finite difference methods (314). Some integral equation techniques are being used (315). In a study of large amplitude vibrations of shells, Raju and Rao (316) used Sander's nonlinear strain displacement relations to derive the element stiffness matrix in a finite element solution.

Rings

R. K. Mittal (317) has studied the response of a thin elastic ring to a concentrated load. Results are given for a half-sine input.

ISRAEL

Mechanical

Gears

Sandler (318) has developed methods for analysis of gear train mechanisms taking into account gearing backlash, errors of teeth pitch and the eccentricity of each wheel.

Structural

Beams

Methods for the measurement (319) and analysis (320) of the plastic deformation of beams under impact loading have been developed.

Bars

In the early 1960's, Bolotin put forth an asymptotic method for the analysis of the vibration of elastic bodies occupying a rectangular region; bars and plates are among the components which can be handled by this method. Bolotin's method gained widespread application in the Soviet Union and is now attracting growing attention in the West. I. Elishakoff (321) has attempted to systematize Bolotin's work with that of others in a recent publication.

Plates and Shells

A limited amount of work has been done in Israel on plates. Modern studies are on orthotropic plates (322) or on vibrations of plates with large deformations (323).

The Technion-Israel Institute of Technology has made extensive investigations of stiffened cylindrical shells. Part of their investigations emphasize the effect of imperfections (324). Other papers have emphasized loading conditions (325, 326) and restraint conditions (327, 328). Several applications of the Karmen-Donnell non-linear shell equations have been made to the solution of stiffened shell problems (329, 330). In two cases the Karman-Donnell equations were solved using the Galerkin method (331, 332).

ITALY AND GREECE

Structural

Strings

A test facility was developed in Italy to study the effects of a torsional vibration resonance on flat cables, ribbon cables and square cables that are used on spacecraft. The tests were conducted using a combination of solar heating and altitude environments, in addition to the torsional vibration (333).

Beams

Dynamic analyses of cantilever beams are of continuing interest in both countries. A study that was performed in Greece concerned the frequencies of free vibration of a cantilever beam-column carrying concentrated masses with rotational and translational springs at its support. The study involves the effect of the rotary inertia of the attached masses on the frequencies of vibration (334). A study in Italy was concerned with the elastic stability of a cantilever beam on an elastic foundation subjected to a follower force (335).

Kounadis and Katsikadelis (336) have investigated the effects of shear deformation and rotary inertia on the flutter characteristics of Becks column.

Cylinders

Aeroelastically-induced vibration of bodies seems to be of concern. Research into vortex shedding vibration of two cylinders is being performed to study effects of one cylinder vibrating in the wake of another (337). The effects of the two cylinders vibrating at the same or at different frequencies was studied. An analytical model of the phenomenon was developed and the predicted results were compared with the experimental results (338). This work has implications for aeroelastic or flow-induced vibration problems where multiple bodies are involved. Particular examples might include heat exchangers or nuclear reactor cooling systems where adjacent tubes might vibrate in the wake of one another, but at different frequencies.

Plates

The vibration of an infinite plate with a frequency independent magnification factor was studied in Italy. The energy dissipation mechanism in the plate was independent of the frequency and inversely proportional to the magnification factor (339).

JAPAN

Mechanical

Absorbers and Isolators

Tsuzuki, et. al. (340) have developed design criteria for shock isolators in bumper systems. Different silicone rubbers were used and the results applied to the design of shock isolator systems of 1974 vehicles.

Blades

Blade analysis activity in Japan has concentrated on noise generation and flutter. Flutter analysis has been performed on blades moving through gusts (341) and blades in stalled cascade (342). Nagamatsu, et. al. (343) have analyzed the vibration of blades using the finite element method and compared the results with experiment. The eigenvalue problem was solved using the subspace iteration method.

Bearings

Recent bearing research in Japan has concentrated on using finite element methods (344) and designing vibration free machine tools (345). Other researchers have developed methods for designing air-lubricated slider bearings for non-contact magnetic recording (346).

Gears

Fukuma, et. al. of Kyoto University have been making fundamental studies of the noise and vibration generation mechanisms in gears. In their 7th report (347), they discuss the generation mechanisms of radial and axial vibration of spur gears. In a corresponding experimental investigation the authors discovered that the axial vibration of a gear body as an elastic disk (which was not considered in the theory) can be large under some conditions. Other research on gear teeth has been concerned with their fatigue properties under random loads (348, 349).

Tobe, et. al. (350) studied dynamic levels on spur gear teeth using with analog computer methods, which appear to be very popular in Japan.

Linkages

Shimizu and Sueoka (351) have developed experimental techniques for measuring the non-linear forced vibrations of roller chains.

Pipes and Valves

Recent work on pipes in Japan by Udoguchi, et. al. (352) has included research on the response of pressurized pipes to earthquakes. Their proposal of allowable stresses under earthquake loading was obtained by modifying those of the Faulted Condition of the ASME Code. The experiments performed proved the adequacy of their proposal. Other researchers have developed methods for the control of the seismic response of piping supported by mechanical snubbers (353). The reason for developing mechanical snubbers was for nuclear reactor applications where oil snubbers cannot be used because of the degeneration of oil under hign radioactivity. The vibration characteristics of the newly-designed mechanical snubbers (MS) are described in the paper by Honma, et al (353).

E. Kojima, et al have developed analytical methods for the prediction of the transient characteristics of hydraulic piping systems (354, 355, 356). The system studied theoretically by Kojima consists of an hydraulic actuator, fluid pipe and operation valve. Of special interest is the pressure surge in a pipe due to sudden valve closure.

Springs

Michio Kato (357) of the NHK Spring Co., Ltd has made experimental and theoretical studies of varying pitch helical compression springs. A varying pitch (v.p.) spring, which has a non-linear response, acts to prevent surge during rapid load changes such as would be experienced by the valve spring of an internal combustion engine. It is also determined that the dynamic stress in a varying-pitch spring is lower than in an equal-pitch spring; the explanation offered is that the dynamic energy is dispersed during the repeated contact and separation of the adjacent coils. Kato has also studied the dynamic buckling of helical compression springs and the large amplitude vibration of a cantilever beam.

Structural

Beams and Bars

Modeling of beams in Japan has centered on several areas: 1 - the response of beams to impact and blast type loads (358, 359), 2 - plastic deformation (360), and 3 - inclusion of shear deformation and rotary inertia effects (361). Saito, et. al. (362) have modeled the forced non-linear vibration of a beam with a concentrated mass at the center. They reduced the equation of motion to a Duffing type which was solved by applying Galerkins method.

Shimogo, et. al. (363) have modeled the coupled vibration of two elastic circular bars in a viscous fluid. They use linearized Navier-Stokes equations under the assumption of small amplitudes.

Frames

Inoue and Ogawa (364) have developed methods for the non-linear analysis of the strain hardening of frames subjected to repeated loading. They used the plastic hinge method proposed by others and extended it to include the effects of strain hardening and the Bauschinger effect. Numerical results agree satisfactorialy with experimental results.

Membranes

Kosuke Nagaya has developed analytical methods for the analysis of the vibration and response of membranes, especially those with included holes (365, 366, 367). K. Sato has developed methods for the analysis of composite membranes (368).

Plates and Shells

T. Sakata of the Chubu Inst. of Technology has developed many analytical methods for the analysis of orthotropic plates (369, 370) and plates with nonuniform thickness (371, 372).

Another prolific author in Japan is Kosuke Nagaya of Yamagat University. Professor Nagaya has developed analytical methods for the analysis of viscoelastic plates (373) using a three-element viscoelastic model. He also had developed analysis methods for handling plates with holes and other configurations (374). Hiramo and Okazaki (375) studied vibration of a circular partly clamped/partly simply-supported plate.

Many authors in Japan analyze the transient motion of plates using Laplace transforms. A typical such analysis is by T. Shibuya (376) in which a problem on the torsional impact of a thick plate is solved using Laplace and Hankel transforms.

Much of the current work in Japan on shells involves pressurized shells, buckling and dynamic stability. Similar to the work in India on shells are the analytical methods developed by Tani (377) on the dynamic stability of shells. Tani uses Donnell-type equations, Bolotin's method and finite difference procedures. Yamaki and Nagai (378) have developed similar shell dynamic stability methods using

Donnell type equations and Galerkin procedures for solution. S. I. Suzuki (379) has developed methods for the analysis of thin cylindrical shells subjected to inner impulsive loads also using Donnell-type equations. Suzuki uses Laplace transform methods in the analysis. Kazimura, et. al. (380) have developed improved methods for the seismic analysis of thin cylindrical shells with attached masses. Many axissymmetric shell structures have been constructed which can be better analyzed using these methods.

Rings

K. Sato (381) has developed methods for the analysis of elliptic rings.

NETHERLANDS

Mechanical

Bearings

Journal bearings have been analyzed using mobility methods (382), and impedance descriptions (383) have been offered for rotor-dynamic applications. Studies have been made on the feasibility of using magnetic oil (ferrofluid) as a substitute for grease in hydrodynamic bearings for satellite momentum wheel applications (384).

Shafts

The effects of the flexibility of a driving shaft on the dynamic behavior of a cam mechanism has been studied (385).

SWEDEN, NORWAY AND DENMARK

Mechanical

Bearings

J. W. Lund (386) of the technical University of Denmark, Lyngby, has written an article reviewing unstable whirl phenomena in rotating machinery. Most rotors have a synchronous whirl frequency because of unavoidable mass unbalance forces. However, under certain conditions the traversed shaft orbit begins to grow, accompanied by a change in whirl frequency, to a nonsynchronous value. This instability is an unstable oil whirl. Lund discusses some of the most commonly recognized sources of instability and, in particular, how to calculate the amount of damping required to stabilize the system. Other work on bearings has been performed by members of Tech. Univ. of Lyngby, Denmark. Christensen, Tonnesen, and Lund (387) have developed an experimental technique for measuring rotor unbalance whirl using membrane transducers to measure the dynamic oil-film pressures. The data obtained with the pressure transducers is then used to balance the rotor. The accuracy of this method compares favorably with methods using shaft displacement probes. Tonnesen (388) has developed a technique for obtaining the damping coefficients of a squeeze-film bearing using impedance measurements.

Prakash and Sinha (389) of the Technical Univ. of Norway, have developed analytical methods for the analysis of cyclic squeeze-films in micropolar fluid lubricated journal bearings.

SWITZERLAND

Mechanical

Bearings

Fornallaz, et. al. (390) have developed a test rig for the automatic analysis of friction and wear in journal bearings under un-lubricated conditions. The design principles governing the elastic mounting of rotor bearings in open-end spinning machines have been discussed (391). Comparisons of calculations with measurements are also presented.

WEST GERMANY

Mechanical

Blades

Several researchers in West Germany are developing turbine blade diagnostic techniques. Two recent studies show how the torsional frequency of a blade is lowered by a crack (392), and how blade damage may be detected by noise spectrum measurements (393). Staheli (394) has developed a blade vibration measurement technique in which a small magnet is embedded in a blade and a detection coil embedded in the stator.

Bearings

Bearing technology in West Germany is quite advanced. Recent research has concentrated on the effects of lubricant grooves on the stability of friction bearings.

Majumdar (395) has analyzed the dynamic behavior of externally-pressurized gas journal bearings. He has constructed stability charts of whirl for various journal speeds, feed and bearing design parameters. The effects of the lubricant groove on bearing dynamics has been studied both experimentally and theoretically (396, 397, 398, 399). W. Miessen (400) has written a digital computer program for the calculation of the dynamic behavior of a hydrostatic spindle-bearing system. The program can be used to optimize the design of a metal-cutting machine or any machine tool containing critical hydrostatic spindle bearings.

Shafts

In any propulsion system with reciprocating engines, accurate values of the elastic properties of the crankshaft are needed. Gantschev (401) has developed an experimental technique for the determination of the influence coefficients of crankshafts.

Gears

Gear research in West Germany has concentrated on the measurement of stress or wear on gear teeth and the sound radiated from meshing gears. Dr. -Ing H. Winter, and his colleagues at the Institut fur Maschinenelemente der T U Munchen have provided much good experimental and theoretical work on gears. Their work includes measurement of the actual strains in gear teeth (402), testing gear lubricants with their in-house developed rigs (403) and measuring the scuffing load capacity of hypoid and bevel gears (404). Prof. Winter has given a complete description of the Inst. fur Maschinenelemente, Forschungsstelle fur Zahnrader und Getriebebau-FZG in a recent article (405). The article contains references to the 14 dissertations and 60 publications produced by members and associates of FZG since 1968.

H. Gross (406) discusses the implications of the new VDI Standard 2151 concerning the operational factors used in designing gears and couplings. Two studies of the noise radiated by geared systems have been published recently (407, 408).

Linkages

A limited amount of work on linkages is being done in West Germany. Cams (409), slip joints (410), and a six-link slider crank mechanism (411) have been investigated.

Structural

Beams and Bars

As with other countries, work in West Germany on structural components consists mostly of refining the mathematical models of the components. Some recent work on beams includes an approximate solution for the deflection of a beam under a series of moving loads (412) and a perturbation technique for calculating the stability of a beam influenced by frictional forces and torques (413).

Kurze (414) has developed a new method for measuring the loss factor in bar-shaped specimens. The method uses the three extreme values of interfering waves close to the free end of the bar.

Plates and Shells

Krings, et. al. (415) have developed a numerical method for the calculation of the dynamic behavior of impact-loaded plates. It is based on a bar grate model of a plate. Teubner (416) has investigated the water-borne sound radiated from rectangular plates with free edges.

Fischer and Steiner (417) have developed a method for determining the resonant fluid mass in the calculation of the natural frequencies of fluid-filled cylindrical shells. In the method, a uniformly-distributed apparent mass density is defined for the empty shell such that the natural frequencies of the modified shell and those of the hydroelastically coupled shell-fluid system will be identical.

IRAN

Structural

There is some analytical work being done in Iran in shock and vibration, mostly at Pahlavi University, Shiraz. The two papers described here are both concerned with the stability or buckling analysis of structural components.

Columns and Arches

Mostaghel (418) has developed methods for the analysis of the stability of columns subjected to earthquake support motion. Lyapunov's functions are used in the stability analysis. Farshad (419) has investigated the lateral-torsional instability of arches subjected to motion loading. He finds that while static loading analysis may predict stability, the arch may loose its stability through non-rigid modes if the dynamic criterion is utilized.

TURKEY

Structural

Shells

Work on shells in Turkey has centered on the buckling analysis of spherical caps and oscillations of cylindrical shells. Akkas of Middle East Technical University, Ankara has developed analytical methods for buckling (420), bifurcation and snap-through phenomena (421) and transient response (422) of spherical shells. A. Ertepinar, et. al. also of Middle East Tech. Univ. have developed methods for analyzing cylindrical shells using small deformations superimposed on the large deformations of cylinders composed of nearly Hookean material (423, 424, 425).

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Chapter 8

SYSTEMS

INTRODUCTION

In the broadest sense, a system is a regularly interacting or interdependent group of items forming a unified whole. A system has a mission or a function to perform. This report is concerned with dynamics problems that must be solved in order to assure reliable system operation. In particular, the concern is with current systems-related shock, vibration and acoustics problems and the advancements that have been made toward their solutions.

Air, sea, ground and space have been selected as basic systems categories. Humans are considered systems in their own right. There are special systems for the isolation of vibration or the reduction of noise. Certain mechanical equipments have been categorized as machinery systems. Structural systems such as bridges and buildings have their own special problems. Admittedly, there are crossover problems among the various systems, but hopefully the coverage will be reasonably complete.

UNITED STATES

Air Systems

Systems considered in this section include various aircraft, helicopters and missiles. There are many kinds of dynamic problems associated with these types of vehicles. Some of the more difficult areas are treated herein.

Aircraft

Vibration in aircraft affects the design of structures and equipment, as well as protective methods for cargo. The vibration environments in transport aircraft has been of great concern. Such environments have been measured (1) and methods for prediction have been developed (2). The newer, rapid-fire aircraft guns induce severe vibration in structures and nearby subsystems. This problem has been studied extensively (3). There are many types of extremely sensitive equipment aboard modern aircraft. Vibration transmission paths to this equipment must be defined so that design levels can be determined. Typical of work in this area is a study on airborne antenna vibration by Pearson and Thaller (4).

Aircraft noise is a problem to the community, to the passenger and, indeed, as a mechanism for inducing vibration and sonic fatigue. Hubbard (5) reviewed the problem in 1975. Putnam (6) addressed the current state of knowledge about aircraft noise propagation. The U.S. House of Representatives held hearings on aircraft noise abatement technology (7). Hardin (8) made a critical assessment of the state-of-the-art in airframe self-noise. The present understanding and methods for prediction of all component sources, such as panels, airfoils, struts and cavities, was discussed. Raney (9) discussed work that is still required in order to understand the mechanisms of aircraft noise generation and propagation. The potential for reducing noise in the existing business jet fleet was considered by Galloway, et al (10). Noise technology requirements for future aircraft power plants have been examined by Pratt and Whitney engineers (11).

Design considerations for aircraft involve many possible dynamic events. Kroll and Miller (12) examined several aerodynamic methods for application to gust and other type loadings. NASA has reviewed current research in sonic boom minimization (13). There is a major program related to the design of aircraft to maximize crash safety (14). Special design problems arise from potential bird impact (15) and aircraft to be launched by catapult from an aircraft carrier have their own design considerations (16). Two studies typify a broad area of research related to flutter minimization (17) and control (18).

The special class of V/STOL aircraft present unique problems, especially related to noise. The propulsion systems can be defined as combinations of free-air propellers, shrouded propellers, variable pitch fans, tilt rotors, helicopter rotors, lift fans, gearboxes and drive engines. A three part study sponsored by the FAA addressed the noise problem in some detail (19, 20, 21). Helicopters have their own set of problems and are discussed in the next section.

Helicopters

The vibration and noise environments on helicopters are extremely severe. The U.S. Army (22) has surveyed the vibration levels on several of their helicopters to assist in the understanding and control of helicopter vibration and to determine valid qualification requirements for helicopter components. Fatigue load and life determination methods were reviewed by Ryan et al (23). It is important that rotor-induced vibration be prevented from reaching the airframe. Boeing (24) has studied isolation methods for this purpose. Howlett and Clevenson (25) have examined the reduction of interior noise in helicopters. There are special dynamics considerations related to the landing of helicopters on small ships in rough seas, as addressed by Tuttle (26). The use of cargo helicopters involve understanding the dynamics of a slung load (27) and increased crashworthiness is, of course, a major design consideration (28). Doman (29) identifies some technological gaps related to helicopter vibration in his useful research review.

Missiles

A missile in flight has many aerodynamic problems similar to those of aircraft. Special considerations may be related to propellants, as illustrated by an IBM study of the dynamic characteristics of solid rockets (30) and a study by Wohltmann (31) on liquid/positive expulsion bladder dynamics for the air-launched cruise missile. An understanding of missile dynamic response is furthered by techniques such as modal analysis (32) and the ship shock problem is usually of concern for all Navy missiles (33). Joint compliance represents only one of the parameters to be determined for structural design (34). Bolds and Barrett (35) show how models in wind tunnels can be used to determine missile dynamic loads. Aircraft launch-ejection shock environments (36) influence the design of air-launched missiles.

Sea Systems

The principal sea systems are surface ships and submarines, although a brief discussion of off-shore structures is also included in this section. As mentioned under ENVIRONMENTS, shock and blast are among the major combat environments that affect ship survivability. Vibration produced by the ship's machinery is important, both from the standpoint of the effect in the ship's equipment and because of the concern for reduction of noise as related to ship silencing efforts.

Surface Ships

Dynamic considerations for ships extend beyond the areas mentioned above. Collision protection is extremely important as indicated by Jones (37). This is particularly true for tankers (38) which may contain a hazardous cargo. Even without collision problems, the lifetime of cargo tanks for material such as liquid natural gas (39) is of major concern. In rough seas ships are subjected to a phenomenon called bottom impact "slamming". An MIT study (40) illustrates typical research in this area. Special vessels, such as drill ships (41), require special positioning analyses. Motion effects on the ship's crew (42) should be considered in the design stage of a ship. There are dynamic problems associated with mooring (43).

Vibration sources for ships are well understood and methods of calculating force distributions are available (44). Many techniques have been developed to eliminate vibration problems on shipboard equipment, such as steam boilers (45). Noise control has been considered (46) and noise reduction techniques have been developed (47).

The ability to develop a wholly satisfactory characterization of the shock environmeent produced by a non-contact underwater explosion in proximity to a surface ship is limited. A useful paper by Oleson and Belsheim (48) describes the current capabilities. Specifications MIL-S-901 spells out the shock test requirements for shipboard equipment. There have been alternate proposals for such specifications (49). Where testing is not possible, dynamic analysis methods can be used to ensure compliance (50). Newer ships,, for the most part, have been effectively shock hardened. It is usually impractical to completely retrofit older ships for shock protection to the required levels.

Submarines

Much of the same technology is applied to submarines that is used for surface ships. The main difference is the pressure hull required for submerged operations. Chaskelis (51) has offered acoustic emission techniques to check submarine hull integrity. Methods of analysis have been used to predict underwater explosion effects (52, 53) in submarines.

Off-Shore Structures

Off-shore structures are of importance to such activities as drilling for oil or natural gas. Dynamic problems are illustrated by four studies related to ocean wave action (54, 55, 56, 57) on floating and tower structures. When a human crew is required for operation, noise control becomes an important factor (58).

Ground Systems

Sub-categories for ground systems have been arbitrarily selected. Mobile systems include off-road vehicles, rail (trains), and highway vehicles. There is a special section on construction equipment. Nuclear reactors (power plants) and problems related to earth and foundations are also discussed in this section. Shock and vibration work related to these systems are surveyed in general, although problems unique to such systems are emphasized.

Off-Road Vehicles

Among the vehicles in this category, agricultural equipment is an important class. These are usually rubber-tired vehicles designed to operate over rough terrain. Dynamic analysis is important to efficient operation, particularly such areas as tire-soil interaction as studied by Karafiath (59). System modeling techniques have been developed (60) to improve the ride environment for the human operators. Here the terrain characteristics and vehicle model are analyzed as a moving system to develop optimum ride characteristics. Increased field performance can be achieved by proper analysis, as exemplified in a study by Ruff (61) of a strawberry harvester. Harris, et al (62) have addressed the problem of agricultural equipment noise as related to OSHA requirements.

Tracked vehicles are of special significance to the military establishment. Tanks, personnel carriers and weapons carriers fall into this category. The bulldozer is a good civilian example of this kind of vehicle. The vibration environment on such vehicles is unique and severe. Lee (63) has conducted an analytical study of this environment. Methods of isolation in tracked-vehicles are important. An investigation of fluidically-controlled suspension systems (64) is an example of attempts to solve this problem. Wheeler (65) has shown how computer programs may be used to advantage to simulate vehicle dynamics when subjected to terrain inputs.

In recent years the development of surface effects or air-cushion-supported vehicles has created some special dynamics problems. These vehicles operate over open terrain or water, supported by a cushion of air. Control is particularly important and difficult. Moran (66) has developed a model for predicting pitch and heave response of a vehicle during overland operation. A phenomenon called trunk flutter can occur as the supporting air escapes from beneath the vehicle. Forzano (67) undertook an experimental investigation of trunk flutter and methods of controlling it. The Boeing Company (68) describes an active control system to improve ride quality.

Rail Systems

Rail dynamics research involves track structure, the wheel-rail interface, truck stability, vehicle dynamics and freight dynamics. Willis (69) has provided an excellent review of research in vehicle dynamics. McConnell (70) has surveyed current problems in track structure technology. Hutchens et al (71) have developed the dynamic response parameters of a rail car to random inputs. Computer models and techniques have been used for calculating rail car vibrations (72). Rail car impact is a significant problem, as discussed under ENVIRONMENTS. Pullman-Standard (73) has looked at vertical motions during impact which may cause decoupling and hazardous penetration of tank car ends. Johnson (74) has examined the effect of impacts on the design of freight car truck bolsters.

A sustained lateral oscillation that occurs above a certain critical forward velocity of a train is called "hunting". This phenomenon causes large dynamic loads between the wheels and track and contributes to passenger discomfort. To alleviate this problem, Cox (75) has studied optimization of the lateral dynamics of a conventional rail car. Hannebrink et al (76) have investigated the influence of axle load, track gage and wheel profile on the severity of "hunting". Since train collisions can be catastrophic, the Department of Transportation (77) has studied the mechanics of such events.

The impact of noise from trains on the environment has become important in the present society. Wittig (78) reviews the current scales for rating environmental noise and applies them to trains. Two studies (79, 80) deal with methods of rail noise prediction and control. A comprehensive five-part paper (81) gives an in-depth treatment of the mechanisms of noise generation from wheel-rail interaction. Design of guideways has been considered as a mechanism for the control of vehicle dynamics (82). Guideway-vehicle interactions are particularly important in the design of tracked air cushion vehicles, as shown by Ravera and Anders (83). Davis and Hawks (84) have analyzed the lateral dynamics of such vehicles.

Road Systems

In this section, research on highway vehicles, highway pavements and certain peripheral structures, such as crash barriers, is considered. Although it is related to computer programs, an article by Bernard (85) offers a good survey of the nature of road dynamics problems. The dynamic characteristics of tires, brakes and suspensions must be considered, as well as the characteristics of the pavement.

Computer graphics has been applied to the design of automobile structures (86). Mathematical models of automobiles have been developed to study cornering phenomena (87) and front end suspensions (88). In general, the approach to automotive design has become more sophisticated in recent years (89). Structural modeling and analysis techniques have often been verified by experimental data.

Automobile noise is, of course, a matter of concern and has been studied from the standpoint of exhaust system noise (90) and noise source identification (91). There is interest in infrasonic noise since this environment (sound below the audible range) may produce passenger nausea or fatigue. Research in the United States on infrasound has been sparse. General ride quality in automobiles has been examined, as in a study by Park and Wambold (92).

Heavier vehicles, such as trucks, have been studied extensively. The U.S. Army (93) has correlated laboratory and field vibration-induced failure on 1-1/4 ton trucks. General Motors (94) has developed a road simulation system to study heavy duty vehicles. Various sources of vibration in trucks have been investigated (95, 96). The dynamics of articulated vehicles (semi-trailers) has been studied extensively, as typified by a Johns Hopkins study (97).

Trucks are larger and generate more noise. Bryson (98) says the problem can and must be solved. Truck tires are major sources of noise. The contribution to noise levels of speed, load, tire tread type, road surface and placement has been studied by Close (99). The effectiveness of regulations on truck noise reduction has been examined by Sharp (100). Methods of improving the ride environment for truck drivers have been developed (101, 102).

The design of road pavements is important, both to the durability of the pavement and the response of the road vehicles. The Army Engineers have studied pavement response (103) to determine performance under traffic loads. The field performances of continuously reinforced concrete pavements has been evaluated (104). Machemehl and Lee (105) have developed a technique for the mathematical simulation of the interaction of heavy highway vehicles with a defined road surface profile. Purdue University (106) conducted a research study on the relationship of road roughness to vehicle performance.

Vehicle crashworthiness may properly be considered under the category of road systems. Dynamic analyses of vehicle crashes are abundant. Welch et al (107, 108) use finite element techniques. Collapse modes are predicted by Saczalski and Park (109). Chander and Pilkey (110) use a new technique called "limiting performance". Chang (111) has developed a design-analysis method for the frontal-crush strength of body structures. Special bumper standards have been written and evaluated (112). Air bags have been developed (113) and evaluated (114) as devices for crash mitigation. Crushable steel structures have also been studied (115) for this purpose. Barriers (116, 117) along the highway and breakaway light poles (118) have been developed to reduce the severity of vehicle crashes.

Reactor Systems

Although conventional and nuclear power plants are faced with somewhat similar dynamic problems, the potential for greater problems exists in nuclear reactor facilities. The major difficulties arise with seismic events and operational vibration problems. Smith (119) offers a concise overview of these areas. Belytschko (120) provides a survey of numerical methods and computer programs available for the dynamic structural analysis of nuclear reactors. Mulcahy and Wambsganss (121) have reviewed the technology associated with flow-induced vibration of nuclear power plant components. Special problems have been addressed, such as vibratory wear of fuel rods (122).

Approaches to the seismic problem begin with consideration of site selection (123). Then, the earthquake ground motions must be defined, as illustrated by Werner (124). Methods of computing the soil/structure interaction effects must be developed, as discussed by Agbabian (125). The entire area of seismic design of nuclear power plants is admirably assessed by Howard et al (126). Stevenson (127) provides a useful survey of the variations in licensing requirements around the world. Finally, in the qualification or test area, Roberts and Shipway (128) provide good insight to current capabilities in the United States.

Foundations and Earth

Man-made sources of ground vibrations are reviewed by Liu et al (129). Natural sources, such as seismic events have been previously discussed. The dynamic properties and response characteristics of rock (130), sensitive soils (131) and frozen soils (132) have been investigated. The design, installation and ultimate performance of different types of foundations are relevant to a number of applications. For example, caissons and piles have been evaluated for construction defects (133) and studied as elements for machinery foundations (134).

Rigid embedded foundations have been analyzed for torsional response (135) and mass slippage on a foundation subjected to seismic motion has been studied (136). The interaction of buried pipelines with soil in motion has been investigated (137). Vibration from underground blasting (138) create design difficulties for a broad range of ground facilities, such as canal locks (139). Dams, when they fail, can cause catastrophic loss of life and property. Recent studies related to the testing (140) and analysis (141) of dams are therefore significant.

Construction

Bulldozers and other earthmoving equipment have been mentioned earlier in this section. Here some other types of construction equipment will be briefly discussed. The important problem area relates to noise and the environment, as emphasized by an Army program for noise reduction on construction equipment (142). Items such as jackhammers, rock drills and mining equipment are particular offenders. There have been some efforts (143) to reduce noise through design, but most fixes have been by isolation and other methods (144, 145).

Space Systems

Systems discussed in this section are satellites, spacecraft, or launch vehicles. Information related to dynamic measurements and testing has been treated earlier under EXPERIMENTATION. Most advancements in space system dynamics have been made because of the unique requirements of specific major programs, such as VIKING, SKYLAB, or SPACE SHUTTLE. Wada (146) provides a comprehensive overview of the Viking dynamics program revealing several advancements in the technology. Pohlen (147) and Leppert, et al (148) discuss dynamics efforts related specifically to the Viking Lander and Viking Orbiter. A compendium of Skylab structural dynamics analytical and test programs is presented by Demchak and Harcrow (149, 150), along with some useful data. Their purpose was to identify lessons learned and to provide guidelines for future analysts and program managers of complex spacecraft systems. In the earlier stages of the Space Shuttle program, analytical studies were made on such areas as wing-body interaction flutter. There have since been many different dynamic studies related to Shuttle problems. Probably among the more significant are those related to the use of models to establish dynamic characteristics (151, 152), brought about largely by severe cost constraints.

For general application to space systems there have been some important steps forward. The use of coupled base motion response analysis of payload structural systems (153), for example, reduces cost and schedule time for detailed structural analysis. Using this technique, base motion procedures are employed where critical segments of complex structural systems or components may be analyzed for various load conditions without having to re-establish the entire structural system coupled modal properties. Kana and Vargas (154) have applied transient excitation forces separately to simple beam-and-mass launch vehicle and payload models to develop complex admittance functions for the interface and other appropriate points in the structure. These measured admittances were then analytically combined by a matrix representation to obtain a description of the coupled system dynamic characteristics.

There is currently considerable interest on the part of NASA and the Air Force Space and Missile Systems Organization on the use of very large, flexible space systems for various applications. This presents a complete new set of dynamic problems, particularly when it is required to include in the analysis such factors as the operation of structural flexibility and momentum exchange controllers. The frequencies of these large systems can be very low. The excursions can be very high. Indeed, the structure may be so flexible that the problem is with traveling waves, not standing waves. There have been some very useful studies (155, 156, 157, 158, 159) in this relatively new area of dynamics, but it still remains a very fruitful area for future research.

The space age began in the late 1950's and men have since been to the moon and back. Launch vehicle dynamics has progressed rapidly. Typical current studies on a program like Space Shuttle relate to on-pad ground winds (160), lift-off dynamics (161), transonic dynamic stability (162), and combustion instability (163). The frontiers of space have just been approached. Surely many new and challenging dynamics problems are still beyond the horizon.

Humans

Human response to dynamic loads is a subject of vital importance. Although there are many problems remaining to be solved, it is fair to say that considerable progress has been made in recent years, to the point that some standardization has been achieved relative to acceptable vibration levels. Von Gierke (164) discussed the field in general, including some of the progress that has been made. The human body is a complex system to study. Strauss and Huston (165) worked to construct a framework wherein the various models of human biomaterials fit in order to describe the body's biodynamic response. Barton and Hefner (166) looked at the complexity of establishing a realistic baseline for standards on whole body vibration.

Applications are numerous related to the effect of vibration on humans. Tools such as jackhammers, for example, can cause serious adverse effects to the hand and arm. Reynolds et al (167) have conducted extensive research related to hand-arm vibration, both physical and subjective. Braunbeck (168) conducted Ph.D. research on the dynamic response of intervertebral joints using a lumped parameter model of the upper torso and head. The main objective was to predict lumbar intervertebral joint deformations. Smith and Suggs (169) used driving point mechanical impedance measurements to determine the dynamic response of the human head to sinusoidal vibration in the frequency range between 30 Hz and 5000 Hz.

Human response to shock or impact is a vital part of automotive collision research. Protective systems have been evaluated extensively (170). O'Rourke (171) has developed a method for measuring the resultant acceleration at the center of mass of a human subject's head during a simulated crash. Finite element head injury models have been created with some success (172). A three-dimensional rigid body dynamics model of the human head and neck region was presented by Huston (173) for the purpose of analyzing head and neck dynamics arising from impact and inertial forces (whiplash). A combined vehicle-occupant, crash-simulation model has been developed (174) and impact studies have been made on a head-helmet system (175).

The exposure of humans to noise may induce hearing damage or may affect performance. Guignard and Johnson (176) have reviewed the hearing damage area. Cohen et al (177) studied noise effects on human information processing and performance, pointing out the difficulties in such research. Mills (178) has reviewed the literature relating to the effects of noise on children. Studies on human ride comfort are illustrated by the work of Wambold and Park (179), Stone (180), and Hoberock (181). For most research in the dynamic response of humans, the difficulties are with the complexity of the human system, the limiting assumptions and limited availability of subjects for experimental purposes.

Isolation and Reduction Systems

Systems directly applicable to the isolation or reduction of vibration, shock, or noise are considered in this section. Specific work dealing with Absorbers was discussed under Damping. Some treatment of Isolators was given under COMPONENTS. Here the concern is more with specific applications in the design of systems. As useful background, two excellent survey articles on materials and systems for noise and vibration control have been prepared by Purcell (182, 183). These papers offer a comprehensive, yet basic, treatment of this technological area and are highly recommended to the reader.

Absorbers

Dynamic absorbers are useful in a number of applications. Vance (184) has prepared an informative paper on applications for torsional vibration. He observes that the number of devices for reducing torsional vibration is small compared to the number of ideas published and patents granted. The number of devices now being successfully marketed is also small, despite a demand that existing manufacturers cannot meet. Furthermore, although the torsional vibration absorber is an old concept, recent literature has not been abundant. A recent example is a concept for using a uniform spinning cable as a vibration absorber introduced by Vance and Woodward (185). Snowdon (186) offers a useful paper on the use of vibration absorbers for machinery vibration.

Shock absorbers are used universally on highway vehicles and the basic designs are well understood (187). There are continuing efforts for shock absorber improvement in other areas as well, such as the work by Wahi (188) on oleopneumatic shock struts for aircraft landing gear. Shock absorbers have also found useful application for improving the efficiency of drilling operations (189).

Absorbers of various types contribute significantly to efforts to reduce damage and fatalities in vehicle collisions. A high energy level pneumatic (HELP) bumper (190) has been useful on transit coaches. Gamble (191) discusses a device incorporated into a tension-type restraint system which provides an efficient method of passenger restraint while reducing the acceleration. Buckling devices have been used on automobile bumpers (192) and crash cushions have been constructed of waste materials (193). Air bags, normally considered for use in automobiles, have been used for the protection of the gunner in an Army helicopter (194). A special air bag, with reliable, repeatable bag-pressure relief orifices, has been designed for use in recovery of a remotely piloted vehicle (RPV) (195).

Noise Isolation and Reduction

Work in this area is normally related to environmental or occupational requirements. There has been some basic research, such as the study by Wilshire (196) on the suppression of sound by sound, but most efforts have been applications-oriented. The Army has established noise limits for its materiel in MIL-STD-1473A (197). Special difficult problems have been attacked, such as the suppression of muzzle blast noise from a cannon (198). Most military noise requirements are related to either personnel comfort and efficiency, or to detectability by a potential enemy.

Sound insulation in buildings of partitions (199) and entrance doors (200) has been studied extensively. Noise reduction for rail transit cars (201) and motor vehicles (202) are problems that have been worked on a lot, but not yet fully solved. Highway noise barriers are used more and more; Simpson (203) has prepared a handbook to be used as a tool for highway designers in their efforts to apply such barriers.

At the request of OSHA, Bolt, Beranek and Newman (204) conducted a comprehensive study of the technical feasibility of noise control in industry. The report categorized noise problems and noise sources, and identified possible engineering controls. A Westinghouse paper (205) looks at in-plant noise reduction using acoustical barriers. Hershey (206) addressed the problem of quieting machinery, such as circular saws, punch presses, textile spinning frames and typewriters. The noise from pneumatic systems was studied by Potter (207) in relation to OSHA requirements.

The principles of design of mufflers for engine exhaust systems are well-known, but some basic analytical studies of performance have been made, as in the work by Young (208). Hubbard and Conrad (209) have examined trends in aircraft noise control. They summarized avilable noise reduction technology as it relates to engine cycle design and to powerplant component design. An inference in future work to be done may be drawn from their discussion of noise reduction potential for such components as exhaust jets, fans, propellers, rotors, blown flaps and reciprocating engine exhausts.

Isolation Systems

Shock and vibration isolation systems may be categorized as passive or active. Passive systems employ normal isolation mounts without active feedback control. Derby (210) has written an interesting paper on the evaluation of mounts, giving guidance on the quantities that must be measured to conduct evaluations of isolator effectiveness. Passive suspension systems have been used effectively on tracked vehicles (211) to reduce pitching of the hull. Pilkey et al (212) offer an efficient two-stage procedure for optional design of suspension systems for rotating shafts. Liquid shock isolation systems have been evaluated by Ashley (213). Milne (214) discussed the analysis and testing of full scale shock isolated equipment floors for a silo-based ICBM system.

Active isolation systems use feedback control based either on relative position, velocity or acceleration feedback. For high speed ground systems, for example, the feedback controls the flow of air into a set of air springs which support the vehicle (215). Whitaker and Cheng (216) describe an active system to reduce the root mean square response of wing vertical bending and rotor flapping for a tilt-rotor VTOL airplane. A dynamic, antiresonant, vibration isolator for helicopter rotor isolation has been developed by Jones and McGarvey (217). Klinger and Calzado (218) describe an active, nonlinear, pneumatic suspension applicable to passenger railcars. In this design, standard on-off valves modulate pressure differences between dual opposing airbags to attenuate vibration and create guidance forces. Ellis (219) introduces a promising new technique for improving circular saw performance using an electronic feedback control system. A non-contacting position sensor measures deviation from a normal undeflected condition and the control introduces increased lateral stiffness.

There are many effective applications for active isolation systems, but the cost is usually rather high. A good rule of thumb would be not to consider an active system when a passive one will do the job.

Package Cushioning

The process of protecting packaged items from the dynamic hazards of transportation and handling involves the use of various isolation materials, or cushioning materials. The most comprehensive treatment of this area was completed by Mustin (220) in 1968. Since then, research papers relating to cushioning materials have not been plentiful. Kerstner (221) has produced a useful work on general principles of package design. Brown (222) has studied the variability of cushioning properties of polyurethanes. A simple, nonlinear Voig-Kelvin model was developed for polyethylene foam by Kennish (223). McDaniel and Wyskida (224) have produced a generalized impact response model resulting in an automated approach to the design of bulk cushioning systems. This has also resulted in a user's manual for cushioning design (225). Palmisano and Neily (226) have successfully applied particulate silicone rubber to the electronic packaging of circuit boards. Typical test procedures for packaging evaluation are illustrated by an Air Force Packaging Evaluation Agency report (227).

Progress has been made in this field, but too many routine packaging studies have avoided the deeper issues such as damping, shape and viscoelasticity. Furthermore, since cushioning materials are excellent isolators, such materials have not been exploited nearly enough in non-packaging applications.

Machinery Systems

A wide class of mechanical systems is treated in this section. Some of the categorizations have been made somewhat arbitrarily and it could be argued correctly that there is some crossover between the categories. However, the reader should not be troubled by unnecessary duplication. It is hoped that the machinery systems section as a whole will provide a reasonable status report on this technical area.

Materials Handling Systems

Systems of this type are designed for the handling or moving of materials or equipment and usually little attention seems to be paid to dynamics problems associated with such operations. There are exceptions. Columbia University (228, 229) conducted a two part study on the stability analysis of lifting rigs (cranes and derricks). A set of guidelines were developed as an aid in the loading or designing of such rigs so as to avoid unstable configurations. The Navy is concerned with container hoppers which are designed to alternate the swinging motions of a maritime van container and then guide the container directly onto a truck trailer. Wolfe and Wang (230) conducted thorough impact and operational tests on such hoppers. Gens (231) has defined the dynamic environment for forklift trucks, while Ellingson (232) has described an Army program to reduce noise from such vehicles.

Mechanical Systems

Mechanical equipment creates vibration and/or noise which may be self-damaging or unacceptable to the environment. Kumar (233) has analyzed structural-vibration related noise using statistical correlation theory. Hsiao et al (234) has formulated a class of optional design problems involving transient dynamic response of mechanical systems. Hodgson (235) uses the surface acoustical intensity method for determining the noise sound power of a large machine in situ. The method involves a summation of the major noise-radiating areas of the machine. Failure analysis of mechanical systems has been studied by Drenick (236), using the concept of critical excitation for nonlinear systems. A critical excitation is one that drives the system to a larger response peak than any other in some class of allowed excitations.

Fly-shuttle loom noise is one of the most significant problems now facing the textile industry. A comprehensive program to identify sources of noise in this machine has been conducted by Eckert et al (237). Patel (238) has developed modeling and dynamic analysis techniques for picking mechanisms of fly shuttle looms. The effects of clearances and link flexibilities on the stresses in joints of high speed planar mechanical systems was studied at the University of California (239). Pierce (240) has assessed methods of controlling anomalous vibrations of rotating wire stranding machinery.

A method for calculating the vibrations of machine parts moving on horizontal slideways using a nonlinear friction force-velocity relationship has been developed by Skladchikov (241). The Whirlpool Corporation (242) has produced an automatic balancer to reduce vibration of vertical-axis clothes washing machines. Methods of reducing noise in wood planers (243) and heavy duty refrigeration units (244) have been developed.

Metal Working and Forming

In connection with machine tool dynamics, Burney et al (245) use a stochastic approach to characterize excitations under actual working conditions. A time series technique develops mathematical models from only one signal, viz., the relative displacement between the cutter and the workpiece. The same research team (246) later used similar techniques to study system stability. A time-sharing computer program has been used in the design of chatter-free machine tools (247). Ostergaard (248) discusses the National Machine Tool Builders Association "Noise Measurement Techniques", reviewing in particular the educational portion of the document.

Computer design has been used to produce a multipurpose minimum vibration face milling cutter (249) in which a weighted fractional usage design method is used to obtain optimim blade spacings. Grinding dynamics has been studied by Brown (250) for his doctoral thesis. His study includes a model for forced vibrations; predictions for the rate of growth of unstable self-excited vibrations; determination and measurement of important grinding parameters; verification of the grinding model by experiment; and development of experimental techniques and equipment for measuring grinding machine characteristics. His work should be useful even outside the machine tool industry.

Pumps, Turbines, Fans and Compressors

Pumps produce pulsation, surge and vibration. Worthington Pump (251) has studied these phenomena to shed some light on pump reliability and efficiency. Brennen and Acosta (252) have developed a transfer function to study pump cavitation. The transfer function relates the instantaneous or fluctuating pressure and mass flow rate at inlet to the same quantities in the discharge from the pump. Because of their long, slender structure, vertical pumps can have severe vibration problems. Meyer (253) discusses these problems and how to solve them. Rund (254) offers a case history of the solution of vibration problems of a large Deriaz pump.

The reader should note that this discussion of turbines may be supplemented by additional useful information under Rotor Systems and Turbomachinery, both of which are yet to come. Turbochargers are specified for engine manufacturers for various charging systems which can deal with high pressure ratios and which are efficient enough to cope with severe conditions. Naguib (255) employed modern analytical and experimental techniques to develop a new radial turbine to meet these requirements. An unbalanced rotating turbine produces a principal mode of vibration in translation in the direction of the machine supports. The foundation forces produced have been studied by Boyce and Kozik (256). Computers have been used for the analysis of turbine vibration (257) and shipboard gas turbines have been evaluated for MIL-S-901 shock, using the Navy Floating Shock Platform (258).

Some of the work related to fans has been previously discussed under Blades. There are many kinds of fans, but whatever the type, the separation of the blade from the hub can be dangerous, even lethal. Hay and Martz (259) have developed design techniques to greatly reduce failures of this type. Dennison (260) describes a procedure for measuring the sound power level of small fans and motors. Fan noise from turbofan engines has been studied by Feiler and Conrad (261), with a view to noise reduction. Bremer (262) observed fatigue failures in a belt-driven engine cooling fan and carried out a program to determine the cause.

Compressors are subject to certain perturbations from steady operating conditions which may cause problems. Greitzer (263, 264) conducted an extensive theoretical and experimental study of surge and rotating stall in axial flow compressors. Good agreement was obtained between theory and experiment. High-speed refrigeration compressors produce nonlinear vibrations in automatic reed valves. This problem has been modeled and solved (265). Patterson, et al, (266) have diagnosed noise from portable air compressors and developed methods of control, including an assessment of the cost to manufacturers. Thornton (267) did some original work on identifying and reducing noise for a rotary vane compressor.

Internal combustion engines require vibration isolation mounting systems. Schmitt and Leingang (268) discuss the design of such mounts and the problem of predicting the amount of noise reduction realized therefrom. Stefanides (269) has studied a huge Diesel engine's capability to survive and work through the shocks and stresses generated by earthquakes. Basic studies leading to practical reductions of noise for Diesel engines have been performed by Coulson and Southall (270). Hutton (271) prepared the final report on the DOT sponsored Quiet Truck Program. Engine noise reduction for small remotely piloted vehicles has been studied by the Air Force (272) and digital fourier transform methods have been used in engine noise research (273).

Rotor Systems

Rotor dynamics has been studied for many years. The problems are reasonably well understood, but complex. Rieger (274) provides a very useful state-of-the-art review on rotor-bearing dynamics. The reader can look to his article for a logical set of conclusions and a clear, concise discussion of problems yet to be solved. An earlier review by Meirovitch (275) gives some insight concerning modal analysis of spinning structures. A paper that provides useful insight into the general problem of critical speeds and response of flexible rotors was provided by Eshleman (276). Vance and Royal (277) looked at current technology for small turboshaft engines, with respect to the rotor dynamics technology needed to solve such problems. Rieger's comprehensive guide to computer programs (278) will assist analysts in the rotor dynamics field.

Researchers have looked at rotor dynamics problems and have employed a number of different techniques in solving the problems. Nelson and McVaugh (279) used finite elements for the modeling of rotor bearing systems. Rieger, et al (280) presented the dynamic stiffness matrix concept as a general technique for calculating the unbalance response, critical speeds (damaged or undamaged), and stability threshold speed of a flexible rotor in damped flexible supports. Simmons (281) suggests that the vibrational energy method may be used to optimize the stiffness and mass distribution for problems of torsional critical speed, unbalance sensitivity and non-synchronous instabilities.

Johnston (282) discussed an aeroelastic rotor stability analysis that provides a very complete description of the dynamics and aerodynamics of fully coupled rotor (airframe) control systems. A technique of component synthesis using discrete frequency impedance matrices has been applied to the prediction of the vibration and noise characteristics of a helicopter transmission by Bowes and Berman (283). Nicholas, et al (284, 285) conducted a two-part study on the effect of residual shaft bow on the unbalance response of a single mass flexible rotor, and presented three methods of balancing such a rotor. Myrick and Rylander (286) developed an analytical method for the simulation of transient and steady-state response of flexible rotors with rotor whirl and whip problems common to incompressible-film hydrodynamic journal bearings.

Turbomachinery

The technology crossover between turbines, rotor systems and turbomachinery has been mentioned before. It turns out that 80 to 90 percent of the problems related to steam turbines involve vibration. Traexler (287), undoubtedly for this reason, has discussed turbomachinery vibrations, particularly those that occur in large steam turbines at central station power plants. The Westinghouse Corporation (288) has surveyed the present status of steam-turbine generator noise and its control. Stimulated by the pogo instability encountered in many liquid propellant rockets, Ng (289) has examined the response of cavitating turbomachines.

Structural Systems

Fixed ground structures such as bridges, buildings, towers and dams are the subjects of various dynamic studies. Earthquakes, explosions and winds are major loading mechanisms for such structures. Machinery and vehicular vibrations induced on the structures are also principal design considerations.

Bridges

The problem of bridge vibration caused by moving vehicles has been studied since the 1847 collapse of the Chester Rail Bridge in England. Two reviews (290, 291) summarize the major work in this area. From the point of view of the contemporary bridge designer, objectives of investigations pertaining to bridge vibrations include considerations for heavy traffic movement, severe earthquakes, and strong or gusty winds. Abdel-Ghaffar (292) has made the dynamic analysis of suspension bridge structures the subject of his doctoral dissertation. Matthiesen (293), in a report for the Transportation Research Board, summarizes a proceedings covering all major aspects of a program dealing with measurements of and design for seismically-induced excitations of highway bridges. Robinson, et al (294) offer a comprehensive discussion of the problem of retrofitting existing bridges to survive strong motion seismic loading.

The most notable example of wind-induced bridge failure was the collapse of the Tacoma Narrows Bridge, an event recorded on film and shown in the media over the years. Scanlan and Gade (295) have recently investigated the buffeting response of suspension bridges from gusty winds, with specific application to existing structures such as the Golden Gate Bridge. Traffic safety on bridges is, of course, a major item in bridge design. The factors, trends and guidelines for bridge rail design have been reviewed by a group at the Texas Transportation Institute (296).

Buildings

Vibration or shock in buildings may be induced by earthquakes, rail or road traffic, turbulent winds, human activity, and machinery vibrations, as well as other factors. An excellent review of the research and engineering tools available for the prediction and control of building vibrations is provided by Ungar, et al (297). It is the opinion of these reviewers that the building vibrations field is still in the early stages of development, primarily because of the multidisciplinary approach required.

Research is active in the area of seismic excitation of buildings. Marmarelis and Udwadia (298, 299) have studied the response of building structural systems to strong ground motion, both for the linear and the nonlinear case. For the linear case they used concepts of system identification with some success, and showed that a marked nonlinear behavior was exhibited by the structure during the strong-motion portion of the excitation. A building was then modeled as a nonlinear feedback system to study the response. Under the sponsorship of the National Science Foundation, Bertero (300) has identified research needs for improving aseismic design of buildings. Prendergast and Fisher (301) provide some useful guidelines for seismic design and analysis of permanent military buildings. The available literature on earthquake damage to single-family masonry dwellings has been reviewed by Benson (302). Available data was found to be limited and general in nature.

Nuclear ground shock and air blast have been mentioned elsewhere in this report. Such loadings on buildings are of particular interest to the United States Department of Defense. Wilson (303) reviewed the methods available for computing the degradation of structural elements due to thermal and thermal-blast effects. Korman, et al (304) offer improved techniques to analyze structural dynamic response to air blast. Air blast axisymmetric loading of protective structures has been studied by Farrell, et al (305.)

Towers

Winds and earthquakes affect the structural design of towers. In a combined theoretical-practical study of hyperbolic cooling towers, Rogers (306, 307) concludes that, as such towers reach immense sizes, more substantial wind and earthquake assumptions are required. The safety of hyperbolic cooling towers is important to the continuous operation of power plants. Gupta and Schnobrich (308) discuss methods of seismic design and analysis to assure such safety. Other types of towers and stacks require similar design considerations.

Dams

The failure of dams can be catastrophic and earthquakes are the events of major concern. Two reports illustrate the experimental (309) and analytical (310) work to prevent such failures. Although much research is still to be done related to dams, significant accomplishments have been made in the past, as shown in the exhaustive bibliography by Hollis (311).

General (Structural)

The Hollis bibliography (311) offers substantial coverage of earthquake engineering research prior to 1971. This report refers to a few significant efforts since then. This is a complex area and additional research is needed for all affected systems, particularly with respect to the design and evaluation of components for conventional and nuclear power plants. Research will continue and some more difficult problems are likely to be solved over the next few years, inspired at least partly by the somewhat parallel threat of nuclear explosions.

The important class of Optical Systems has not yet been mentioned in this section. The dynamics problems associated with these systems are very difficult to solve, primarily due to the troublesome effect of dynamic excitations on system alignment, a critical factor in optical system design. Although urgency has produced advancements for particular systems, new research is needed to develop techniques for the design and protection of sensitive optical systems.

AUSTRALIA AND NEW ZEALAND

Humans

Australia is concerned with the effects of low-frequency noise (infrasound) on human performance. An experiment has been designed, based on a series of tasks, which tests the effects of infrasound on performance (312).

Isolation and Reduction Systems

Noise Isolation and Reduction

In Australia, noise control efforts appear to be aimed at noise control in buildings and the control of noise emitted by equipment. The noise control community in Australia is well aware of the need to consider noise control in the initial design of buildings and equipment. (313).

Techniques are available, in the initial design stage, for controlling the noise in buildings that is produced by mechanical equipment and the external environment. The use of barriers for reducing noise is a well known retrofit technique for controlling noise, however their effectiveness as a means of reducing traffic noise in buildings is limited (314). Model investigations of alternatives were undertaken and the alternatives appeared to be more effective from the standpoints of cost, appearance, and acoustic performance.

Noise generated in water supply systems is often a cause of building noise. An energy absorption technique was developed that suppresses pressure pulses and hydraulic noise over a wide pressure range (315). This technique might be useful for attenuating flow induced noise in shipboard fluid piping systems.

Noise sources from several types of pneumatic motors have been investigated to find methods for reducing their noise output. The air exhaust part was a major noise source and the noise was reduced by redesign (316). This is a retrofit to achieve noise control on existing pneumatic equipment. The redesigned air exhaust might be considered in the design of new pneumatic equipment.

Many case histories of practical construction plant noise attenuation are available (317). They should be revíwed to see what might be applicable to controlling noise in American plants and equipment.

Isolation Systems

Current practice in the design of isolation systems is to represent the isolated unit as a rigid mass and ignore its flexibility. Design criteria were developed for vibration isolation systems that consider the flexibility of the critical elements of the system (318). The isolation system and the isolated unit are modeled as a two-degree-of-freedom system instead of the usual single-degree-of-freedom system. While the analysis reveals no new principles, it should be considered in the design of isolation for real systems.

Design criteria were developed for vibration isolation systems to be used for equipment on suspended floors. This procedure takes the flexibility of the supporting structure into account by modeling the floor and isolated system as a two-degree-of-freedom system (319). This analysis is particularly appropriate for the isolation of machinery that is mounted on upper floors of a building, or for the analysis of the response of isolated equipment that is mounted on a flexible foundation. A new theatre in Sydney, Australia was built directly over railroad tracks. Vibration isolation techniques were developed and were incorporated in the initial design stage to reduce the noise transmitted to the theatre.

The shock and vibration environment was measured on military trucks operating over rough terrain. The environment is statistical in nature. The results re applied to the design of shock and vibration isolation systems to protect vehicle equipment during off the road operations (320).

There have been past proposals for isolating nuclear reactor power plants from earthquakes by using horizontal, flexible supports at the base, however, this scheme was not applied because there was no practical way to damp out the quasi-resonant build-up that would occur. The development of a hysteretic damper, combined with a system for providing flexibility for horizontal motion, has made this scheme practical (321).

Machinery Systems

Pumps and Fans

The following case histories from Australia describe the steps that were taken to reduce the noise output from pumps and fans in the design stage. Hydraulic control systems often use gear pumps which are a major noise source in the system because of their pulse-like discrete pumping action. Pressure relief grooves relieve the abruptness of the pump discharge pulses and the noise emission potential of a pump. A new pressure relief groove system was developed to be incorporated in a gear pump to reduce its noise emission potential (322).

Solutions to many fan noise problems often result in a case of the "cure being worse than the disease". A program was undertaken to develop a quiet fan and overcome some of the problems associated with conventional silencing techniques (323).

Rotor Systems

A new method was developed for determining the vibration modes and the stability of a helicopter blade with complex damping. The technique was used to study flutter of a helicopter blade in a slow forward flight (324).

Structural Systems

Bridges

The theory of free torsional vibrations of single-span box-girder suspension bridges has been applied to three different bridge systems. The author pointed out that little has been published on vibrations and that there has been no comprehensive analysis of the torsional vibration of box-girder bridges (325).

A study of the response of a nine-story steel-frame building to the February 1971 San Fernando Earthquake was performed. The results showed that it was possible to use a linear viscously-damped model to accurately predict building motions in response to a specified ground motion. Dynamic tests were performed on the building to recover lower mode periods and damping ratios, and the values were compared to earthquake records and analytical results (326).

UNITED KINGDOM

Air Systems

Aircraft

Dynamics problems related to aircraft are studied extensively in the United Kingdom. Research efforts involve take-off, in-flight dynamics, and landing.

Continuing interest is evident with respect to landing gear dynamics and taxi loads on aircraft. Three studies in this category are cited. The response of flexible aircraft to rough runways is one area of concern; a study of the aircraft response to runway roughness using power spectral density methods was performed (327). Two studies of undercarriage dynamics were performed. The purpose of one investigation was to develop an undercarriage design technique to minimize aircraft taxing response without deteriorating the landing response (328). The other investigation concerned a hybrid computer technique to optimize the aircraft landing gear characteristics (329).

Aircraft noise studies are numerous in Great Britain. One study addressed the noise on the structure of an in-flight aircraft with the engine above the wing (330). Another study considered the problem of the effect of flight on the sound radiated by a high frequency source embedded in a constant area jet pipe in the presence of flow (331). One approach to reducing jet engine noise is to locate the engine so that the vortex shed from the wing reflects the sound away from the ground. An experimental investigation was undertaken to evaluate this concept (332). This technique for controlling jet noise seems promising enough to pursue further; if it is effective it should be considered in the design stage for close support military aircraft.

Many studies concerning aircraft as noise sources and their control were performed. One study concerned the relationship between the growth of civil aviation and noise measurement (333), while another study addressed the relationship between economics and noise of subsonic aircraft (334). Research on aircraft noise reduction has been performed. One study predicted some of the more likely ways to reduce jet noise (335); another study was concerned with the control of V/STOL aircraft noise (336). In two other reports, the relationship between noise control and other design parameters was studied (337), as well as the problems in developing quieting treatments for the Anglo-French SST (338).

Flutter is another active area in Great Britain and many studies have been performed. A technique was developed for analyzing the results of a multi-degree-of-freedom flutter calculation so that similar flutter conditions are achieved with only two-degrees-of-freedom (339). A practical approach to predicting unsteady wing loading in mixed subsonic and supersonic flow was developed for flutter clearance in subsonic flight (340). Wind tunnel flutter tests were performed on a half-wing model with a fan engine nacelle attached by a pylon (341). The flutter stability of a two dimensional rigged wing was analyzed. Only damping and simple aerodynamic forces were considered (342).

The possibilities of flutter in airships (lighter-than-aircraft) was investigated. Particular attention is paid to the symmetric modes. The flutter determinant is set up for the six-degrees-of-freedom model involving hull bending, hull vertical translation, hull pitching, fin bending, fin torsion and elevator rotation (343). During World War II airships carried out combat missions such as radar picket and ASW. They have also been used in research platforms for various types of electronic equipment. The fact that this study was performed indicates that some interest in the dynamics of this craft exists, even though its future is uncertain.

Dynamics of deformable aircraft are another area of interest in Great Britain as indicated by three studies for the Royal Aircraft Establishment (344, 345, 346).

Sea Systems

Surface Ships

Hovercraft have been in service in Great Britain for several years and development work continues. Two studies were conducted to understand the mechanism of leading skirt collapse or "tuck-under", which is thought to precede overturning (347, 348).

Off-Shore Structures

The discovery of petroleum under the North Sea has lead to several studies of the response of marine structures to wave forces. A typical study concerns the wave excited vibration of a sea platform (349). Another study was concerned with the response of jetty built-up from box-girders (350).

Ground Systems

Rail Systems

Studies of railroad vehicle dynamics are a continuing effort in Great Britain. The areas of investigation can be divided into vehicle dynamics or vehicle noise.

A survey of the British Railways vehicle and track dynamics program was prepared (351). The major problems that were discussed included methods of predicting the speed at which an instability called "hunting" occurs and methods of minimizing vertical track loads.

Two studies of the relationship between steering and the dynamic stability of rail vehicles were performed. One study considered the performance of existing and proposed vehicle configurations in terms of a linear approach to dynamic stability and curve negotiation (352). Another study considered the static and dynamic stability of three axle vehicles with perfect steering (353).

A study of the dynamics of monorail railways was performed which contained a review of the published literature and an assessment of the current state-of-the-understanding of the dynamics of these vehicles; areas for further study were cited (354).

Internal acoustics in railway vehicles is of concern as it relates to passengers. One study was performed that showed how internal noise levels could be analyzed by components and which components were significant (355). Another study on the same subject was performed to determine how the noise reaches the passenger, and also to develop methods for assessing the internal acoustic performance of the vehicle at the design stage (356). Both of these studies should be very useful for developing specifications and design criteria for interior noise levels in future rail passenger vehicles.

Several studies of environmental noise from railroad operations were performed. One study addressed the problem of noise propagation modes in open terrains to arrive at the important parameters. The purpose was to develop a technique for predicting railway noise levels in residential areas (357). Two studies addressed the problem of predicting noise due to high speed trains One of the studies summarized existing prediction techniques and assessed the current rail noise environment (358). The other study described a model that could be used to predict environmental noise from fast electric trains (359). A method was developed in Great Britain for reducing the annoyance of railway noise and vibration. A floating track slab isolates the track from the ground. Its effectiveness was demonstrated in cut and cover tunnel construction (360).

Road Systems

In the area of road vehicle noise, an investigation was undertaken to determine the noise environment in the cabs of heavy trucks at speeds up to 50 mph. Data collection in the 2-20 Hz frequency band was emphasized to determine the levels of infrasound (361). A study of noise and vibration characteristics of motor vehicles was undertaken to establish the frequencies at which levels exist (362). The acoustic characteristics of a car cavity were determined by using a 1/2 scale model. The results of this study identified the major noise sources in the car body (363).

Identification of major sources of external noise from vehicles is also important. In one study noise sources were separated as power train noise or rolling noise. Examples of the former include engine noise, transmission or driveline noise. Rolling noise includes body rattles and tire noise (364). A study of operating parameters was performed to determine their effect on the vehicle noise sources (365). A study was undertaken to develop an understanding of the mechanism of disc-brake squeal (366).

A program was undertaken to develop a quiet heavy truck; part of the program was to estimate effects of the use of such a vehicle on the overall noise level (367). One study was specifically directed at predicting the effect of reduced vehicle noise on traffic noise (368). The study was based on vehicles that were lighter than 1-1/2 tons as well as vehicles that were heavier than 1-1/2 tons.

A technique was developed in Great Britain for identifying the vibration modes of an automobile from acceleration time history data measured on the structure (369). A theoretical and experimental study of the vibration of an automobile driveline was performed and a simple model that ignores the coupling with the body vibration modes was developed. This simple model may be adequate to predict the most important driveline modes (370).

A study of stochastic road inputs and vehicle response was undertaken. The results established that a stationary Gaussian process provides a satisfactory basic model of a road surface (371). The techniques that were developed in this study could be applied to the development of realistic inputs to mathematical models of vehicles so that inputs to cargo or passengers may be derived for further analyses or as test criteria.

Several studies have been performed on the response of motor vehicles to steering inputs. In one study, a theoretical approach was used to describe the responses to steering and side wind inputs in terms of transfer functions and parameters that define the transfer functions (372). Another study considered the yaw rate response for a two-degree-of-freedom car model (373). The response of an articulated double bottom vehicle to steering and braking was also studied. The effects when certain axles were locked were considered (374). A study of the analysis and interpretation of steady state and transient vehicle response measurements was performed to assess the state-of-the-art of measurement and behavior (375).

The use of motorcycles has become more common in Great Britain and they are not without their dynamics and noise problems. Studies of their dynamics problems include low speed wheel flutter (376) and the interaction between a motorcycles vertical and lateral natural frequencies (377). An inexpensive system of motorcycle silencing was developed (378).

Foundations and Earth

In Great Britain a variety of studies have been performed that pertain to the interaction between structures and earth.

Vibratory pile driving seems to be an area of continuing interest. One vibratory pile driving technique that is being studied is the use of a spring mounted mass, driven by a rotating unbalanced mass, to impact the top of the pile. Piles that are driven into soft soils tend to wander from their assumed line of action during installation. A study of the directional stability of piles during driving was undertaken to develop directional stability limits for steel pile sections in soils (379).

Interest also exists in the soil-structure interaction effects. One study is being undertaken to determine what soil or structural parameters influence the dynamic response of tower structures embedded in the earth. A combined analytical and experimental investigation was undertaken to find new methods of damping unsupported steel chimneys to reduce their response to wind-induced vibration. The flexibility of the chimney at its base, due to the soil and the viscoelastic damping layer interposed between the chimney base plate and its foundation, is considered (380).

Humans

Human response to shock, vibration and noise is an area of great interest in Great Britain that has given rise to many studies. M.J. Griffin (381) prepared an excellent review of the ride comfort studies that have been performed in Great Britain. Another noteworthy effort is on the application, of the limits on vibration set forth in International Standard (ISO) 2631, to ride quality criteria. This study described the difficulties of defining comfort and setting the appropriate acceptable levels (382). Recently, limits of exposure to whole-body vertical vibration in the 0.1 to 1 Hz frequency range have been proposed (383). (It should be noted here that International Standard (ISO) 2631 cuts off at 1 Hz, and that the Standard is a guide for the evaluation of vibration exposure).

Anyone who has ever flown in a helicopter is aware, often painfully, of the vibration environment. A guide was prepared for evaluating helicopter vibration in terms of recommended vibration exposure limits for the crew (384). The internal noise and internal vibration environment in helicopters is an area that needs further study.

Two studies of noise and vibration were run to determine the effects on a ships' crew (385, 386).

Infrasound is an inaudible airborne vibration below 20 Hz and its presence can be felt. A literature review on the effects of infrasound on people inside road vehicles was written by Rao (387).

Many studies on the subjective response to shock and vibration have been performed. The purpose of one of the studies was to validate techniques for determining subjective response to vertical vibration (388). Closely related to this study was one to assess the capabilities of humans to judge the frequency of whole-body vibration (389). A study of the relation between low frequency sinusoidal vibration and human comfort was performed. The subjects were exposed to vibration for short durations but they were requested to estimate the comfort levels preferred had they been exposed to vibration for longer durations (390). Two studies concerned subjective equivalence. One study was concerned with the equivalence between noise and whole body vibration (391), while the other was concerned with the equivalence between sinuosoidal and random whole-body vibration (392). An experiment was conducted to determine the effect of duration of whole-body vertical vibration on relative discomfort (393). Experiments were conducted to assess a method of measuring whole-body vertical vibration experienced by people seated on soft seats (394).

Two studies of the transmission of vibration to the human head were performed. The effects of time-of-exposure and vibration amplitude were considered along with effect of bending knees (395). The transmission of angular vibration in yaw to the head of a seated subject showed that response can be excited in all three directions (396).

An evaluation of human exposure to hand-transmitted vibration was performed to assess the relative importance of some of the parameters in predicting the effects of such vibration (397).

Isolation and Reduction Systems

Noise Isolation and Reduction

There is considerable interest in noise reduction techniques in Great Britain and studies have been performed for many applications.

Quieting jet engines is a major interest and one study was performed to develop design techniques for more efficient silencers (398). Another study of silencers for jet engines examined the noise and turbulence parameters of a series of flows for silent jets (399). Studies of noise control in process plants (400), in automated bottling lines (401), and open plan offices (402) were also carried out.

Studies of the properties of materials for noise control as well as methods for obtaining these properties is an important part of the noise control efforts. Methods for determining the normal incidence absorption coefficients and acoustic impedances of single-layer fibrous lining materials (403) and perforated sheet liners (404) for lining gas turbine ducts were developed and data were collected. Acoustic properties of a mineral wool fibrous material at temperatures up to 500°C were also determined (405).

Isolation Systems

Interest is evident in different applications of isolation systems. A study was performed to determine the effects of an automobile suspension on the motion of a vehicle during braking and acceleration (406). Another study addressed the problem of protecting avionics from the motion of a nonrigid supporting structure (407). This study should be useful in designing isolation systems for a wide variety of flexible mounting applications. Another study concerned an unusual isolation application for a building (408). This study might be useful in isolating sensitive equipment inside buildings from the effects of earthquakes.

Machinery Systems

Metal Working and Forming

Most of the activity in this area relates to noise sources due to the operation of machine tools and the dynamics of machine tools. The latter category includes improving the structure of grinding machines and investigating the cause of chatter in the grinding process (409). Another study of machine tool dynamics involves the use of epoxy resin bonding to build stiffer and more heavily damped machine tool structures (410).

Stability of a machine tool during its operation is an important consideration and dynamic tests are performed to determine these limits. Dynamic acceptance tests were run on a center-type lathe to determine the stability limits of its operation (411).

A dynamic acceptance test was performed on a milling machine to determine its dynamic characteristics and the stability limits of its operation (412). An investigation of metal cutting was carried out to determine the effect of modulating the spindle speed on the amount of metal cut and the onset of chatter (413). Vibration tests were conducted on three designs of boring bars to determine which one would yield the most increase in stable metal removal rates (414).

Identifying noise sources in machine tools and metal working equipment is a major area of interest in Great Britain. A technique for identifying the sources of noise from several simultaneously-operating machine tools was developed (415). Studies were conducted to examine the mechanism of noise in various impact type metal working tools. In one study, sudden billet expansion in impact forming machines was identified as a noise source (416); in another investigation, the noise due to an upsetting process on a laboratory drop hammer was studied (417). The mechanism of noise produced by a platen of a drop forging machine was determined (418).

Fans

Investigations of fan noise are significant in Great Britain. The literature on fan noise can be divided into two categories, fans used in propulsion and fans used for heating and air conditioning.

Studies of noise generated by ducted fans are continuing. The objective of one study is to determine the relations between aerodynamic flow disturbances upstream of the blades and the characteristics of the generated noise (419). A technique was developed to measure the aerodynamic forces on an oscillating model of a fan-engine nacelle in a uniform airflow (420).

A survey of the published literature on reducing the noise in centrifugal fans used in ventilating and air conditioning systems was prepared. The survey was limited to investigations that were made to reduce the generated sound by modifying the fan itself (421). A study of the noise emitted by cooling fans in trucks was carried out in connection with developing techniques for reducing the noise from automotive cooling systems. Two types of fans were studied, centrifugal fans and axial flow fans (422). A theoretical model for investigating acoustic radiation resulting from fluctuating forces at a downstream stator row with nonuniform, circumferentially-spaced stator vanes was developed. Uneven distribution of stator vanes was found to reduce interaction tones significantly (423).

Reciprocating Engines

Most of the studies of reciprocating engines are carried out to reduce noise. Understanding the mechanism of noise generation in automotive engines is a continuing effort.

A technique was developed to predict the overall radiation of noise from various parts of an engine based on average surface vibration measurements. Studies of the frequency content of the surface vibration of a Diesel Engine have been carried out to locate noise sources and reduce the radiated sound (424).

Structural response investigations of Diesel Engines are being carried out to predict the radiated noise level at the design state of the engine. Simple finite element models were used to model the engine structure. The use of pseudo-random binary sequence and cross correlation techniques were used to identify the dynamic characteristics of a large medium speed Diesel Engine (425, 426).

Piston slap at top dead center is another source of noise in internal combustion engines. A technique was developed to simulate the phenomenon on an analog computer (427). Engine manifolds are another major source of noise in internal combustion engines. A study of the periodic pressure fluctuations in internal combustion engine intake manifolds was performed to find a technique for determining the combined steady and oscillatory pressure at any point in the manifold (428). A study of the noise radiated out of the tail pipe of an internal combustion engine was also performed (429).

Rotor Systems

The dynamics of rotors is an area of concern in Great Britain. The studies in this area may be divided into several topics such as stability analysis, modal analysis and noise.

One study was undertaken on stability analysis to determine the cause of a vibration instability exhibited by a high pressure rotor above a certain load (430). Bearing instability is often suspected as a cause of high nonsynchronous vibration of a rotor and its bearings. Several studies have been performed on the relationship between rotor vibrations and the characteristics of bearings. In one study a technique for predicting rotor behavior as a function of bearing clearance was developed to arrive at the optimal clearance in a journal bearings (431). A method for stabilizing externally-pressurized gas journal bearings was developed to counteract self-excited translational whirl (432). Research has also been carried out to establish instability criteria for flexible rotors with shafts supported on oil-film bearings (433).

Model analyses of rotating systems have also been performed. One fundamental study was prepared to make practicing engineers aware of the applications of modal analysis and the balancing of rotors (434). A compact distributed inertia solution was developed for finding the natural frequencies and mode shapes of free torsional vibrations of a shaft with attached rotors. The method may be used on a "programmable" calculator (435). The vibrations of a rotor on a cracked shaft were examined using an analog computer simulation to determine whether crack growth in a balanced rotor and shaft could be detected from the main and subcritical speeds (436). The response of a rotor in hydrodynamic bearings to mass unbalance was studied. Modal resolution of unbalance response was studied in relation to balancing (437).

Several studies on noise generated by rotors or propeller blades have performed. An investigation of the mechanism of converting an unsteady velocity inflow into sound radiated from an open rotors was carried out (438). The acoustic properties of periodic unsteady rotor blade forces were investigated for a variety of operating conditions and types of blade loadings (439). Rotor spectra from a variety of axial-flow machines were compared (440). A study of the mechanisms of propeller and helicopter rotor blade noise generation was undertaken. Both discrete frequency and broad band noise were considered (441). A method was developed for estimating the peak harmonic sound pressure levels from isolated rotors and propellers from test rig data (442). A study was made of the geometry of the waveforms of a supersonic rotor (443). The results appear to have value in delineating potential regions of shock formation in the free field. Applications include shock radiation from supersonic fans in jet engines or advancing blade slap in helicopters (443).

Turbomachinery

Two studies of blade cascade noise were performed. One study concerned research into the noise generation mechanism (444); the other concerned an experimental investigation of wake-excited resonances in an annular cascade of flat blades (445).

In one investigation, gas turbine exhaust noise controlled experiments were carried out to study the noise characteristics of a model turbo-jet exhaust system. The noise data were related to aerodynamic conditions in the model (446). A theory was developed to calculate the acoustic power produced by temperature fluctuations in the flow from the combustor to the turbine section. This mechanism was used to predict the acoustic power emitted from a gas turbine exhaust for three different engines (447).

Structural Systems

Buildings

Vibration studies of buildings concern dynamic loads on the buildings and the transmission of noise and vibration through the buildings. A review of the literature of the dynamic loads and the response of buildings showed that larger, lighter, and hence more flexible structures are being built in Great Britain. The study pointed out the need to do a better job in defining the characteristics of the dynamic inputs to buildings (448). A continuum method was developed for the dynamic analysis of asymmetric tall buildings (449). An investigation was carried out, experimentally and analytically, to determine the response of unusually-shaped power station buildings to wind-induced excitation (450).

Two studies on the transmission of noise in buildings are offered. One study (451) is being done for the purpose of separating the direct airborne noise from the sound pressures developed by vibrations in a structure caused by either groundborne disturbances or ultrasound. Power flow techniques were used to determine the amount of sound that is transmitted both directly and indirectly in a building. The effect of furniture and boundary conditions on the sound attenuation in an office was studied to arrive at a method of predicting the amount of sound attenuation (452).

General (Structural)

Significant interest exists in wind-induced vibration of structures is indicated by a review of the literature (453) which describes world-wide work in this area. Practical solutions were developed in this review article to some wind-induced vibration problems.

The Strouhal frequency was determined for several structural shapes, and from this, the critical wind speed for the onset of instability can be calculated (454).

Two studies of wave propagation and natural frequencies of periodic structures were performed. In the first study, monocoupled periodic structures were studied and the relationship was obtained between the bounding frequencies of the propagation zones and the natural frequencies of individual elements (455). Multicoupled systems, both with and without damping, were examined in the second study; and again equations were derived for the bounding frequencies of the zones within which waves could be propagated through periodic structures (456).

Thin-walled structures are used in many aerospace applications. A study of the optimum design of such structures was performed (457).

CANADA

Air Systems

Aircraft

Most of the Canadian interest in aircraft is centered around acoustic studies. One of the studies was an investigation of the effect of aircraft maneuvers on the focusing of sonic booms. The atmosphere model was considered to be piecewise linear with regard to wind and sound speeds and piecewise constant with regard to wind direction (458).

Mechanisms for reduction of jet and airframe noise have been studied (459). Acoustic tests were performed on a fan-in-wing model to assess the effects of increasing the depth of the inlet on the noise characteristics of the fan (460).

Sea Systems

Surface Ships

The development of an active-passive motion compensation system for marine towing is significant. The system is designed to minimize the undesired motion due to the ships response to wave actions (461, 462).

Ground Systems

Off-Road Vehicles

Snowmobiles are useful for off the road transportation in the winter. They are, however, objectionable because of the excessive noise. Unfortunately, problems exist in performing noise tests because of the shortcomings in the test procedures (463).

Rail Systems

Two studies of importance were performed on rail systems in Canada. The first study concerns the use of composite concrete rails as a means of reducing rail noise (464). The Composite concrete rails are stiffer and heavier, allowing a more flexible roadbed which in turn reduces the noise at its source. However, the state-of-concrete-technology needs to be advanced before this technique can be considered to be practical. The other study is concerned with the effects of axial forces produced by a moving load on a continuously welded rail which is mounted on an elastic damped foundation (465).

Reactor Systems

Studies of the vibrations in nuclear reactors in Canada are concerned with the flow-induced vibrations of fuel bundles (466) and fluid elastic instabilities of cylindrical structures due to high axial flow velocities (467).

Foundations and Earth

Research has been conducted in Canada on foundation vibrations and the problem of interaction between the foundation and the earth. Studies relate to the prediction of the dynamic stiffness and damping generated by soil-pile interactions (468) in vertical and horizontal vibration (469, 470), the resistance of soil to a horizontally-vibrating pile (471), torsional vibrations of pile fondations (472), and vertical vibrations of floating piles (473). A current development effort concerns the analysis of the interaction of all components of a machinery system, from the elastic rotor, through the bearings and foundation, down to the piles and soil.

Construction

Winter freeze-up in Canada limits construction operations such as earth moving and trenching. This is mostly due to the large force that is required to cut the soil. One technique that has been investigated for reducing the force required to cut frozen soil is the vibrating blade technique (474).

Space Systems

A topic of interest today in Canada is the dynamics of flexible spacecraft. Typical examples of such structures are communications satellites and/or their appendages, such as solar arrays. A mathematical model of the solar arrays of the Canadian Communications satellite was developed. Mode shapes and natural frequencies for both the one-g ground vibration survey and the zero-g on-orbit state were calculated and compared (475). A functional and dynamics test was also performed to verify the predicted mode shapes and natural frequencies of the flexible solar arrays on the Communications Technology Satellite (476). A method was developed for extrapolating structural damping values deduced from ground test data on a flexible spacecraft to estimate its structural damping in zero-g orbit. This method evolved during the development program for the Canadian Communications Satellite (477). A dynamic analysis, using the finite element method, was performed on a flexible spacecraft that resembled the Communications Technology Satellite (478). A method for obtaining in-flight dynamic response data on the Communications Technology Satellite was proposed. (479). The method suggested that the spacecraft be excited by its thrusters during flight so as to produce pulse trains near one of its resonant frequencies.

Studies were performed on the influence of stored angular momentum on the natural frequencies of a spacecraft with flexible appendages (480). Many of the Canadian experiences with the dynamics of flexible spacecraft will be applicable to the United States large space structures program which is just getting underway. In particular, it will be necessary to have the means to accurately predict the on-orbit zero-g dynamic characteristics of large flexible space structures. Thus, the experiences of the Canadian Communications Technology Satellite program might provide a base from which to start.

Humans

The investigations of dynamic effects on humans in Canada concern the effects of noise. Human reaction to sonic boom is the most significant area of investigation. One study was concerned with the effect of sonic boom on automobile driver performance under actual driving conditions (481). Another important study relates to the noise hazard associated with the operation of aircraft ground service equipment (482). This study was aimed at hearing conservation for flight line personnel who operate this equipment; a study of this nature in the United States would be appropriate.

Isolation and Reduction Systems

Absorbers

In the application of active and passive control systems, an important problem is the interaction between the structural dynamics of a body and its control system. A study of the interaction between a flexible body and a passive damper was performed to insure that the damper was designed to reduce the structural oscillations of the body rapidly, so as not to upset the performance of the control system (483).

Power Transmission Lines

In all countries, including Canada, the reduction of the vibration of power transmission lines is important. A review of the problems associated with low-frequency vibration of single and bundled conductors was prepared by a Canadian author (484). It reports on forms of instability not previously covered as well as methods for preventing "galloping".

Machinery Systems

Fans and Compressors

A significant amount of work has been performed on the vibration of fans and blowers; most of this concerns noise emission.

The existing literature on centrifugal fan and blower noise was reviewed to establish further areas of research that are needed to develop a quiet blower. Noise measurements were also made on a wide variety of blower sizes to identify frequency components from various types of blowers (485). Fans and blowers are used in many shipboard applications therefore this development of cheap quiet blowers will be of direct benefit to the Navy.

Other studies included an identification of the physical phenomena that govern the generation of discrete tones in the inlet vortex of an axial flow fan and the dynamic performance of a variable pitch turbofan using a hybrid computer.

Vibration studies of compressors in Canada have been concerned with the unstable vibration of high pressure centrifugal compressors (486), methods of improving the life of valve assemblies, and the analysis of the vibrations of vanes on impellers.

Rotor Systems

Analysis of the instabilities of rotors is also of interest in Canada. A study was performed to determine the effects of both internal and external damping on the flutter boundaries of a rotating system under the influence of an axial force (487).

Turbomachinery

A survey of the impact problems that confront the designers of turbomachinery was prepared and it described some of the solutions.

Oil-film dampers are used in turbomachinery to suppress unwanted shaft responses. The effect on the damper geometry on the rotor response and the operating speed at which the dampers could be used were determined (488). A finite element analysis was performed to determine the vibration modes of a rotating blade disc system (489).

Structural Systems

Bridges

Significant research efforts are underway in Canada in connection with the vibration of bridges, such as is caused by aeroelastic instability. One study was performed to determine the flutter speed of a bridge deck (490).

The vertical and torsional motions of a suspension bridge was the object of another study. Both self-excited wind loads, due to bridge motion, and buffeting wind loads were considered (491).

A finite element scheme was developed for the dynamic analysis of box bridges. Special purpose elements were developed to represent the behavior characteristics of thin box sections (492).

Buildings

In a study of the response of box-like buildings to weak explosions, the finite element method was used to predict the response of the building to weak blast waves. A second purpose of the study was to determine the critical factors that govern the response of buildings (493). A study of the response of steel-framed buildings with setback towers to earthquake loads was also performed. The input data for this study was taken from the El Centro earthquake (494).

Floor vibrations in new construction are as much of a problem in Canada as in many other countries. Methods of predicting floor vibration in the building design stage, as well as correcting it after construction, have been developed (495).

Structures (General)

The stability of structures in Canada is of sufficient interest. A study was undertaken to develop criteria for determining when a structure could be analyzed for stability purely on the basis of statics (496). Another study was undertaken to investigate the stability of guyed towers when the guy wires were ice-coated.

FRANCE

Air Systems

Aircraft

Many papers on aircraft flutter are available from France, most of which are from two recent meetings sponsored by the Advisory Group for Aerospace Research & Development (AGARD), Paris, France. The first meeting was called "AGARD Specialists Meeting on Wing-With-Stores Flutter" (497) and was held in Munich, 9 October 1974 during the 39th Meeting of the Struct. and Mater. Panel of AGARD. The second was called "AGARD - Flutter Suppression and Structural Load Alleviation" (498). In (497), which is an evaluation report, results are presented from a conference on information and procedures in use in the various NATO nations to solve the flutter problems associated with the carriage of external stores on wings. Nine presentations were given and are summarized. Recommendations concerning possible future efforts on the subject are given. Two papers from the Flutter Suppression meeting are concerned with active flutter suppression systems (499, 500). Another paper on active flutter suppression, load alleviation, and ride control is available, again from AGARD (501). P. Rajogopal (502) has developed experimental methods for the ground simulation of unsteady aerodynamic forces which act upon an aircraft in flight by means of an electromechanical apparatus.

Helicopters

New methods have been developed in France for the calculation of the structural dynamic characteristics of helicopters using branch-modes (503).

Sea Systems

Surface Ships

The Bureau Veritas, Paris, France, has for many decades been serving as a "trouble shooter" for ship builders and owners who have experienced in-service vibration problems. Guy C. Volcy, Head of the Studies and Applied Research Department has been closely associated with these efforts. In the process of solving ship vibration problems, Volcy and his associates have built up a wealth of experience over the years. Fortunately for the rest of the world, these experiences have been well documented by Volcy and his colleagues. In 1976, Bureau Veritas put together a special publication entitled, "Machinery Hull Interaction-Vibrations," which is a re-publication of nine significant papers by members of the Bureau which adequately portray their efforts over a 20-year period (504). The following discussions will attempt to summarize these past efforts of the Bureau and outline their current investigations.

First, reasons for increased vibration problems should be discussed. Due to changes in world economy and the influence of political events, such as the closing of the Suez Canal, there has been a shift of emphasis in commercial shipbuilding towards vessels which are much bigger and faster, such as the giant tankers called VLCC and ULCC. In addition, modern high-speed computers and analytical methods, such as the finite element method (F.E.M.), have allowed shipbuilders to construct much lighter structures with fewer scantlings. This has caused a significant increase in the flexibility of hull structures. To make matters worse, on these more flexible structures more and more powerful propulsive plants with shorter, stiffer shafts have been installed. This incompatability between the flexibility of the steel work and the stiffness of the line-shafting led to many vibration-related problems. Among the problems were failures of stern tubes, fractures in the hull structure, failures of propulsion shaft bearings, failure of crankshafts and/or their bearings, and damage to the main reduction gears.

The detective work done in determining the root causes of the failures is a story in itself. Old construction practices and many pet theories have been done away with, but not without considerable resistance to "new" explanations. Some of the older simple explanations of phenomena and suggested solution methods have been 180° out of phase with reality.

On the basis of their experience Volcy and his associates have come to the conclusion that the tendency to simplify the treatment of technical phenomena leads to overwhelming costs through the unexpected consequences of failure. The situation with experimentation is, however, exactly the opposite. One of the hallmarks of the Bureau's investigations has been their intelligent use of simple instrumentation. It is surprising how much useful information can be obtained with simple instrumentation, if the investigators are experienced and they have good physical insight into the problem. Too many investigators waste time and money when they strap accelerometers and strain gages all over the place, take great quantities of data and process it with digital computers. An ounce of physical intuition during the selection of instrumentation is worth much more than exotic digital data analysis.

In several basic investigative reports by members of the Bureau, they have studied the forced-vibration of the hull and the static alignment of the propeller shaft (505), the dynamics of elastically-supported propeller shafts (506), the behavior of crankshafts and their bearings (507), and crankshaft alignment (508).

In (505) Volcy discusses early experimental and theoretical efforts at understanding failures in shaft stern tubes. Even in 1967, it was becoming clear that the increased stiffness and weight of the shaft, coupled with the increased flexibility of the ship structure, made alignment very critical for proper dynamic performance. If an analysis is made of the shaft-propeller system as a simply-supported beam, then it becomes clear that under static forces the shaft sags and bows in some form; it doesn't lie in a straight line, but it aligns itself some other way. With older more flexible shafts one could try to force the shaft to lie in a straight line without causing any serious vibration problems. The newer shafts are much stiffer; much more thought must go into an alignment procedure. Volcy determined that it was possible to come up with a rational method for alignment of the shaft which allows the shaft to assume a more natural shape. This would necessitate, for instance, the boring of a lignum vitae stern tube liner on a specified sloping axis. In (505) Volcy describes a practical method for shaft alignment which takes into account all of the above factors. Also discussed in (505) are the vibrations caused by hydrodynamic effects on the propeller. It makes a difference whether you have an even or an odd number of blades on the propeller. However, depending on the flow conditions, closeness of the hull or shape of the blades, it is difficult to choose a particular propeller which will give the overall vibration characteristics desired. In an investigation of the dynamic characteristics of elastically supported tail shafts, Volcy and Osoufi (506) describe the results of an experimental measurement made at sea and of the measurements made using the Bureau Veritas vibration generator. This simple mechanical generator has two counter-rotating adjustable weights, frequency range of 0.5 to 17 Hz, and can put out an oscillating cosine force of up to 12.5 tons. In conjunction with the theoretical investigations, a series of measurements of hydrodynamic excitations were made in a towing tank. The experiments proved to be cumbersome, time-comsuming and relatively expensive. Another problem was the lack of reliable information about the flexibility of the bushing material.

In a report on the behavior of crankshafts and their bearings, Bourceau and Volcy (507) report on investigations carried out on 32 vessels. Among the topics discussed in (507) are deformations of the bed plates, thermal distortions in the engines, loading due to different sea states, and deflections of the crankshafts themselves. The authors point out that flexibility of hulls, double bottoms, bed plates, and supporting structures of propulsive plants is increasing, while the flexibility of the crankshafts is decreasing. So in one sense the crankshaft riding on its bearings in the engine block is affected by externally-caused deformations much like the propulsion shaft is influenced by externally-caused deformations. In another investigation Volcy and Trivouss (508) apply the techniques of rational curved alignment to crankshafts.

One of the recommendations in (508) is that it now seems necessary to revise the criteria of "no sag-no gap" coupling of the crankshaft with the line shafting, the same being valid for the old-fashioned straight-alignment of coupled shafting without sag and gap which the authors have proven is not the optimum configuration for convenient running conditions.

In further works Volcy (509) reports on the damage caused to main gearing due to shafting mis-alignment. Again the techniques of rational alignment are illustrated. The all important techniques for computing the deformations of the hull and ships steelwork, using both simple beam models and the powerful finite element method, are given in (510).

In (511) the topic of forced vibration resonators and free vibration of the hull is considered. In many cases, unexpected forced vibrations are found to be excited by sources which were considered to be insignificant, such as non-rational shaft alignment and whipping of the tail shaft, transverse vibrations of the main engines, longitudinal vibrations of the thrust block, etc. In all these cases, the presence of a resonance between the excitations and the response of the concerned local systems must exist.

In (511) the authors give an exhaustive discussion of ship vibrations and their excitation implications. They feel that for a rational and efficient study of vibratory phenomena the most important question is to understand the physical nature of the problem! With the development of finite element methods many structural dynamics calculations have become easy, which leaves more time for the analyst to wrestle with the understanding of the physical phenomena. It was in this spirit that the paper by Bourceau and Volcy (511) was written, i.e., to give their point of view on the physical side of the various vibratory phenomena they met on ships. In (511), owing to the similarity between the mechanical vibratory phenomena and electrical oscillations, the authors make extensive use of electrical analogies wherever the discussions would be illuminated by so doing. Reference (511) is a monumental work, 41 pages in length, which is the result of the years of experience gained by members of the Bureau.

In (512), Restad, et al apply many of the previously-mentioned techniques to the investigation of the dynamics of an LNG tanker with an overlapping propeller arrangement. It contains excellent discussions of the hydrodynamic propeller excitations and introduces elastodynamic calculations using finite element methods. In later works the members of the Bureau have made extensive use of charts and graphs which display the scaled vibratory motions of selected points on ships. These graphs are very useful in gaining a physical understanding of the vibratory phenomena. A summary of all the current techniques used by the Bureau in performing a chain of static and dynamic calculations on propulsive plants and engine rooms of ships is given by Volcy, et al (513). It is called the CAF system, and it is an assembly of manual or automated tasks which can be inter-connected between themselves, and which are conceived in parallel with several computing programs.

In more recent years these various techniques have been successfully used in the design stage, which is the most efficient way to correct vibration problems, i.e., before they exist.

In (514) one of the main concerns was the fatigue behaviour of the after sections of hull girder and propulsion machinery. The object of the investigation was to determine the life span of structures by employing Minor's fatigue accumulation criteria to stress data measured and recorded with a specially designed electronic system called SEFACO. The system, developed by Bureau Veritas, was installed on the ship BELLAMYA. Its system was designed to provide stress data as a function of environmental conditions and to indicate their effect on the fatigue potential of the structure. These data will serve as feed-back for correlation with and improvement of theoretical prediction methods. At sea vibration measurements of the T/T BATILLUS and T/T BELLAMYA were taken, some using a vibration exciter.

In an investigation of cracks in the steel work of four tankers, Volcy, et al (515) made both experimental and theoretical investigations of the causes and suggested cures. The aim of the experimental work was to determine the major sources of excitation and find those areas of the structure which had maximum response. They found that the propeller forces, hull pressure forces, or unbalanced inertia forces in the engine were not responsible. They did find excessive axial vibrations in the crankshaft and dynamic amplification of the excitation in the engine room. The dynamic analysis was accomplished by using a 3-dimensional finite element model which was run on a CDC 6600 computer in use at Bureau Veritas (the largest in the world available at the time - 1975). Even so, the computer expenses involved were prohibitive and the analysis was limited to one wing of the cargo tank structure.

From their analysis of the mode shapes and frequencies Volcy, et al (515) tried several theoretical structural modifications and re-ran the modal analysis. The results showed little change in frequency. They concluded that, for any steel structure, it is extremely difficult to cause large changes in the spectral band of the natural frequencies in order to shift them away from excitation frequencies. Consequently, the program of structural modification and stiffening which followed involved the elimination of areas of stress concentration, i.e. welding in cuff brackets, substituting round-edge instead of previous square-edge tripping brackets, and, in several other places, putting in larger brackets. The other course was to reduce the level of excitation at the source, i.e. the crankshaft. They were able to achieve a 90% reduction in the axial vibration of the crankshaft by installing a damper on the free end. One of the problems remaining is the determination of the direction and phases of the excitation. Volcy and his colleagues feel that it is within this area that much study remains to be done. For example, in (515) it was quite impossible to define the field of excitation in advance.

A booklet is available (in French) (516) from the Bureau Veritas in which methods for inspection of the vibration limits/levels in ships are given. Also given in (516) are descriptions of excitation mechanisms, responses of the hull and construction methods which will reduce vibrations.

In the single paper on ship shock from France, Aquilina and Gaudriot (517) applied mechanical impedance concepts to the coupling problem of structures in a shock environment.

Space Systems

France has a very active space program. Several papers on spacecraft control problems were presented in a recent meeting of the European Space Agency in 1976 entitled "ESA-Dynamics and Control of Non-rigid Space Vehicles" (518, 519, 520). This was a timely meeting considering the possibility in the near future of placing very large flexible structures in orbit with the United States

Space Shuttle. The individual papers were concerned with the synthesis of flexible spacecraft commands (518), development of a computer program for the Dynamic Analysis of Solar Arrays (DAFSA) (520) and the design of a control loop with inflight identification of the flexible modes (519). Results of the design and test of damping for the ITOS-A satellite has been published (521). Vibration tests have been carried out (522) on the Symphonie type carbon fiber reinforced plastic reflector which is mounted on titanium. These experiments take on increased significance because of the importance of knowing the damping and fatigue properties of composites suitable for space applications.

Humans

In a recent standards meeting (523) experts from ten countries discussed the proposed ISO guide for the evaluation of human whole-body vibration exposure. Although the knowledge of human reaction is inadequate for all cases of vibration exposure, there still exists a demand for regulations to evaluate the vibration exposure of human beings. Ventre, et al (524) have made an objective analysis of the protection offered by active and passive restraint systems. Statistical data, accident surveys, theoretical studies and crash test results were used in the analysis.

Isolation and Reduction Systems

Absorbers

Sound attenuation is usually obtained by means of absorbing materials. However, there are active sound absorption techniques being developed in France which rely on destructive interference of sound waves. Mangiante (525) has proposed a general theory, using Huygens principle, for three dimensional sound wave propagation.

Noise Reduction and Isolation

An interesting development has taken place among practitioners of noise control. There are steps being taken by French regulatory bodies (526) which would require that typewriter manufacturers put informative lables on their machines stating the nose emission properties. This would put consumer pressure on the manufacturers to produce quieter machines.

Daumas and Selva (527) have developed model and numerical techniques for acoustic barrier design. The authors state their methods to be efficient for acoustic barrier design, i.e. precise, easy to program, needing only short computation times. They also say that more realistic geometries and boundary conditions can easily be introduced using their method.

P. Fontanet (528) has made a cost efficiency compromise study of several noise reduction schemes for two production line cars. Fontanet concludes that the results of such cost-efficiency studies argue for the modification of current noise measurement standards.

Machinery Systems

Turbines, Fans, Compressors

Most of the technical efforts on fans and compressors in France are aimed at noise reduction. Helical detuners have been developed which reduce the compressor noise by placing them on the intake duct (529). The helical detuners generate a vortex flow in the intake duct which exerts a favorable effect on acoustic cut-off. Bridelance and Quiziauz (530) have made fundamental investigations of noise sources in air foils which will hopefully be of use in the design of low noise turbofans. Recent progress has been made in reducing the noise from the CFM56 turbofan engine (531).

Tubromachinery

Larguier and DeSievers (532) report on the work at ONERA on the dynamic measurements in turbomachines. Data are presented on surface pressures on moving blades and on the external casing, opposite the rotor, and on determination of the wake by pressure sensor and hot wire anemometry.

Structural Systems

General (Structural)

Cromer and Lalanne (533) have developed an interesting combination of experimental measurements and the finite element method. The dynamic behavior of a complex system was obtained using a substructure technique. Part of a complex structure was modeled using the finite element method. Substructures with properties determined by experiments were then connected to those modeled by finite element techniques. This reduces the large number of degrees-of-freedom in the calculation which would be prohibitive for complex structures.

INDIA

Air Systems

Aircraft

A review of recent trends in aircraft flutter research has been given by Murthy (534). Rao (535) has performed a flutter analysis of multiweb aircraft wing structures using finite element methods. The results of RAo's calculatins using the finite element method compare favorably with these given by other conventional methods.

Ground Systems

Off-Road Vehicles

The problems of flotation and traction encountered by a cross-country vehicle when traveling over rough terrain require that more than two axles be used. To identify the significant parameters Rao, et al (536) studied the response of two- and three-axled vehicles traversing bumps which were shaped as a half-sine and a double sine.

Road Systems

The response of suspension systems to ground roughness is important for both the landing and takeoff dynamics of aircraft and the ride quality of vehicles. Nigam and Yadav (537) have developed methods for calculating the dynamic response of accelerating vehicles to ground roughness. They have illustrated their method by computing the first passage probability of tire bottoming for an aircraft during takeoff. An important quanity to know for the design of advanced braking systems is the coefficient of friction for pneumatic tires on hard pavement. Kant, et al (538) have investigated the effects of tire flexibility and sliding of the wheel on this coefficient of friction. Still, the value of the coefficient remains partly empirical in nature.

Isolation and Reduction Systems

Absorbers

Two dynamic vibration absorber devices have been developed in India. The first is a laboratory model developed by Kulkarni and Singh (539). The second (540) is a viscously damped dynamic absorber mounted at the center of a clamped circular plate. The damper can be tuned to suppress the first or second resonant frequency of the plate.

Noise Isolation and Reduction

A review of exhaust noise and its control has been published by M.L. Munjal (541) of the Indian Institute of Science, Bangalore, in which descriptions are given of recent developments in the field of analysis and design of exhaust mufflers. Only exhaust noise is discussed. In another publication Nunjal (542) gives a new matrix method for the evaluation of the dynamics of a muffler with mean flow.

Isolation Systems

Munjal (543) has developed a set of general design criteria for the synthesis of non-dissipative vibration isolation systems. Using these methods one is able to write down easily the velocity ratio and hence the transmissibility of a linear dynamical system in terms of the constituent parameters. Venkatesan and Krishnan (544) have developed a new shock mount employing dual-phase damping which will reduce the absolute transmissibility over a large frequency range.

Machinery Systems

Metal Working and Forming

M.S. Selvam (545) has developed experimental techniques for measuring the frequency content of tool vibration and the surface profile in turning by measuring the frequency spectra of tool vibration. The predominant frequencies of tool vibration and the surface profile in the circumferential direction were found to be the same.

Reciprocating Machines

M.S. Pasricha and W.D. Carnegie (546) of Vanaras Hindu University, Varanasi, India have investigated the causes of several cases of fractures in the crankshafts of large slow marine engines. The cause of the fracturing has been attributed to a secondary torsional oscillation resonance caused by the variable inertia of each slider-crank mechanism relative to the position of the crank. The effects of variation in inertia on the torsional vibration of the system are examined in detail.

Rotors

A new method for calculating the critical speeds of a general flexible rotor supported by flexible or rigid bearings has been developed by Joshi and Dange (547). The new method takes into account the gyroscopic effect of the rotor and combines distributed parameter and lumped mass techniques.

Structural Systems

Bridges

An analytical method for determining the free vibration frequencies of stiffened curved bridge decks has been developed by Ramakrishnan and Kunukkasseril (548).

Buildings

A new non-dimensional parameter called the "nature parameter" (549) has been developed to assist the seismic engineer in making an approximate determination of the frequency of the fundamental mode and of a few higher modes for buildings. The "nature parameter" relates the fundamental, the highest frequencies and the total number of floors. It indicates the inherent behavior of a building in vibration. The "nature parameter" of four well-known buildings in the world and a number of research frames, including those of U.S. researchers, have been compared with the ideal patterns.

ISRAEL

Air Systems

Aircraft

Several papers on flutter control and gust alleviation using active controls have been published by Nissim, et al (550, 551), of Technion-Israel Institute of Technology. Hadan and Eshel (552) have measured and analyzed the vibrations in external stores of the Phantom F4E. Statistical relationships between the vibration levels and dynamic pressure, Mach number, store structure, etc. were observed and explained.

Machinery Systems

Reciprocating Machines

J.F. Ury has produced several papers on reciprocating engines. In (553) the effects of cylinder block sidewall vibrations on emitted noise are explored. In (554) Ury proposes a novel method for the numerical computation of Fourier coefficients in the range of higher frequencies. An example from the field of Diesel Engine research is given in which the computed spectrum is compared with the spectrum recorded by an electronic harmonic analyzer.

ITALY AND GREECE

Air Systems

Aircraft

The compatability of wing-mounted weapons with the carrying aircraft has been studied in Italy (555). Wind Tunnel tests were conducted on many different configurations to determine which parameters had the most influence on the flutter speed of wings with attached weapons stores. Coupling between wing bending and weapons store pitch was found to induce wing flutter. The factors that tended to reduce the minimum flutter speed were identified from the test results.

Machinery Systems

Materials Handling Systems

Vibration produces many undesireable effects, nevertheless some useful applications of vibration do exist. Vibrating conveyors for bulk materials is one example. A survey of the research on this application was performed in Italy to assess and compare the results of studies that have been undertaken in Italy and in other countries (556).

Reactors

Studies of pipe-whip analysis for nuclear reactors have been carried out in Italy to identify the problem areas. Two of the problems that were discussed included the prediction of input forces and the prediction of breakage locations (557). This study might be useful for pointing out areas where more research is needed. A study of modeling techniques for pipe-whip analysis was also performed to describe both the pipe and restraint system. The pipe is modeled by a series of finite elements with a complex elasto-plastic behavior. The model will be used to predict the response of the pipe and its restraint system to an earthquake (558).

Space Systems

The mechanics of spinning bodies containing fluids and the dynamic characteristics of spheriodal and cylindrical containers were studied. The goal of the study was to determine the effects of the liquid motion on the attitude stability of and on the disturbances that are produced on manuevering spacecraft.

Rotor Systems

Several interesting studies of shaft and rotor dynamics were performed in Italy. Experimental studies were conducted on shafts of two turbogenerators as part of a research program to improve automated surveillance techniques (559). An analysis of large amplitude whirl of a shaft rotating in a lubricated bearing was performed to determine the effect of a certain class of lubricants on the response of the shaft. The results indicated that the analysis would be partly applicable to some more general cases of lubricant response (560). In another study (561) several methods for analyzing the effect of lateral inertia on the calculation of shaft critical speeds were examined. Procedures for extending the validity of some of the methods to this type of analysis were included in this study (561).

JAPAN

Air Systems

Aircraft

Research in Japan on aircraft dynamics has centered on flutter characteristics/suppression and on the prediction of full-scale dynamic response from model tests.

Morita, et al (562) have compared the transonic flutter characteristics of a cantilever sweptback wing (with airfoil section) with the characteristics of a thin cantilever swept-back wing. The tests were conducted in the National Aerospace Laboratories (60 cm X 60 cm) transonic blow-down wind tunnel using models of the swept-back wings.

Hanawa, et al (563) have developed experimental methods for estimating the response of full-scale structures, such as aircraft, by performing vibration and shock measurements on simplified scale models. Their method is based on an analytical method which was shown in the book "Aeroelasticity" written by R.L. Bisplinghoff , et al. (564). Hanawa and his associates use the approximate Rayleigh-Ritz procedure to compute the modes of the structure. Their techniques are useful for predicting vibration characteristics in the early design stages of a structure. They have applied the method to a model with built-up wings and a fuselage (563) and also to plate beam combination structures (565). Although the powerful finite element method is the most common approach for aircraft structural dynamics calculations this method cannot be overlooked.

Sea Systems

Surface Ships

Much work has been done in Japan on reducing noise in ships.

N. Nishiwaki and T. Mori (566) of the Noguchi Institute, Tokyo, has developed experimental techniques for identifying low frequency noise source vibration problems on a ship equipped with a Diesel engine. Nishiwaki and Mori's investigations were aimed at locating the particular excitation source on a ship which was causing windows to rattle in residences when the ship passed through a narrow channel. Measurements were made in the engine room, on the funnel, on the roof of the pilot house, at the bow, and inside and outside of the chief-officers room.

Irie and Takagi (567) have made fundamental studies, both experimental and theoretical, of structure-borne noise in ship structures. New stricter habitibility noise regulations in Japan for ships have caused naval architects to consider noise control in the design stage. Structure-borne noise (SBN), caused by machinery vibration and transmitted through the hull structure, is the major noise problem in the crew accomodation spaces. It is obvious then that it is important to identify the transmission path of SBN energy flow and its attenuation over its path length. The problem is that it is not easy to evaluate the SBN transmission in such complex structures as a ship. Recent advances in Statistical Energy Analysis (SEA) methods (568) have been applied by Irie and Takagi (567) to describe SBN transmission analysis in two large steel structural models. The first model is a 3-dimensional cubical honeycomb model with 148 panels; the second is a 1/10 scale model of the engine room and accommodation spaces of a 36,000 tdw bulk carrier with 337 panels. Using the SEA theory, Irie and Takagi computed the vibration transmission properties of the models and compared them with the experimentally-measured transmission properties of the models. Their report contains numerous discussion of results of the experiment. For instance, in the 1/10 scale ship model it was found that a simple deck-to-deck calculation is applicable for rough estimation of SBN transmission in ship structures. The predictions of SEA compared favorable with measurements.

The main conclusion was that SEA network method is applicable for estimating the SBN transmission in large-scale steel structures and is a useful tool for finding the path of SBN energy flow in structures.

Off-Shore Structures

Recent set-backs in the Japanese ship bu ing industry have forced some Japanese shipyards to try other construction markets. One of the markets investigated is the construction of entire floating factories. Some of these have already been built in Japan and floated to foreign buyers.

Ground Systems

Off-Road Vehicles

Japan produces many agricultural machines such as tractors and combines. Some of the combines are quite small. The operator is exposed and located close to the noise sources. Add this to the fact that Japan 8-hour permissible noise exposure level is 90 db(CA), the same as OSHA's, and one can see why noise reduction in small agricultural machinery is important. Miyazawa and Irie (569) have used acoustic holographic methods for the identification and localization of noise sources in such equipment. They also employed mechanical impedance measurements. The acoustic holographic technique was useful in identifying noise sources. By making holograms before and after different noise reduction schemes are tried out it is possible to evaluate their effectiveness. Mr. Y. Oka of the Nagasaki Technical Institute developed the acoustic holographic technique.

Rail Systems

Recent studies in Japan on railway systems have been about the optimum design of current collectors for high speed railways and the high speed "hunting" and stability of railway vehicles. Dr. Hidehiko Abe of the Japanese National Railways has been concerned recently with drafting standard specifications for the design of structures which protect railways from falling rocks due to earthquakes. There was a bad accident in 1977 in which 30 tons of rock fell from a hilltop onto a train, overturning it. This has caused a renewed interest in protective shelter designs. Some experimental work has been done on the effects of falling rocks on the concrete side walls of these protective shelters. Seismic effects on rail structures have also been studied.

Taro Shimogo and Kazuo Yoshida and others at Keio University have developed new designs for sliding current collectors for high speed railways (570, 571, 572). New high speed railways will reach speeds of up to 500 km/hr and reliable current collectors are needed which are light, wear-resistant, quiet and as free of contact bounce as is possible.

The current collector designs of Shimogo and his colleages were analyzed using the equivalent linearization technique. They have considered the effects of coulomb friction between the contact and rail and the effect of coulomb friction within the power collector.

Several rail research efforts in Japan have been concerned with the "hunting" motion of rail cars. Yokose (573) has investigated "hunting" of high speed railway vehicle truck design. The design was from the Sanyo Shin Kansen transportation system. Fujii, et al (574) have modeled the derailment dynamics of a two-axle railway wagon caused by the lateral "hunting" motion. A digital simulation was used which compared favorably with experimental data. Shimogo, et al (575) have studied the running stability of a train which is constructed of several bogie cars coupled by a spring-dashpot system. The running stability of a train is characterized by the lowest critical speed at which "hunting" motion occurs. Their conclusions were as follows: 1 - in the case of the supporting system of the body without damping, the critical speed of "hunting" motion is almost independent of a coupler stiffness; 2 - in other cases the critical speed increases gradually when the coupler stiffness becomes large; 3 - the critical speed has a minimum value for a certain value of the time constant of coupler damping and in some cases it is desirable that the coupler has no damping.

Road Systems

All of the automobile manufacturers in Japan have made studies of the crashworthiness of their vehicles.

Some researchers have studied vehicle crashworthiness using non-linear finite element methods (576). Wada and Inove (577) studied the crashworthiness of three different body constructions of compacts. The three constructions were the result of choosing three types of suspension systems. Arima, et al (578) have studied the integrity of fuel tanks during rear end collisions which is a topic of current high interest in the United States.

Reactor Systems

Since Japan is earthquake country, the earthquake-resistant design of nuclear reactors has been an important consideration and the Japanese have contributed heavily to this technology. Recent studies have included the bell-ring seismic vibration response of a nuclear containment vessel (579) and an investigation of the possible failure modes of a nuclear plant (580). In (580) Shibata, Akino and Kato took earthquake damage survey information from industrial plants caused by several violent earthquakes since 1960 and applied the information to estimate failure modes in nuclear power plants.

Taketani et al (581) have set up a seismic verification test program using a series of experimental models of Very High Temperature Reactors (VHTR). A VHTR core is composed of tightly-packed hexagonal graphite blocks. The blocks are in layers and columns. In the test series outlined in (581) small portions of the graphite block core had to be tested in sequence starting with a 1-dimensional section (column) and ending with a full 3-dimensional vibration test of the entire reactor. Also proposed are impact fatigue strengths and elasticity of the graphite blocks. Many computer programs are being used to analyze the graphite core dynamics; some are being especially developed; others are just being applied. The names of the computer program are as follows: PRELUDE-1, PRELUDE-2, SONATINE, CRUNCH-1, CRUNCH-II, COSAM-1, COSAM-II, SECA-1, MULTI-SECA, COCO-1, MULTI-COCO-1 and MULTI-COCO. Some of these programs are under develoment by the Japanese Atomic Energy Research Institute, Tokai, Japan. Of primary interest for seismic safety are the response characteristics of the blocks, the side restraint mechanisms and the core bottom support mechanism (the experimental reactor has 2000 blocks and weighs 200 tons).

Space Systems

Japan has made great progress with launch vehicle technology. For advanced communications satellites, they still rely heavily on United States technology. Japan's National Aerospace Laboratory, in Tokyo, has produced many excellent technical reports, most of which are available only in Japanese.

H. Mori (582) has made a system study of the wind-induced bending moments and vibration on a model launch vehicle (SS-3). The results of the study showed the present model configuration is not affected much by turbulence and has a firm structure.

Takemasa Koreki, et al (583, 584) have been performing experimental investigations of an acoustic instability problem in solid rocket motors. The authors became painfully aware of the phenomena when they experienced a longitudinal pressure oscillation in the motor of an S-310 sounding rocket; the rocket was developed for observations in the Antarctic. Previous investigators have proposed instability criteria for pressure oscillations, but few had verified them experimentally.

Human

In Japan several studies have been made of the effects of vibration on a hand-arm system and the subjective response of people to the vibration of the "bullet", a high speed passenger train.

Two excellent papers on the experimental measurement of the effects of vibration on the hand-arm system have been published by Tadayoshi Sakurai (585, 586) of the Dept. of Environmental Health, Kurume, Univ. In the first study several human subjects gripped a handle on a shake table and were exposed to different combinations of vibration amplitudes and frequencies. The response of the forearm muscles (extensor and flexor) were measured with an electromyogram. The forearm muscles were investigated because the electromyogram of the forearm muscles for the patients of vibration diseases (Raynaud's syndrome) frequently show abnormal patterns. The effects of gripping strength, exposure time, vibration amplitude, frequency, handle diameter and room temperature were studied. This was a basic experiment which explored those variables which are thought to be related to the causes of vibration disease, e.g amplitude, exposure time. Results of the electromyogram test showed an increase in the measured low frequency forearm electromyograms when amplitude, grip force, handle diameter or exposure time were increased. One of the benefits of the test may be methods for improving the operating conditions of vibrating hand tools. In a second report Sakurai (586) reports on observing the change in skin temperature of the hand due to vibration. The experiments were conducted much like those of the first paper except this time the skin temperature of the third finger tip of the left hand was observed with a thermister during vibration. During vibration the skin temperature drops. In a healthy person the skin temperature rises rapidly when the vibration source is removed. However, on a patient with vibration disease (Raynaud's syndrome) the dilation of the blood vessels and consequent temperature rise is very slow after removal of the vibration source.

Two immediate applications of this technique come to mind: 1 - It may be possible to use this technique as a screening test to detect vibration disease in workers exposed to high hand vibration or 2 - this technique could be used as a vibration dosimeter. When a worker has accumulated their daily "hand vibration dose" then he/she must stop. For example, the "vibration dosage" in an assembly plant could be defined by instrumenting several workers and recording acceleration and time, etc., while monitoring the workers skin temperatures. Empirical formulas are given for the time-dependance of the skin temperature during both the cooling and recovery process.

Yoshiharu Yonekawa (587) of the National Institute of Industrial Health has evaluated the effects of train vibrations on people near railways. The experiment was carried out on a vibration table using 10 male subjects (volunteers). First, recordings of measured vibrations from a real train pass-by event (from the high speed "bullet") were played back through the shake table. The subject was then told to match the sensation to a second continuous reference vibration (sinusoidal or continuous random). Once the transient train passage vibration was matched then the equivalent continuous vibration levels were used in further experiments to evoke the usual emotional responses such as unpleasant, nervous, etc. Vibration levels were given to the subjects in three levels, 75, 85 and 95 dBVL, which were representative of actual train vibration.

dBVL is the <u>weighted</u> vibration acceleration level and is equal to 20 log A / A (ref) where A <u>is rms vibration</u> acceleration in m/sec^2 and A (ref) is 0.00001 m/sec^2. This <u>weighting</u> circuit possesses the frequency characteristic simulated with the <u>human vibration</u> response in both vertical and horizontal directions which is standardized internationally in ISO-2631. The matching continuous reference signal (20 Hz) was also measured with the value of dBVL. One result noticed in the sensation comparison experiment was that the longer the rest time between sample train vibrations the lower the equal sensation values become.

In a final human paper Yonekawa (588) reports on methods for evaluating the emotional response of humans to one-shot shock pulses. Some method is needed to evaluate human response to single shot shocks in, for instance, those houses with thin floors where people below are "annoyed" by children jumping on the floor above. In this experiment the subject first familiarized himself (only male subjects were used) with the shock of jumping on a hard floor. Instrumentation consisted of an accelerometer in a shoe and one held between the teeth of the subject. The subject then matches the real jumping sensation with shock motions on a shake table at various pulse durations, i.e. 40 ms, 60 ms and 100 ms. These table shocks are in turn matched with a continuous sinusoidal vibration at 10 Hz. The subjects are asked for emotional responses during the shock tests. Results show the "unpleasant" response for shock motions corresponds to 114 dBVL (pulse duration (PD) = 40 ms), 116 dBAL (PD = 60 ms) and 119 dBAL (PD = 100 ms). dBAL = 20 Log A/A (ref); A = rms acceleration (m/s^2) and A (ref) = 10^{-5} m/s^2, in dB. These numbers may possibly be a starting point for a rating system.

Isolation and Reduction Systems

Absorbers

Recent technological advances on absorbers in Japan have been related to dynamic vibration absorbers for machine tools and the analysis of shock absorbers which use plastic deformation.

K. Seto (589) of the National Defense Academy, Japan, has developed a dynamic absorber using eddy current damping instead of oil damping. The absorber markedly improves the cutting performance of machine tools with a long overhung ram, as in vertical lathes and milling machines. It is possible to build such a device because of the availability of high-performance permanent magnets composed of rare-earth cobalt. Ohmata and Fukuda (590) have developed methods for the dynamic analysis of impact attenuation systems which are modeled as rigid-perfectly plastic. The load-displacement curve after initial yield is approximated by a cubic nonlinear curve which is equivalent to a system with a non-linear spring and a slider.

Noise and Isolation and Reduction

Japan has very strict noise and pollution control laws. In 1978, their Environment Agency reduced the accelerated pass-by noise level limts to 86 dB(A) for heavy duty vehicles, instead of the current value of 89 dB(A). This will be the most stringent law in the world as of 1979. These laws have caused intense activity on noise reduction in vehicles.

H. Yamazaki (591) of Nissan Diesel Motor Col, Ltd. has reported on an intensive joint effort to reduce noise in trucks and busses in Japan. Yamazaki considered the joint project to be the most unusual ever to occur in Japan! Four competing companies (Nissan Diesel Motor Co., Mitsubishi Motors Corp., Isuzu Motors, Ltd., Hino Motors, Ltd.) each took individual portions of the basic study. They then exchanged individually-developed techniques and, finally, built experimental vehicles taking full advantage of the disclosed knowledge. The sub-systems studied by each company were as follows:

engine capsule technique - this consists of installing a close-fitting steel shield over the entire engine, a technique originally developed by the AVL, Austria. This is a good noise reduction technique, but causes problems with maintainability and may cause a fire hazard if oil puddles in a cavity in the shield;

noise reduction of a cooling system - this was optimized by varying shroud clearance, fan speed and fan blade design;

exhaust noise reduction - the two major successful noise reduction techniques involved the installation of a resiliant element in the exhaust pipe to isolate engine vibration and to make the edges of the muffler internal structure into a horn shape;

engine noise reduction - this was accomplished by stiffening the cylinder block and changing to turbocharging from an aspirated carburetor system. An unresolved problem is to determine what materials to use for sound absorption in and around engines. The currently available materials are good sound absorbers, but they absorb oil readily creating a potential fire hazard. Actually, Japanese law forbids the use of porous type material like glass-wool in the engine compartment of rear-engined buses. If such a non-porous sound absorbant material could be developed, it would find immediate application to ships which are especially vulnerable to fires, but also need noise reduction. Even with these noise reduction techniques, the engine noise was still the greatest single noise source in all the experimental vehicles, except the one with the encapsulated engine.

Sano, et al (592) have developed experimental and theoretical methods for the analysis of independent rear suspension and body structure to reduce interior noise in a vehicle. Abe and Hagiwara (593) have developed an inexpensive noise reduction device which can be mounted on the side flanges of the final drive. The addition of this device makes the driveline and its vibration non-symmetrical with respect to the final drive. This decreases the vibration level of the hypoid gear itself, and changes the resonant frequency of the driveline.

Fujiwara, et al (594) have developed methods for estimating the noise reduction by a thick barrier. The method is useful for estimating the excess attenuation of a band of noise by the barrier whose thickness is larger than half a wavelength. Mitsuo Ohta and Hirofumi Iwashige (595) have developed a unified theory of sound transmission loss of general double walls. Their method allows for the accurate prediction of transmission loss of sound at random incidence and can be extended to cavities filled with absorbent materials. The solution method involves the use of an equivalent distributed constant circuit to model the response of the double wall and does not depend on the direct solution of the wave equation. In the industrial noise control field, Shimode and Ikawa (596) have developed methods for predicting noise reduction in plant buildings.

Isolation Systems

Most of the recent work on active or passive isolation systems in Japan has been on vehicle suspension systems.

Iwata and Nakano (597) have developed an active vibration isolation device which controls the pressure in the air springs of a vehicle suspension system. The unique feature of the system is that the front part of the vehicle function acts as the sensor for the vibration isolation of the rear half-part. They also provide design criteria for the optimum design of the isolator. Fujiwara and Murotsu (598) have developed methods for the optimum design of vibration isolators for systems subjected to stationary random excitation. In an application of these methods Fujiwara and Murotsu (599) synthesized vibration isolators which optimized riding comfort for systems with white noise excitation and with roadway excitation. An interesting result is that, under the conditions given in the two examples, optimum vibration isolators can only be designed with active elements. They do point out, however, that a good approximation to an optimum system can be set up using passive elements.

Electrical and Control Systems

In Japan, as in several other countries, their have been great advances in the use of control systems. Included under the category of control systems are servomechanisms, relays and active vehicle suspension control. Note, however, that the separation in this report of active dampers and active vibration isolation systems from control systems is somewhat arbitrary since they both contain control elements.

One of the most important electrical servomechanisms is the circuit breaker. The aseismic design of large power distribution circuit breakers is of fundamental importance in Japan. Fujimoto, et al (600) have computed the transient response of a 500 KV circuit breaker with non-linear damping devices. Their analytical approach, which was dictated by the non-linear characteristics of the damper, is somewhat novel. Three basic assumptions were made: 1 - a simplified dynamic model of the circuit breaker was adequate; 2 - the input was taken to be nonstationary Gaussian white noise in the horizontal direction; 3 - the probability density of response of the circuit breaker has a Gaussian distribution. Under these conditions the response of the system is governed by a Fokker-Planck (FP) equation. A solution of the FP equation gives the time evolution of the probability density function of the response. Using all of these analytics, Fujimoto and his associates were able to study the effects of various parameter changes on the dynamic response of the circuit breaker. Shusaku Ogino (601) of Yamagata University has been studying non-linear phenomena in servomechanisms. He has developed an exact solution for the transient response of second order relay servomechanisms. Methods for computing the condition for the system to have a limit cycle and a chart to calculate the period and amplitude of the cycle are given. In later works, Ogino investigated the step response of a second order servo incorporating a piecewise linear hysteresis element (602) and the step response of a second order servo containing saturation with hysteresis (603).

Methods using preview control have been applied to the optimal control of vehicle suspensions (604) and to the vibration reduction of an elastic beam subjected to a moving load (605). Preview control is concerned with those systems in which the future value of an input can be picked up before it makes some effects upon the system. In general, it is expected that control using the future value of input will yield better effects than that of the control using a present value. Sasaki et al (604) developed an optimal preview control system for vehicle suspensions in which the future road profile is sensed with the front half of the vehicle and an active control device is used on the rear suspension to control the rear transmitted force. In another paper Sasaki, et al (605) investigates how to control the vibration of a beam undr a moving load using preview control techniques by placing a sequence of sensors at the upstream position of a movoing load.

Dr. Yoji Okada of Ibaraki University Hitachi, Japan, has developed several different types of damping devices which are either electromagnetic or electrohydraulic. One of the more interesting damping devices which he developed is an electromagnetic servo damper which has self-adaptive control. Other developments on servomechanisms in Japan have been concerned with stability problems in hydraulically-controlled systemd (606) especially numerically-controlled machine tools (607).

Machinery Systems

Mateiral Handling Systems

Vibrating conveyers are used in industry to transport granular materials. Sakaguch (608) has developed an analytical model of the vibrating conveyance of granular materials (rice, gravel, alundum).

Metal Working and Forming

Japan is one of the most advanced countries in the world in the development of machine tools. Since all manufacturing depends on extensive use of machine tools it is in a country's best interests to be a leader in this technology.

Current efforts in Japan have been concerned with the reduction of chatter, increasing allowable cutting speeds, improving the dynamic characteristics of long boring bars and optimizing the overall dynamic characteristics of machine tool systems.

Some of the benefits of this type of research will be longer tool life, longer machine life, reduced material waste, reduced shop time and much improved quality and accuracy. All of this will result in reduced manufacturing costs and better quality control which has long been one of Japan's competitive economic advantages.

Most of the available literature on various aspects of machine tool research in Japan has come from departments of Universities and Colleges in Japan which specialize in machine tool research with a limited amount of information available from the large manufacturers (Kawasaki, Mitsubishi IHI, etc...). (Note: Germany is also very active in machine tool dynamics research).

The most important parameters needed for the analysis of machine tool dynamics are the overall stiffness and damping of the machine. Much of the work on computer-aided design of machine tools has been discussed in Chapter 3 while discussions on damping in machine tools are contained in Chapter 5 (Phenomenology).

Yoshimi Ito of the Department of Mechanical Engineering for Production, Tokyo Institute of Technology has been actively researching the dynamics of machine tool structures for some time.

Ito, et al (609) have discussed the importance of knowing the damping capacity of bolted joints and the influence of bolt joints on the overall stiffness of a machine (609) for CAD studies. Ito also states that the fundamental problem is how to determine the boundary conditions of the joint surfaces between two bodies in contact. It is difficult to solve this problem because the available theory of elasticity is suitable only to analyse an elastic body as a whole and not to-be-assembled elastic bodies. Ito's technique allows for the prediction of the joint stiffness matrix of the bolted joint. Ito, et al (610) have made a related experimental study in which they determined the interface pressure distribution in a bolt-flange assembly.

Studies on chatter have been documented in several publications. Among these are methods for active suppression of chatter by programmed variation of spindle speed (611) and the development of a new anti-chatter boring bar (612).

Moriwaki and Iwata (613) have performed both theoretical and experimental investigations of the stability of a machine tool against self-excited regenerative chatter. Their novel experimental measurements were performed on a structural model. The model dynamics were identified during cutting under stable (non-chattering) conditions by applying a technique of system identification based on time series analysis of the random cutting force variations measured by a specially-designed tool dynamometer. This last development is all the more important because of all the sophisticated electronic digital data analysis equipment available today. Perhaps this machine tool dynamics area is at the proper stage for the application of some of this sophisticated test equipment, especially modal survey equipment.

One study (614) was on the effects of the tangential oscillation of the workpiece during abrasive cut-off operations; this is found to improve grinding performance when relatively wide workpieces are ground. Other researchers have investigated the influence of forced vibrations on the geometrical accuracy of ground surfaces (615) and the effect of transient vibrations on tool life during interrupted cutting (616). In (616) an analog simulation was performed of the tool wear caused in an interrupted cutting system using lumped parameter modeling.

Pumps, Turbines, Fans, Compressors

A limited amount of publications are available in Japan in this area, most of which are concerned with noise reduction.

Ishii, et al (617) have developed a numerical solution of the equations of motion for a small reciprocating compressor. Kosuge, et al (618) have investigated the performance of radial flow turbines under pulsating flow conditions.

Reciprocating Engines

Reciprocating machines are notorious vibration and noise producers and most of the recent developments in Japan have been concerned with noise control in engines and the development of a vibrationless reciprocating engine.

Murayama, et al (619, 620) have investigated combustion noise in engines. In (619) the authors reported on the separation of combustion noise from engine noise. The pressure vibration caused by combustion is damped in the structure and radiates from its surface. The author's technique involves determining the transfer coefficient between the cylinder pressure and the engine noise. With this coefficient and the burning rate curve (pressure variation), it is possible to compute the contribution to the over-all engine noise due solely to combustion. Results show that the transfer coefficient is not influenced by engine speed. In a later paper (620), in which the authors used the results of this method, they proved it is possible to find a combustion process in which engine noise can be decreased without sacrificing performance.

Nakamura (621) reports on the development of a new in-line 4-cylinder low vibration engine which contains a unique balancing system consisting of a rotating counter balance shaft.

Ishida, et al (622) have developed a vibrationless reciprocating engine utilizing an eccentric geared crankshaft rotary device. They have designed, manufactured and tested this small two-cycle vibrationless engine. In a related basic study of the dynamics of a perfectly balanced rotation reciprocation mechanism, Ishida, et al (623) prove it is possible for the specific device considered by them to perfectly balance inertia and torque. In an experimental effort Fugimoto, et al (624) have measured piston slap in reciprocating machinery by placing four minature inductive displacement transducers on the piston skirts. Comparison of calculated and measured movements showed the importance of the oil cushion effect on piston slap.

Rotor Systems

Japan is very active in the area of rotor dynamics. Much work has been done on the dynamics of a rotor passing through a critical speed, the effects of both bearing stiffness and damping on rotor dynamics, and non-linear effects.

T. Iwatsuba (625) has written an excellent review of the vibration of a rotor passing through a critical speed with constant acceleration, and the effects of limited power on the ability of the system to pass through the critical speed. Two other researchers (626, 627) have also studied the effects of limited power on the ability of a rotor to pass through resonance. Other researchers have investigated the effects on rotor dynamics of flexible mounting and damping (628) or the effect on vibration of asymmetric elastic pedestals (629).

Yamamoto and Ishida (630) have discussed the dynamics of a rotating shaft with non-linear spring characteristics.

A rather unique rotor is the elastic seesaw rotor. Kawakami (631) has developed a new method for analyzing the dynamic behavior of a seesaw rotor. The equation of motion generated can be solved using Geesow's method which, previous to Kawakami's report, had been limited to a nonelastic rotor. The equation of motion also includes the Blankenship method for calculation of the load distribution on a seesaw rotor.

Turbomachinery

Destructive transient torsional vibration of the turbine blades, generator shafts, and other components in modern large turbines can be caused by lightening strikes and high speed reclosings. A. Hizume (632) of Utility Power Systems, Mitsubishi Heavy Ind., Ltd. has investigated the effects of these abrupt load changes for both sinusoidal torque fluctuations and stepwise torque fluctuations.

Structural Systems

Bridges

The response of a structure to a moving load has been of fundamental interest to bridge designers for some time.

Kurihara and Shimogo (633) have developed solutions to the basic moving-load-on-a-beam problem. In (633) the vibration of an elastic beam subjected to discrete randomly-spaced loads moving with a uniform speed are given. The assumption is made that the input load sequence is a Poisson process. In other bridge studies, Yamada and Takemiya (634) have investigated the effects of nonlinear foundations upon the random response of a long-span suspension bridge tower.

Komatsu and Kawatani (635) have investigated the dynamic characteristics of cable-stayed girder bridges.

Buildings

The earthquake resistant design of reinforced concrete (R/C) structures is of fundamental importance in Japan. Nonlinear models have been generated (636) for the purposes of simulating the inelastic response of a planar reinforced concrete frame to severe earthquakes. Shibata and Sozen (637) have developed design methods for R/C buildings which take into account the effect of energy dissipation in the non-linear range of response. They have made analytical tests of several multi-story frames designed according to the proposed method. Takizawa and Aoyama (638) have developed a new formulation of the two-dimensional restoring force model of R/C columns acted upon by biaxial bending moments.

NETHERLANDS AND BELGIUM

Air Systems

Aircraft

Many excellent papers were presented in the "AGARD Specialists Meeting on Wing-With-Store Flutter", Netherlands, 1975. The Aerodynamic loads on oscillating wing/store configurations in subsonic flow have been both calculated (639), measured in scale model wind-tunnel tests (640), and have had calculated and experimental values compared (641).

Aircraft flutter investigations continue in the Netherlands. The vibration and flutter behavior of the Standard Cirrus plastic glider has been investigated (642). Stochastic methods have been used to determine modal parameters in the flutter analysis of an aircraft wing and a few non-aircraft structures (643).

Sea Systems

Surface Ships

The normal mode method has been used to calculate the wave-induced vibrations of a ship hull (644). Calculated results for two Great Lakes bulk carrier models are compared with measured results.

Off-Shore Structures

The wave-induced motions and drift forces on a floating drilling rig have been calculated and the results have been compared with experimentally determined values of the model (645).

Ground Systems

Reactor Systems

The use of energy absorbers for the containment of whipping pipes and fragments in a Nuclear reactor accident has been experimentally investigated (646).

Space Systems

The dynamics and control, design verification and flight qualification of satellite and spacecraft continue to be areas of active research. This is especially true in the Netherlands where the efforts are coordinated by the European Space Agency (ESA). They have supported studies on the linear (647, 648, 649) and nonlinear (650) dynamics of satellites. The dynamics of tethered satellites have also been studied (651).

Isolation and Reduction Systems

Noise Isolation and Reduction

A recent work describes Belgium's first attempts at keeping the noise levels in the turbine room of a new power generation plant below the levels recommended in their new occupational noise control regulations (652). Wheel-rail noise reduction by the placement of absorbing material between the rails has been investigated (653). The fundamental noise mechanisms in aircraft have been discussed (654) and an extensive bibliography of the world's literature on pure aerodynamic noise has been prepared (655).

Isolation Systems

Using an analog computer with springs and masses modeled by electrical components, the dynamic characteristics of vibration isolation systems on building floors have been studied (656). Simplified methods suitable for manual computation are presented.

Machinery Systems

Rotor Systems

J.L. Bap (657) has described how vibration sensors can be used for monitoring the condition of rotating machinery.

SWEDEN, NORWAY AND DENMARK

Air Systems

Aircraft

G. Ehn and T. Landen (658) of the Aeronautical Research Institute of Sweden, Stockholm have made measurements of the dynamic stability derivatives of an ogive delta wing model at transonic and supersonic speeds.

Sea Systems

Surface Ships

Ship researchers in Sweden have lately been concerned with the experimental measurement of the vibration level of ship's reciprocating engines for use in structure borne noise studies (659) and the measurement of propeller excitations (660). J. Plunt (659) of Chalmers University of Technology, Goteborg, Sweden displays the results of making structure borne noise measurements on 14 cargo ships. With this and other published data, Plunt has developed a useful set of empirical formulas for predicting the velocity levels of rigidly-mounted main propulsion Diesel Engines and for either rigidly or resiliently-mounted auxiliary Diesel Engines. Plunt feels the empirical formulas will give structure-borne noise analysts better estimations of source levels. Measurements from 50 main engines obtained from a recently started Nordic ship noise project conducted by NORDFORSK were to be used by Plunt to generate corrected formulas in the spring of 1978. A model experiment has been conducted in the cavitation tunnel of the Swedish State Shipbuilding Experimental Tank and the results have been compared with at-sea trials of the full scale container ship M/S NIHON (660). The measurements of full-scale vibration were analyzed and compared with criteria of comfort.

In Norway the recent ship research by Det Norske Veritas has been concerned with structure-borne sound. Other research efforts at Det Norske Veritas have been an investigation of the noise produced by the propeller, the acoustical coupling between the propeller and hull plating, and a general program to develop methods for noise prediction. The results of all of this research should be of direct benefit to shipbuilders, both for commercial and military applications.

In several of their papers on structure-borne sound the members at Det Norske Veritas have progressed over the years through several stages of understanding. In two fundamental theoretical papers Nilsson develops methods for predicting the wave propagation in simple hull frame structures of ships (661) and the attenuation of structure-borne sound in super structures on ships (662). In a series of model tests Nilsson (663) develops methods for the reduction of structure-borne sound by utilizing measurements made on models of simple ship structures. A final report (664) by Nilsson draws together all of the knowledge available on the prediction and prevention of structure-borne sound on merchant ships.

From Denmark we have a four-part review of analytical and numerical tools used to calculate ship hull vibrations by J.J. Jensen and N.F. Madsen of the Technical University of Denmark, Lyngby. Mathematical models are described in Part I (665). The second part on modeling of physical phenomena contains descriptions of mathematical models of the hull (666). Numerical determination of the equations of motion is discussed in the third part -- methods of solution (667). The fourth part (668), comparison of beam models, is a review of methods used to solve the equations of motion.

Ground Systems

Road Systems

Magnusson and Arnberg (669) have developed experimental techniques for measuring road roughness and its relation to rider comfort.

Reactor Systems

In investigating nuclear reactor safety one of the common calculations made is the determination of the response of the spherical containment structure to an impacting aircraft.

Lundsager and Krenk (670) of the Danish Atomic Energy Commission, Riscoe, Denmark have calculated the response of a cylindrical/spherical shell to the impact of a Boeing 720. Calculations were performed using the FINEL, SAP and STARDYNE codes.

Humans

In a paper designed to improve the understanding of the human reception of sounds, Osmundsen and Gjaevenes (671) have measured the diffraction of short duration impulsive sound waves by an artificial head.

Isolation and Reduction Systems

Noise Isolation and Reduction

Two papers, one from Sweden and one from Norway, are related to noise control. R. Friberg (672) of Rockwood AB, Skovde, Sweden has published simplified formulas and methods for the production of the noise reduction in industrial halls cause by the application of acoustic treatments. From Norway (673) comes the results of experiments on the use of aerodynamically shaped elements as narrow band sound reflections in a duct.

Machinery Systems

Mechanical Systems

Many excellent papers were presented at the INTER-NOISE-78 meeting (San Francisco, May 1978) which were concerned with noise reduction in machinery. Among the specific machinery discussed were big shuttle looms (674) and newspaper printing presses (675). In a general paper on noise radiation and machine design, M. White (676) discusses the use of double-skin integral panels to reduce noise.

Rotor Systems

J.W. Lund of the Technical University of Denmark, Lyngby is a world authority on rotor dynamics. In two recent works Lund has developed methods for computing the linear transient response of a flexible rotor supported in gas lubricated bearings (677) and a rotor balancing method which uses the free shaft modes of the rotor (678). In Sweden, L. Larsson (679) has developed a method for determining the influence coefficients in rotor balancing using linear regression analysis.

SWITZERLAND

Ground Systems

Rotors

Methods for rupture analysis under extreme dynamic loading conditions have been developed for the analysis of reinforced and prestressed concrete structures (680). Applications are to Nuclear power plants.

The impact of an airplane on a spherical reactor building dome has been studied (681).

Turbomachinery

Sulzer Brothers, Ltd., Winterthur, have developed a special gas turbine test rotor which is for the measurement of compressor blade vibrations and turbine rotor temperatures (682).

WEST GERMANY

Air Systems

Aircraft

Noise reduction of aircraft is a major and continuing concern in West Germany. A report from the European Space Agency discussed the major sources of aircraft engine noise, human reaction to aircraft noise and wind and tail screening effects on aircraft noise (683). A survey of the technical problems of quiet aircraft technology was performed in West Germany. It included a low-noise vertical take-off procedure, the use of bypass fans with subsonic tip speeds, and the use of the quieter atmospheric ion engines (684). Most of the aircraft noise reduction studies concern jet aircraft, however, in Germany, two investigations of propeller aircraft noise were performed. One of the studies was a survey of noise sources and mechanisms of noise generation of propeller driven aircraft (685). The other study concerned noise reduction measures such as shortening the propeller, control of tip radius and profile and the use of large low speed propellers (686). Propeller-driven aircraft are quieter than jet aircraft, hence the impetus for quieting them lies in reasons other than noise emission criteria. However, small propeller-driven aircraft are often used for surveillance or spotting missions by the armed forces where stealth or lack of detectability is essential. Therefore, the previously mentioned techniques for silencing propeller-driven aircraft might be useful in reducing the detectability of aircraft that are used for these missions.

Acoustic screening is a noise reduction technique that relied on sound diffracting around a barrier. Three studies were performed to develop and verify techniques for predicting the ability of the wing, tail or airframe to reduce aircraft flyover noise by shielding (687, 688, 689). Here again the results may be of some use in reducing the detectability of surveillance or spotter aircraft.

Noise level measurements were made in the cockpits and cabins of four different aircraft, for flight phases ranging from taxi to cruise (690).

An experimental study was performed to determine the noise that is radiated due to air flow over various landing gear/wheel well configurations during landing (691).

The sonic boom produced by aircraft in supersonic flight is well known. A study of the state-of-the-art of sonic boom reduction through aerodynamic design of aircraft was undertaken in West Germany. The shortcomings of current design methods were outlined and suggestions were made for their improvement (692).

An experimental study showed that broadband jet noise could be amplified by pure tone excitation. The study also pointed out that the amplification occurs at sound pressure levels that are present in real aircraft engines. An attenuator was developed to significantly reduce the amplified jet noise (693).

Several studies of aircraft flutter have been performed in West Germany. Two of the studies related to the use of active systems to control flutter (694, 695). A third flutter study considered the problem of wing-store flutter on variable swept-wing aircraft (696).

Dynamic stability and control of aircraft is another important research area in West Germany. One study considered the influence of velocity dependent pitching moments on the longitudinal stability of aircraft (697). Two studies concerned control configured vehicles (CCV). One study assessed the control technology problems associated with such vehicles (698) while the other study concerned artificial stabilization of flight vehicles (699).

Ground and flight vibration tests are carried out on aircraft to determine their natural frequencies and normal modes; the results of these studies are used in flutter analyses and they are also used to determine control system performance and aircraft flight handling qualities. Two studies were reported. One ground vibration test contained results which displayed the nonlinear behavior of an aircraft (700). Another study concerned the status of testing for aircraft system identification (701).

Several studies have been performed on aircraft wings in West Germany. A structural strength model of a wing was developed to predict damage due to explosions of ammunition and the impact of fragments (702). Two studies of unsteady aerodynamic pressures acting on oscillating wings were performed in West Germany. One study concerned a numerical method for calculating the pressure distribution due to incompressible flow (703). In the other study, unsteady pressure measurements were made on an oscillating wing-body combination and the experimental results were compared with predicted results (704). A wing vibration model was constructed to investigate the vibration of a variable sweep wing and its pivot drive. The model contains provisions for the inclusion of the effects of clearance, the static friction, and velocity (705).

Helicopters

West Germany, like everybody else, is trying to reduce the noise in helicopters.

A study was undertaken to identify the sources of noise in helicopters and to survey the possibilities for their reduction (706).

Sea Systems

Ships

An analysis of the vulnerability of a shipboard nuclear reactor to the impact of an aircraft on the collision barrier on the side of the ship was undertaken in West Germany. This study was performed as a part of a general safety analysis of shipboard nuclear reactors (707).

Ground Systems

Rail Systems

Interest in rail systems activity in West Germany can be divided into the dynamics of vehicles on guideways, magnetically levitated or "maglev" vehicles, and conventional wheel-on-rail systems.

Magnetically levitated vehicles have been proposed as a means of high speed long distance transport. In specifying the system dynamics of magnetically levitated vehicles it is necessary to couple the vehicle dynamics, the suspension control and the guideway dynamics into a multivariable dynamical system. Two studies of the overall dynamics of magnetically levitated vehicles on flexible guideways have been performed; the response of the vehicle to both stochastic and deterministic disturbance was determined (708, 709). In addition, a general purpose digital computer program was developed for simulating the dynamics of multibody vehicles moving over elastic guideways. The program automatically constructs the linearized state equations of motion for the vehicle and it combines these equations with those for the active subsystem to form the vehicle system equations. The vehicle system equations are combined with the modal equations of the elastic guideways and the coupled equations are solved by numerical integration (710).

The dynamics of two interconnected multibody systems were studied in which the controlability and the stability of the composite system were determined by examining the characteristics of the lower order subsystems. The results were applied to the stability analysis of a magnetically levitated vehicle on an elevated guideway (711). Studies of control system performance for magnetically levitated vehicles on guideways were also performed (712, 713, 714).

The analog computer has been used in West Germany to simulate impacts between conventional railroad cars during switching. The masses, relative velocities between the cars and the dynamics of the draft gear can be simulated to determine the responses of the colliding cars (715).

A study of the effect of wind gusts on high speed trains was performed. Peak gust speeds and gust factors were obtained from meteorological data for a typical high speed train route, and this allowed the relationship between train speed, gust speed and yaw angle to be determined for use in model tests that were conducted in a water towing tank (716).

Trains are usually modeled as moving loads on elevated guideways or bridges and, under the proper conditions, excite resonance in these types of structures. Since the amplitude of vibration increases with time and train length, a study was performed to find a method for predicting the length of train where the vibration reaches a critical or dangerous level (717). The noise prouduced by the passage of trains is also a serious concern in Germany. Measurements of the noise produced by passing trains have been made in West Germany to determine if they are in compliance with noise requirements (718) as well as the factors that affect the peak levels and frequency spectrum (719). Based on the work that has been reported here it is the feeling in Germany that the technologies associated with rail systems need further investigation. This is particularly true for high speed magnetically levitated vehicles. Many of the studies that pertain to conventional rail systems might be useful for United States conventional rail systems. This is particularly true of the effects of train length on the vibration of bridges because of the tendency of many United States railroads to running of long heavily-loaded trains.

Road Systems

The crashworthiness of vehicles is another area in which West Germany has been doing some work. Studies of the characteristics of occupant protection systems such as air bags (720) and seat belts have been performed (721). One of the studies concerned a recently developed digital computer program for simulating and optimizing the dynamic behavior of seat belts (722). Seat movement relative to the passenger compartment was explored as another method for occupant protection in the event of a frontal impact (723). The mechanical properties of a motor vehicle were studied to find methods for absorbing the crash energy and thus protecting its occupants in the event of a collision (724). The use of rigid and deformable moving crash barriers has also been explored as means of preventing vehicles from colliding with hazardous obstacles (725).

Many vehicle noise reduction studies have been performed in Germany. The sound isolation capabilities of various materials and their application to vehicle body and engine noise reduction was explored in one of the studies (726). Techniques for noise reduction during vehicle development and production were examined in another study (727, 728). In another study, the noise sources in large trucks were identified and practical testing methods were developed so that the contribution of each source to the total vehicle noise could be determined (729). A study was undertaken to find a method independent of the surrounding noise. The noise measurements would reveal whether a vehicle was noisy because of natural wear, tampering with parts or a defective acoustic condition such as a hole in the muffler (730). Open field rolling noise tests on vehicles were performed and the results were used to determine the relationship between noise level, vehicle speed, tire type, tire size and tire material (731).

The dynamic behavior of tires has been explored in Germany. One study was performed to determine the transient lateral frequency response of tires (732) and the other study dealt with the friction relation of tires (733).

The dynamic behavior of vehicles is also of interest in Germany. One study was performed to develop and validate a mathematical model that could be used to predict the dynamic directional behavior of tractor semi-trailer vehicles (734). The stability of motion of a vehicle with its axles suspended in the lateral direction was also studied (735).

Reactor Systems

Nuclear reactor technology is a highly developed area of technology in Germany and many studies have been performed.

The structural integrity of nuclear reactor containment structures is an area of considerable interest. The use of reliability based design techniques for reactor safety containments was the subject of one study (736). Methods for performing dynamic ultimate load calculations for reinforced concrete plates and beams were developed. The calculations include rotationsl inertia and shear deformation effects of concrete beams. Time-dependent bending and shear laws for reinforced concrete are also used (737). The dynamic loads on the pressure suppression containment due to pressure fluctuations induced during blowdown were measured. Two series of containment response experiments were performed on real pressure suppression systems (738).

Nuclear reactors and their associated equipment must be protected from many external hazards such as earthquakes. The problems in the aseismic design of a turbine foundation were considered in one study (739). Another study reviewed methods for predicting the maximum seismic loads on nuclear power plant structures and components (740). Chemical explosions pose another potential hazard to nuclear reactor power plants. Methods for plant protection that include both design techniques and explosive storage and handling practices were discussed in a recent paper (741).

The impact of an aircraft with a power plant poses another potential hazard for the power plant and its equipment. Nuclear power plants in Germany are required to be designed against aircraft crashes. A study was undertaken to compare aircraft crash loads against earthquake loads as well as to suggest suitable floor design spectra as inputs for the analysis of equipment (742).

An experimental investigation was undertaken to verify the structural model that was used to analyze the nonlinear dynamics of liquid metal fast breeder reactor fuel elements. A special model of the fuel element was developed that was characterized by point masses connected by elasto-plastic beams or nonlinear springs (743). Experimental studies on nuclear reactors have also been undertaken to determine what parameters should be monitored as well as developing monitoring techniques to yield significant diagnostic information (744, 745).

Space Systems

Modal analyses of spacecraft is an important area of interest in Germany. In one study a modal survey was performed on a spacecraft and the results were used to predict its dynamic response to launch loads. The effects of nonlinear damping were considered in the same study (746). The concept of the dynamic qualification of spacecraft based on measured modal characteristics was explored. Special emphasis was placed on modal coupling and dynamic response analysis on the basis of modal data (747). The modal synthesis approach has also been used in Germany for the dynamic analysis of spacecraft (748).

Interest exists in the dynamic behavior of large orbiting flexible space structures. One study was performed to find methods for deriving the equations of motion for elastic structures with coupled rigid bodies (749). In one effort, a special 3-axis controlled gimbal system was developed for precise pointing and stabilization of spacelab experiments. A special feature of this system is the flexible suspension that reduces the sensitivity of the gimbal configuration to crew motion and Shuttle Orbiter jet firing (750).

A study was undertaken to demonstrate the attitude stability of a German satellite in a geostationary transfer orbit (751).

Humans

The activity in human response to shock, vibration and noise is extensive in Germany. A study was performed to determine the effect of noise on human productivity; it considered the human experience of noise and the factors that influence the noise experience (752).

The effects of vibration on human beings and animals have also been studied in Germany. In one study the combined effects of vibration and a deficiency of oxygen produced a significant increase in the mortaltiy rate of rats (753). Two studies of the effects of vibration on human beings were performed. One study was carried out to compare calculated and simulated transient vibrations in underground personnel shelters subjected to nuclear blasts to safety limits for humans (754). The other study was undertaken to determine the effects of vibration on the visual acuity and the tendon reflexes of humans during atmospheric reentry (755). A study was carried out to determine the effects of vibration on passengers in a drive simulator (756).

Modeling the dynamic characteristics of the human body is a continuing effort in Germany. A study was undertaken to reduce the noise and vibration levels in a drill hammer. A physical model of the hand-arm system was developed to aid in assessing the degree of improvement (757). Dynamic analysis techniques that were used for machinery were used to investigate the mechanical properties of skulls (758). Another study was conducted to review the bio-mechanical models that can be used in evaluating human vibration stress (759).

Collision tolerance studies have also been carried out in Germany. One study concerned the use of an analog computer for calculation of the Head Injury Criterion (760). Another study was performed to determine the influence of neck flexibility of a dummy when calculating the Head Injury Criterion (761).

Isolation and Reduction Systems

Noise Isolation and Reduction

In Germany, many studies have been performed to develop quieter systems during the design stage or to reduce the noise emitted by existing systems.

General technqiues for designing quiet machinery have been developed in Germany (762, 763). Also a study of the causes of noise in machine tools was performed and techniques for building quieter tools have been published (764).

Reduction of noise by using single and double acoustical barriers has been investigated (765). The same study included the influence of different barrier shapes. The noise radiated from a power plant chimney was investigated to determine sources and develop methods for its reduction (766).

Noise reduction of engines has been investigated in Germany. In one case noise reduction studies were carried out as a part of the design of a Diesel engine (767). In the other case an existing aircraft engine was quieted by a sound attenuator that was a combined resonator with absorption (768).

Isolation Systems

Studies of active isolation have been performed. The design concepts for a fully active helicopter vibration isolation system were explored. Concepts taken from the theory of output vector feedback were used to develop the controller for the system (769). The active damping of vertical vibrations of a motor vehicle was also investigated (770). The characteristics of an electromagnetic bearing were studied for use in the design of an active vibration controller of a rotor (771).

Machinery Systems

Mechanical Systems

A calculation technique, based on the Fourier transforms of measured signals, was developed to determine the dynamic characteristics of a multidegree of freedom linear system (772).

Metal Working and Forming

Interest in the stability of the machining process and the dynamic behavior of machine tools exists in Germany.

Chatter during a machining operation is a self-excited vibration that exists between the tool and the work. It causes shortened tool life and poor surface quality of the work. Two studies dealing with chatter have been published. One study concerns a method of overcoming chatter by periodically varying the rotational speed of the work piece (773). The other study concerns the development of a mathematical model of a cutting process that can be used to predict the onset of chatter (774).

During our search for information we contacted the Laboratorium fur Werkzeugmaschinen und Betriebslehre der Rheinisch in Aachen, Germany. In reply they sent a list of their fields of research. Studies of the dynamic of machine tools are carried out in Lehrstuhl fur Werkzumaschinen (Institute for Machine Tools).

Machine investigation and assessment concerns experimental studies of the dynamic behavior of machine tools (775). Studies of the static and dynamic stiffness of machine elements and various types of machine tools have been carried out both under idling and operating conditions. Experimental and theoretical investigations of the damping of the contact areas such as joints, guideways and bearings have also been carried out. The vibration mode shapes and natural frequencies of machine tool structures are studied as a part of machine investigation and assessment. The application of auxiliary mass dampers to cutting tools has been investigated as a means for reducing chatter. An investigation of dynamic behavior of many types of machine tools has been carried out to develop evaluation criteria measurement standards and quality standards. The dynamics of the cutting process has been investigated to determine the cutting force coefficients and the cutting force. These studies are also carried out to collect data that can be used to prepare stability charts.

The noise behavior of machine tools has been investigated both in the laboratory and in operation. The noise behavior studies also include an analysis of the sources of noise, the determination of noise transmission paths, and practical methods for noise reduction. The noise behavior studies are also being performed to establish the rationale for noise measurement standards and what factors influence the measured results.

Many analytical studies of the dynamic behavior of machine tools have been carried out in the Institute for Machine Tools (776).

Digital computer software was developed to determine static and dynamic machine tool characteristics such as deformations and stresses, noise transmission properties and noise emission properties. Software has also been developed for calculating the dynamic behavior of shaft-bearing systems. A program library is being prepared and some programs will be adapted for use on desk calculators. Software is also being developed for processing machine tool acceptance test data as well as data structures for calculation programs. This includes the recording of component geometries from drawings and the generation of finite element models.

Control systems for machine tools are also being developed (777). This includes the use of mini-computers and microprocessors. It also includes the development of system monitoring software as well as systems for automatically controlling the machining operation and avoiding machine tool chatter.

Fans

Studies on the determination of fan noise include the development of a guideline for determining the acoustic power of fans (778). An investigation was undertaken to determine the noise produced by centrifugal fans. The noise output was divided into a harmonic part and a random part (779).

Studies have been carried out to determine the influences of various factors on the noise produced by centrifugal fans. One study concerned the influence of the viscosity of the working fluid (780). In another the effects of the fan casing (781) were studied.

Many noise reduction studies have been performed on fans. One study summarized the research work that was undertaken to reduce both the harmonic and the broadband components of fan noise by modifying the fan (782). The use of an acoustically-lined casing for reducing fan noise is another example of modifying a fan to reduce noise (783). Quieter cooling fans are being developed for air cooled internal combustion engines (784).

Reciprocating Engines

Studies have been made of how to reduce the noise in reciprocating engines. Three studies of the noise caused by pistons in internal combustion engines have been performed. Suggestions for reducing the noise (785, 786, 787) were provided.

A study of the contribution of an air filter to the reduction of internal combustion engine noise has been undertaken. The study showed that constructing the air filter as a helmholtz reonator reduced air intake noise with a slight penalty on performance (788). Structure-borne noise studies were performed on a Diesel Engine to determine the noise transmission from the combustion chamber to the outer walls and the effect of different crankcase materials (789).

Vibration studies have been performed on internal combustion engines. One study was undertaken to determine the stresses produced in the crankshaft of a four cylinder engine due to large flywheel deflections (790). A method was developed for predicting the vibration modes caused by the free forces of a freely vibrating rigid reciprocating engine. A procedure was also developed for measuring the vibration modes of an engine which is not dynamically rigid. By comparing the two modes it is possible to determine to what degree engine vibrations exceed their predicted minimum (791). A photoelastic analysis of shock sequences was performed on valves of an internal combustion engine following a shock strain. The results were compared with strain gage measurements (792).

Rotor Systems

Studies of rotor dynamics is a major interest in Germany and many studies have been performed.

The stability analysis of rotors is a branch of the rotor dynamics technology where many studies have been performed. A general method for the stability analysis of rotating shafts was developed. A continuous rotor, with any number of discontinuities and subject to linear and nonlinear forces, was modeled (793). Another study examined the interaction between normal modes during self-excited rotor vibration (794). Turbine rotor instabilities can be excited by steam forces, bearing oil whip or unsymmetrical steam admission. These causes of instability have been studied in tests on scale model turbines and full-scale operating turbines (795). Internal linear damping has a well known destabilizing effect on rotating shafts. However the effects of nonlinear internal damping forces on rotating shafts are not known. A study of the effects of nonlinear damping forces and nonlinear restoring forces on the stability of rotating vertical and horizontal shafts was carried out (796). Two studies of the stability of a Laval shaft were undertaken. The gyroscopic effect of the rotor mass on the limiting speed for the onset of self excited bending vibrations was the subject of one study (797). The other study concerned the stability of a Laval shaft excited by a random speed variation (798).

The balancing of flexible rotors is an active area of study in West Germany. One study was undertaken to provide practical guidelines for the selection and application of flexible rotor balancing techniques (799). A systematic procedure for balancing flexible rotors, based on a combination of experiments and data processing was developed. The method yields balancing weights that reduce the amplitude of vibration in the explored speed range (800).

Vibrations of flexible rotors in bearings are an important part of the rotor systems technology. One of the studies led to the understanding of the vibration of an electrical generator by considering similar geometric and dynamic conditions on a model with various types of bearings (801). The vibrations of large turbo rotors in fluid-film bearings which rest on elastic foundations were studied. Factors such as internal and external damping forces, gyroscopic forces and fluid-film forces were considered (802). The dynamic behavior of a rotor consisting of a disc on a flexible shaft with a cross-sectional crack was analyzed (803).

In Germany, as in many other countries, interest exists in simplified prediction techniques. A study was made of simplified vibration analysis techniques for a machine shaft resting on a block foundation (804).

Turbomachinery

In Germany interest in vibration of turbomachinery is in the areas of measurement and shaft stability. There is interest in monitoring the vibration of turbines to detect dangerous operating conditions as well as the condition of the machine (805).

In another study, linearized differential equations were developed to calculate vibration amplitude variations inside the casing or bearings. Measurements of the gap between bearing block and casing are used as input parameters for this method (806).

Studies of the stability of turbomachinery have been performed. Self-excited vibrations of turbomachinery can be caused by steam leakage flow between the rotor and the casing. A method for calculating these forces was developed and the predicted results compared favorably with test measurements (807). Another study concerned the stability of operating points of self-controlled turbomachinery. Simple conditions were developed which made it possible to determine the stability of the operating points of self-controlled running turbines from graphs of the characteristics of the turbomachine and the plant (808).

Structural Systems

Buildings

Shock and vibration studies of buildings have been performed in Germany. Two computer programs were developed to determine the loading of both closed rectangular frame buildings and open-frame buildings produced by the shock waves of a nuclear explosion (809). Impact tests of floors have also been conducted in Germany. The problems of testing associated with shaker impedance, elastic layer mounting and nonlinear material mounting have been reviewed (810).

General (Structural)

Interest exists in general analytical or experimental structural analysis techniques in Germany. An analytical approximation for the response of a beam on multiple supports to moving loads is an example of the former (811). An orthogonality method for determining the dynamic parameters of an elastic body from its resonance test is an example of the latter (812).

EGYPT

Space System

Egypt will be using the U.S. Space Shuttle for some of its space research.

President Anwar Sadat of Egypt has reserved space for four "getaway special" space shuttle payloads that will be launched into orbit carrying Egyptian designed experiments. These launches will be at the rate of one payload per year for the first four years of the shuttle flight program. Getaway specials are small, self-contained space shuttle payloads that will be fitted around other larger payloads in the shuttle cargo bay (813).

Machinery Systems

Rotor Systems

I. Fawzy and R.E.D. Bishop (814) have developed methods for analyzing non-ideal rotor-bearing systems, i.e., when it is not housed in free, pinned, clamped, or sliding bearings. Using Fawzy and Bishop's method no simplifying assumptions must be made to deal with the "non-ideal" system such as would have to be made when using a linear modal analysis of the rotor-bearing system.

Metal Working and Forming

Research is being done in Egypt on the dynamics of machine tools, especially at Ein-Shams University, Cairo. M.M. Migm, et al (815) have developed a theoretical model of the dynamic cutting process. They have also compared the results with experimental data taken with high speed photography. S.M. Said, also of Ein-Shams University, has developed methods for the optimum design of milling machines with respect to structural stability (816).

IRAN

Ground Systems

Vibration and noise reduction in tractors is an active research area in Iran. A. Owzar (817) has made measurements of the vibration characteristics of tractors in order to evaluate the effect of vibration on drivers. Hakimi and Kachru (818) have evaluated six different noise/vibration isolating mounts to determine their effectiveness in reducing the noise experienced by an operator.

TURKEY

Structural Systems

Buildings

Research is active in Turkey on the earthquake resistant design of buildings.

Damanogly and Severn of Karadeniz Technical University have investigated the extent to which foundation properties influence the response of framed structures to earthquakes (819). The authors attack the problem in three stages. First, the theoretical model is validated by model studies. Secondly, a proven computer program is used in a parametric study to obtain a large number of results. Thirdly, the dynamic response is considered. A shaker table was built on which the models were subjected to a number of actual earthquake records, which had been suitably scaled and recorded on magnetic tape. Aktan, et al (820) have developed methods for calculating the response of spirally reinforced concrete (R/C) columns carrying a concentrated mass. Finite element techniques were used with dynamic input earthquake accelerograms from the 1940 El Centro, the 1962 Taft and the 1971 Pacoima Dam earthquakes.

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Chapter 9

INTERNATIONAL TECHNOLOGY TRENDS

INTRODUCTION

Earlier in this report (Chapters 2 through 8) a broad look has been taken at different segments of the shock and vibration technology. Scientific and engineering activities related to shock and vibration have been examined in the United States and a number of other countries, principally by a study of the available open literature. The references cited in each of the seven preceeding chapters were selected for one of several reasons. Primarily, the citations indicate accomplishments significant enough to justify acceptance by the world scientific community. Acceptance, in this case, does not mean that all experts agree with the findings, but only that the implicit rules of quality in various technical publications have been met. The references are also clear indicators of interest or national needs. Some research studies are driven by individual academic interests, but most are motivated by requirements to satisfy national priorities in such areas as defense, industrialization, space research, and citizen comfort. Of course, both within a given country and between different countries certain developments arise from competition, the insatiable urge to be first.

It should be emphasized that the investigations cited are only indicators, hopefully reflecting the current trends. In such a broad context it would be foolhardy to attempt an objective assessment of the impact of a given work on technological advancement. The reader, as an expert in a given area, may wish to make such a judgment. That is his privilege. The main purpose of this report is to summarize what is happening in our field and to identify some of the people that are making it happen. Again, as in the PREFACE, the authors extend apologies to those that are not mentioned.

The seven major subject areas covered in this report are listed in Table I, which is a purely subjective summary of international activities related to shock and vibration. Each of twenty one countries are given an A, B or C when in the opinion of the authors, noteworthy accomplishments have been made, progress is indicated or significant interest is demonstrated in a specific subject area. It is expected that many readers will disagree with the assessments in Table I. It is equally expected that, if there were an opportunity for comparison, the readers would often disagree with one another. The letters A, B and C are not, as in the classroom, indicators or comparative levels of excellence, nor should they be viewed in that light.

In the rest of this chapter a difficult task is undertaken. Each of the major subject areas, and the sub-topics within those areas, will be discussed again. This time the objective is to summarize and to describe general trends. Several countries will then be discussed in a similar light, but with more emphasis on specific accomplishments. This implies a comparison of capabilities, and indeed it is. More than that, however, it is a comparison of interests.

Table I: Summary of International Shock and Vibration Technology

Explanation of Symbols

A - Major Accomplishments
B - Current Progress
C - Demonstrated Interest

	Subject	United States	Australia	New Zealand	U. Kingdom	Canada	France	India	Israel	Italy	Greece	Japan	Netherlands	Belgium	Sweden	Norway	Denmark	Switzerland	W. Germany	Egypt	Iran	Turkey
ANALYSIS & DESIGN	Analogs & Analog Computation	C					B					A	C	C			C		B			
	Analytical Methods	A	B		A	A	C	A	B		C	B	A	C		C	B		B			
	Nonlinear Analysis	A			A	A	C	B	B	A		B	B			C		C	B			
	Numerical Methods	A			B	B	A	B	B			B	A	B		C	B		A			
	Statistical Methods	A			A	C	C		C			C							C			
	Parameter Identification	A			C	C	B		B			C	C						B			
	Design Techniques	A			B	C	B	B				B					C		B			
COMPUTER PROGRAMS	General Purpose Programs	A			A		B			B		A			C	B			A			
	Special Purpose Programs	A	C		B	A	B		C	B		A	C		C	B	C	C	A			
ENVIRONMENTS	Acoustic	A	A		A	B	B	C	C	C		A	B	B	A	A	B	C	A			
	Periodic																					
	Random	B			A	C	C	C	C			C							C			
	Seismic	A	C	C	C	B	C					A							C			
	Shock	A			B	B	C	C				C	C						B			
	Transportation	B			C							B							C			
PHENOMENOLOGY	Damping	A	A		A	C	B	B				A	B		B			B	B			
	Fatigue	A	C		C	B	C	C	B			A	B						B		C	
	Elasticity	A				C			B	C		C							C			
	Composites	A	B		C	C	C	C	B			C							B			
	Fluids	A			A	B	C	C			C	A				C	C		C			
	Soil	A				C					A	C							B		C	
EXPERIMENTATION	Measurement & Analysis	A	B		A	C	B	C	A	C		B	B		B	B	C		A			
	Dynamic Testing	A	B		A	C	A	C	B	C		C	A		A	A	B	C	B			
	Diagnostics	A	C		A	B						B							C			
	Scaling & Modeling	A			B	C						A				B			B			
COMPONENTS	Electrical	B				C																
	Mechanical	A	A		A	C	B	A	B	C	C	A	B	C		C	C	B	A			
	Structural	A	A		A	A		A	B	B	B	A	B	C					B		C	B
SYSTEMS	Air Systems	A			A	C	A	C	B	C		B	A		B				A			
	Sea Systems	A			A	C	A					A	B		B	A	B		C			
	Ground Systems	A			A	B		B		B		A	C	A	C	C	B	B	A		C	
	Space Systems	A			B	A	A			C		B	A						B	C		
	Humans	A	C		A	C	B					A			C				A			
	Isolation & Reduction Systems	A	A		B	C	B	C				A	B	B	A	C	B	B	A			
	Machinery Systems	A	C		A	C	C	B	C	C		A	C		C	C	A	C	A	C		
	Structural Systems	A	B		A	B	C	B				A							B			B

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Remarks made in this report should not be viewed as an attempt to rate the technical excellence of one country over another. It is certain that, given the motivation, along with the physical and financial resources, scientists from any country in the world can solve even the most difficult problems. In any event, the opinions offered in the rest of this chapter are based partially on the published literature and partially on the correspondence received from foreign investigators (Appendix). The results are also influenced by the insight gained by the staff of the Shock and Vibration Information Center over the last two decades.

STATE OF THE TECHNOLOGY

Analysis and Design

Analogs and Analog Computation

Digital computers have replaced analog computers for most computational requirements, particularly in the United States. Perhaps this is because the United States has been blessed with very rapid advancement in hardware and software capability in the digital area. In any event, research on analog devices in the U.S. has been somewhat limited, except in the area of industrial control applications and certain specialized test control. This appears to be less true in some of the other countries. The capability in France for real time visualization of transonic flow by analog simulation is a case in point. Japan uses analog computers for many nonlinear vibration problems. In West Germany, analog computers were used to simulate oscillations of bar-shaped systems. Perhaps U.S. researchers should give more attention to the analog approach for the potential solution of some of their problems.

Analytical Methods

The sections on analytical methods in this report are very general in nature and deal with studies primarily concerned with the solution of equations which represent the behavior of physical systems. Most new developments in this area are discussed in more specific sections under Analysis and Design, both herein and in Chapter 2.

Nonlinear Analysis

Over the years conventional analysis has been based on assumptions of linearity. It is recognized that, for many physical systems, such assumptions may lead to significant errors in the results. Concern for more closely approximating the actual results has motivated numerous studies in nonlinear analysis throughout the world. New methods that arise are as varied as the nonlinear physical problems that motivated their development. No methods are currently available that will yield exact solutions to arbitrarily-selected nonlinear differential equations. The most common solution technique is some form of numerical, step-by-step integration coupled with a local linearization. Approximation techniques, such as Galerkin's Method are used for time-dependent nonlinear problems. Important questions confronting the nonlinear analyst are convergence, stability, existence and uniqueness of solution. Graphical procedures are commonly used for estimating regions of stability and existence of solutions.

Many efforts are aimed at computing the response to different excitations of simple systems which are governed by the classical nonlinear equations of the Duffing or Van der Pol type. Other current studies are aimed at improving the accuracy of the numerical integration schemes. Many nonlinear structures are being analyzed today because actual measurements proved the response of the structure to be nonlinear. Examples of this are the large deflections in buildings produced by seismic events, the plastic behavior of materials under impact, and nonlinear wave propagation. Significant progress has been made worldwide on the understanding of the nonlinear dynamics of bearings, an important component in all rotating equipment. Optimization methods are also being used to design nonlinear systems.

There is need for much additional work on the solution of nonlinear problems. A good example is in the area of large deflections. Professor D.J. Johns* of the U.K. has pointed out that large deflection behavior of shells appears not to be well understood. Depending upon the theory used and the "modes" considered, various analyses indicate opposite nonlinear behavior (either hardening or softening). A more refined theory is needed to explain the difference in results.

Numerical Methods

Numerical analysis methods are increasing in popularity due to the enormous increases in the capabilities of digital computers. Much improved numerical integration methods are now commonly available. Larger time steps may be used, the algorithms are numerically stable, accuracy in modeling physical problems is greatly improved and the numerical dissipation of algorithms can be adjusted with a parameter (other than the time step). Three numerical integration methods, Wilson Theta, Newmark Beta and Houbolt, have almost become standard methods; information concerning their use is commonly available. Galerkin's method for the approximate solution of differential equations of motion has become used throughout the world.

Although lumped parameter methods are well known, new developments have been made. Among the new techniques are a lumped parameter modeling of a bar with random distribution of properties, and the response of a lumped parameter system to random excitation. Developments in finite difference methods find heavy usage in several shell analysis computer codes. Newer, more stable methods are available for difference dynamical systems and nonlinear systems. Finite difference techniques have long been popular in computational fluid dynamics and are now being used to simulate crack propagation.

*Refer to the Appendix for complete information on persons mentioned.

The finite element method is now universally accepted. Large general purpose computer programs based on the finite element method are available, on almost any medium, to large size computers. The development of high speed communicaton networks (such as the DARPA net in the United States) and the availability of inexpensive high speed portable terminals have made these computers and software widely available. Advances in finite element methods have resulted from "consumer" pressures to do larger problems at a cheaper cost and at a faster rate. Early efforts along these lines were aimed at more efficient utilization of machine capacities, such as sparse or banded matrix techniques. Other clever matrix manipulation schemes have been developed over the last years which allow for more accurate eigenvalue extraction, etc. Today much larger finite element problems may be handled due to the development of virtual memory techniques, improved time integration algorithms, modularity in programming and sub-space iteration methods. The newest techniques such as substructure modeling and component mode synthesis are aimed at reducing the total number of elements needed to model a structure, which reduces the computational effort. New consistent methods are available for selecting modes in the substructure modeling method, the selection of the proper modes being crucial to the success of the method.

Newer higher order finite elements have been devised to decrease errors and computation time. New hybrid elements based on the complementary energy principle are also under development. Advancements have been made in handling large deformations, nonlinear problems and shock wave propagation in nonlinear solids. Advances have also been made in the finite element modeling of soil-structure interaction problems, especially the response of nuclear power plant foundations to earthquakes. Professor G.B. Warburton of Nottingham University is currently developing information on structural and soil parameters which affect the dynamic response of tower structures, including off-shore structures. His results will be used as guidance on large-scale computations for complex-coupled systems, consisting of structure, soil and water, using the finite element method. Breakthroughs are still being awaited on the modeling of fluids which are still mostly modeled using finite difference methods.

Optimization techniques are popular because of the ease with which they can be implemented on a computer. Their application has not been universal, perhaps because of a lack of understanding of the nature of the limiting criteria. Some of the classical optimization techniques are nonlinear programming, time domain analysis, optimal control concepts and root locus techniques. Many otpimizations are made on minimum values such as minimum weight, minimum stopping distance, minimum noise take-off paths, etc. Other techniques are available which optimize the dynamical properties of a structure, e.g., techniques for the minimum flutter design of aircraft, or designs which minimize machine tool chatter. Control systems and isolation systems can easily be designed optimally, i.e., with respect to some performance criteria.

Perturbation methods are well developed and can in some cases give a solution where nothing else will. They can also save computational time and effort by preventing the re-running of a complex analysis. The problem can be run both ways. It is possible using perturbation methods to predict mode and frequency changes in a structure due to slight structural changes. The inverse problem can also be solved, i.e., what slight changes in the structure will affect the proper frequency shift? Perturbation methods also are being used successfully today on nonlinear problems.

Statistical Methods

Statistical methods are still not commonly used, probably because of the deterministic training of engineers. Statistical Energy Analysis (SEA) has found some applications in noise control problems, especially for the prediction of noise propagation in complex structures such as ships. Many important parameters with stochastic characteristics are being treated today, such as road or runway profiles, traffic distributions, and noise and vibration data. Assumptions of standard statistical properties such as Gaussian or Poisson distributions, "white noise", and "random" inputs are becoming more common place. The solution to some problems has involved the solution of the Fokker-Planck equation which predicts the probability density distribution of the response. The responses of nonlinear and linear systems to random inputs are typical of the problems solved.

Many first-passage failure problems are being solved with statistical methods. A typical application involves computing the probability of a landing gear bottoming due to a combination of runway roughness and landing impact. A recent statistical method to evolve is the characterization of the physical dimensions of a structure, e.g., the diameter of a bar, as a random variable.

Parameter Identification

Although there is considerable literature available on parameter identification there is a lack of application, perhaps due to the mathematical nature of the technique. Parameter identification techniques are used in dynamic test laboratories to extract structural dynamics information, usually from an aircraft or spacecraft. Techniques for single or multiple input, linear or nonlinear systems are available. New developments in parameter identification techniques have included the ability to identify stochastic parameters or disturbed parameters, the use of optimal parameter identification methods, and the ability to identify nonlinear parameters.

It should be made clear that parameter identification is a technique involving the marriage of experimental data and analysis. In effect, the test data is used to form an analytical model or to modify an existing model for the purpose of gaining confidence in response calculations. The techniques have been developed to do this appear to offer practical approaches to structural analysis problems, with the appropriate technique dependent upon the type of structure, the nature of the test, and the intended application of the results. The progress in this area is substantial, and several new important applications are anticipated in the future as practical usage begins to catch up to the theory.

Design Techniques

Analytical design techniques are not nearly as popular as computer-aided design (CAD) and optimization methods. Optimization of design at an early stage can save time and money and avoid fruitless design approaches. The aseismic design of buildings and the minimum weight design of trusses can both be optimized easily on a computer. A new standard design response spectra for nuclear power plants or rock sites is now available. Numerous on-going research studies are aimed at practical applications of analytically-oriented design techniques. Dr. D.J. Ewins of Imperial College, for example, is developing methods to optimize the design of complex pipe systems from a vibration standpoint. Potential applications become more unlimited, as confidence is gained in the techniques that are developed.

COMPUTER PROGRAMS

General Purpose Programs

Very large and complex shock and vibration problems can be solved today using general purpose finite element programs such as NASTRAN, ANSYS, DAISY, MARC-CDC, NISA, STARDYNE, STRUDL-II, ADINA, ASAS, BERSAFE, PAFEC, TITUS, EURDYN, PAS, ISTRAN/S, SESAM-69, SAMBA, ASKA AND COSA. Many of them were developed as working tools for aerospace companies (DAISY) or for the shipbuilding industry (SESAM-69). The development of some programs, such as NASTRAN, was supported by the Government. Many problems still exist with program transportability, configuration control and maintainability. The problem of selection of a general purpose program for a particular problem remains a difficult one. This is partly because the information available about program capabilities, particularly proprietary programs, is somewhat clouded, and partly because there has been no systematic software evaluation effort. Recognizing the need, Dr. Nicholas Perrone of the Office of Naval Research has spurred the organization of an Interagency Software Evaluation Group (ISEG). The aim of this group is to provide information to simplify the currently complex software selection process. The produce of the group will be unbiased information about programs, a commodity now difficult to obtain. In time the ISEG is expected to produce consumer reports on software to guide the potential user to the best code for his purpose. Such information will be invaluable as the extensive list of computer programs continues to grow.

Most of these programs require extensive experience before they can be used efficiently. The biggest drawbacks to some programs are their size and running costs, lack of nonlinear capabilities and lack of some of the latest, most efficient algorithms.

New developments are expected and needed to solve nonlinear dynamics problems. ANSYS, MARC-CDC, ASKA and ADINA have addressed themselves to these problems. More work in this direction is indicated, so that tools will be available to cope with nonlinearities in material behavior, large displacements and geometric nonlinearities, such as gaps.

The use of general purpose finite element programs continues to increase among the aerospace community, shipbuilders, civil engineering firms, nuclear reactor designers, vehicle manufacturers and the designers of off-shore structures.

Special Purpose Programs

Several references cited in Chapter 2 contain information on program capabilities, solution methods, language, hardware on which program runs, usage, program developers, and ordering information, as well as general comments on both general purpose and special purpose programs. There are also many software dissemination centers available on a world-wide basis.

To make it easy to discuss special purpose programs, we have arbitrarily grouped them into the following broad subject categories: Numerical methods, material mechanics, aeroelasticity, stability, fluids, seismic, shock, transient analysis, shells, cables, piping systems, components, bridges, computer-aided design (CAD), Sea systems, rail, crash simulation, rotary systems, noise prediction, test data reduction and processing and, lately, symbolic and algebraic manipulations.

Advancements have been made in numerical methods such as integration algorithms, eigenvalue extraction routines, stiff integrated routines, modal analysis routines and inteactive graphics techniques. Many special programs are available to handle problems in the broad area of material mechanics which includes composites, weld problems, nonlinear continuum, fracture mechanics, plastic analysis, thermal stress and creep, viscoelasticity and time-dependent material properties. Many of the large general purpose programs will also handle several of these topics. Programs dealing with aeroelasticity are readily available today. Many deal with flutter analysis, stability and control of elastic airplanes, and the prediction of aerodynamic loads on wings and rotors. The analysis of structural stability or dynamic buckling of structures is most often handled with general purpose programs, but many special purpose programs are also available for this purpose. The calculation of the stability of cylindrical or spherical shells under constant or transient loadings is the most common shell analysis. Other programs are available which will handle the dynamic buckling of buildings, bridges, and frames.

Fluid-structure interaction problems are still very hard to model and expensive to run on computers. Modeling of structures is usually by the finite element method and the modeling of fluid cells are by finite difference methods. When the two are used together the capacities of most machines are quickly exceeded. The situation is further complicated by the fact that the motion of the structure is "fed back" to the fluid which changes the loading on the structure resulting in modified structural response. However, some advances have been made recently in modeling underwater shock fluid-structure interaction problems using the Doubly Asymptotic Approximation (DAA). Other programs are available for handling fuel slosh problems and transient dynamic problems occurring in hydraulic systems. Seismic analysis and design has become very important in the U.S. and other countries. Large general purpose finite element programs are used extensively in seismic work. The United States and Japan are prominent among the countries concerned with seismic analysis. This has caused these two countries to develop many special purpose computer-programs for the seismic analysis of buildings, bridges,, nuclear power plants, fuel storage tanks, and so forth. Problems still exist concerning selection of inputs for earthquake accelerograms, but some design response spectra are available, as well as aritifical earthquake transients which have well-defined statistical properties. Nonlinear programs and soil-structure interaction programs are commonly used in seismic work.

Many computer programs for blast wave propagation and its interaction with structures were developed for militry purposes, but are now available to the general public. Many shock wave problems can be handled with numerical hydrocodes (such as BAAL). For systems which must be isolated from mechanical shocks there are computer programs available which optimize shock isolator designs. Most transient analyses of structures is done with general purpose programs, but there are a few special purpose computer programs for calculating the transient response of systems, such as turbojet and turbofan engines, and nuclear gas turbines. Many special purpose shell codes are available; usually they use finite differences. Some are now available which use finite differences for the thin shell segments and finite elements for the thick shell segments. Since submarines are basically thin shells, the U.S. Navy has long been a big user and developer of shell codes.

There are few special purpose codes available for cable analysis. Most have to do with guyed towers, buoy-cable systems or mooring line systems. With the large off-shore structures and large ocean thermal energy extraction structures being designed today, it would be wise to emphasize the development of even better cable dynamics programs. The available piping system computer programs fall into two main categories, those which deal with internal fluid-induced excitation and those which handle externally-caused motions, such as earthquakes or underwater shock. Current efforts center on developing codes for analyzing the whipping of ruptured pipes in nuclear reactors caused by nuclear detonation or earthquake.

It is relatively easy to write a computer program for the static or dynamic analysis of a simple structural members such as beams. For this reason many excellent interactive computer programs are currently available on several time sharing networks for the analysis of beams, plates, torsional systems, springs, disks, etc. Similar, but more complex, programs have been developed in Japan's shipbuilding industry, e.g., for frame analysis and the static or dynamic analysis of stiffened plates. Many bridge design/analysis programs are available which will handle a specific bridge type such as curved girder, curved girder on flexible bents, etc. Other programs address the response of bridges to the moving traffic loads.

Computer-aided design (CAD) techniques are being actively used today to aid the designers of engineering and architectural structures, ships, aerospace vehicles, buildings, towers, dams, etc. Civil engineers have been active users of CAD techniques. Many programs have the Civil Design Codes for the selection and sizing of I-beams embedded in the program. A similar situation exists for some pressure vessel design programs where the ASME boiler codes are contained within the program. In building design, for instance, the computer is used for the selection, sizing, and spacing of beams, creation of drawings, minimizing the weight of the materials, optimizing the static and dynamic properties of the structure and even optimizing the size and location of windows and duct work to minimize energy loss. CAD techniques are in common use in several countries with major shipbuilding industries; the use of computer-aided ship design in the United States is not as advanced. Computer-aided design of machine tools is a rapidly expanding field today as evidenced by active support of this work in several countries. Although some programs exist, it is safe to say that we are still on the learning curve, i.e., much basic research is being done to first understanding the problems. Applications will come later.

Many special purpose programs are available to assist in the design and analysis of ships and off-shore structures. Some design/analysis programs have been created for specific ship types, such as tankers and ships with large hatch openings. Others are for sizing and arranging scantlings or for computing the fluctuating stresses due to dynamic waveloads in the seaway. Programs have been written which will analyze floating platforms and fixed off-shore structures. The analysis of fixed off-shore structures may include both wave-forces and soil-structure interaction calculations.

Frequency domain computer programs for the analysis of rail vehicle dynamics are now available. Research on high speed rail systems is very active which leads to the expectation that many new programs will be developed as the phenomena are better understood. In the field of crash simulation two classes of programs have evolved, those which investigate vehicle crushing dynamics and those which simulate the motion of the victim. The Highway Safety Research Institute has developed many programs for crash victim motion, impact data analysis, etc., which are now available for public use. Rotary systems such as turbomachinery and ship power transmission systems have their own set of torsional dynamics problems. Several programs have been written to handle rigid and flexible rotor problems, as well as general torsional vibration problems. One torsional analysis program (BEIGE) can be used in the design state using only data taken from construction drawings.

There has been an explosive increase in the number of computer programs available for noise prediction. Programs are available for predicting highway noise, aircraft noise, community noise, tire noise, industrial noise, sonic boom, jet engine noise and helicopter rotor noise. In the area of test data reduction, emphasis has shifted away from the taking of data in analog form. Much of the data is reduced with portable digital analysis equipment, thereby greatly reducing the amount of data analysis done by special purpose computer programs. At the same time, in the larger vibration laboratories, powerful small digital computers are making their appearance. Increasingly sophisticated data reduction/analysis programs have been written for these systems, which has required the development of new programming techniques. Most of this new software is not readily available yet, either because it is too proprietary or too specialized. As upsetting as it might be to some test engineers, it appears that the computer programmer/analyst is now a member of the test lab.

Lastly,, we come to the more exotic area of symbolic and algebraic manipulation. Many shock and vibration investigators are not aware of this one. However, it is being developed to augment man-machine communication, especially with respect to programming languages such as FORTRAN. It offers the potential of greatly aiding the computer programmer by actively assisting him/her in manipulating formulas. Today the programmer writes everything down on a FORTRAN coding form and has it punched. In the future, this process will be shortened by the direct entry of formulas into the machine via an interactive terminal.

ENVIRONMENTS

Acoustic

Aircraft Noise

Jet aircraft and helicopters are the major producers of aircraft noise. Many laws have been enacted limiting the allowable noise emitted by aircraft. There is currently an FAA noise regulation for the SST. Noise monitoring of aircraft, especially at airports during take-off has become common place. The basic aerodynamic and engine noise producing mechanisms have been identified as well as noise transmission paths and the shielding effects of the wings. Problems have been encountered in evaluating different noise control procedures because of the high background noise level in most wind tunnels. Plans are underway in Europe, however, for the construction of an anechoic wind tunnel to handle this aspect. Many analytical and empirical methods for available for predicting the noise of aircraft, some of which have been put into computer codes.

The situation for helicopter noise is not nearly so well developed. The noise production qualities of rotors with different tip shapes and configurations is still being researched. Harsh vibration environments still exist in helicopters, especially the military versions. Human performance is severely degraded after exposure to these high vibration levels for any significant period of time. Dr. M.V. Lowson, Chief Scientist at Westland Helicopter, Ltd. in England, feels that the critical unknown areas are related to helicopter internal noise. He points out that the helicopter, as well as other forms of transport, suffers from a multiple discrete tone excitation of its interior. Present internal noise theories are not helpful new research efforts are recommended.

Sonic Boom

Sonic boom is an environment produced by aircraft in transonic flight. Sonic pressure pulses have been measured and the effects have been studied. Research results are available for computing the response of bridges, windows and human ears to sonic boom. The magnitude of the sonic boom reaching the ground can be affected by atmospheric conditions such as wind direction or temperature inversion. Wind tunnel measurement methods are available which allow prediction of flight sonic boom levels.

Machinery Noise

Recent OSHA regulations on the maximum noise levels to which a human being can be exposed has spurred investigations of the background noise in industrial facilities which, in large part, is emitted by machinery. Initial efforts were aimed at measuring machinery noise levels. Later, assessments were made to locate the individual sources of the noise and either modify the machine, shield it, or shield the nearby humans. Some of the greatest problems are with impact type machines such as punch presses, drop forges and pneumatic hand tools. Recent breakthroughs have occurred in the understanding of the physical laws and mechanisms governing sound production in these impact type devices. Design criteria are also available for the design of low noise electric motors and quiet fans. Fans, however, are still one of the biggest remaining noise producers.

Vehicle and Highway Noise

Interest in vehicle noise is in both overall emitted noise levels and noise source location. Methods are commonly available for predicting the noise due to traffic. Investigations have defined the noise levels that can cause speech interference. Other recent research has defined the noise characteristics of front-end loaders and tramways. Interior noise in the heavier American cars has never been much of a problem, but with the new lighter energy-conserving cars, this may yet be troublesome. Studies of the sources of highway noise have shown that tire tread patterns, road roughness and wheel enclosures have various effects on the emitted noise. Noise prediction models for tunnel noise are available, as well as guidelines for designing roadside noise barriers.

Community Noise

Many surveys have been made of community noise. The most common noise polluters have been identified and control methods have been developed. Methods are also available for predicting the environmental impact of race courses and raceways on nearby communities.

General

Some developments have been made in the characterization of structure-borne sound, but much work remains to be done in the measurement and labeling of machine footings and isolators, especially their impedance and sound propagation properties. Methods are also much needed for estimating source impedance from mechanical designs. Well-developed practical techniques are available today for the calculation of the propagation of sound. Many variables must be included such as wind direction, quality of the ground cover, and whether there is a temperature inversion. Sound scattering and diffraction around barriers must also be allowed for. An interesting technique has been developed in dynamite blasting to prevent sound propagation. Adjustable expendable microprocessor-controlled blasting caps are used which are detonated in a time sequence. This causes destructive interference of the blast waves which minimizes the propagation of sound energy away from the blasting site.

Noise is a world-wide problem. Det Norske Veritas in Norway has an active research program on noise prediction and control. A report on the Veritas prediction program is imminent, if not already available. A major area of research at Monash University in Australia is on transient noise radiated by impulsive machines. They are attempting to predict the radiated sound fields theoretically, then compare the predictions to the measured results. Jorgen Svensson of Ingemansson Acoustics AB, a consulting firm in Sweden described various research tasks including those related to community noise, occupational noise, traffic noise, valve noise and impulse noise. It is only in the recent past that we have by force of law, attended noise as an environmental problem. There is much research to be done, much yet to understand. N.A. Cumpstey of Cambridge, England, for example, feels that we have a surprising level of ignorance surrounding the aerodynamic wakes and distortions which are known to cause a large part of the noise from rotating machinery. The indications are that noise research on this and other problems will increase over the next several years.

Random

Random vibration as an environment became important in the shock and vibration field as rocket and jet engines were introduced, which produced vibration only describable in stochastic terms. Such vibration may be engine-induced or aerodynamically-induced as a result of high speed flight. Progress has been significant in both analytical and experimental research on random environments. There is still much to be done,, not the least of which is to strive for greater understanding. Professor J.D. Robson at the University of Glasgow feels that, "the great power of random vibration analysis techniques depends firstly on their simplicity and secondly on engineers being aware of it. Complex manifestations of random process theory are virtuous in some circumstances, but they will leave most practicing engineers unmoved if they are too complicated for normal use. Simple solutions can not only solve problems - they can encourage the wider use of similar techniques."

Seismic

Seismic events are normally thought of as earthquakes, but they are also caused by large chemical explosions in quarries, small chemical explosions in oil exploration studies, and real or simulated nuclear events. Great advances have occurred in the seismological research area as a spin-off of research efforts caused by the nuclear test ban treaty. This treaty caused several countries to monitor all world seismic events very closely. The earthquake research community has benefited from the development of this seismological monitoring instrumentation. Many design codes must be followed when designing earthquake resistant buildings and nuclear reactors To aid engineers, seismic risk maps are available which tell the probability of an earthquake occurring in a particular geographical area. Design response spectra, based on measured or predicted environments, are also used. Information on past earthquakes has been tabulated and is available. Japan has been especially good about making thorough damage surveys and social response surveys after each Japanese earthquake.

Shock

Most of the advancements in shock technology have come from military research. This includes underwater shock (Navy), air blast, and ground shock. Many accurate empirical formulas are available for predicting the propagation of air, ground or underwater shock waves. Their interaction with structures is far more difficult to predict, especially for air blast, but many computer codes are available to assist the analyst. Air blast caused by gun and missile firings is another shock environment. In the aerospace area there are many shock environments which occur, such as the blast wave caused by the igntion of a large rocket motor, or the shock caused by the firing of pyrotechnic devices during stage separation. One of the most common shock environments occurs during rail transportation in rail switchyards. Box cars are rolled down a "hump" and are coupled together, sometimes, at speeds up to 10 miles per hour. Significant shocks to cargo also occur in other transportation modes such as bouncing in trucks, aircraft (landing shock), and rough handling (dropping) of containers. Shock measurement, analysis, design and testing are discussed elsewhere in this report.

Transportation

New environmental data available for transportation vehicles is relatively sparse. There are scattered reports on vibration in trucks, trains and transport aircraft, but these data are usually taken for special purposes and do not serve the general need. Much older data is still used for this reason. For railcars, where the basic dimensions and designs have remained practically the same, this doesn't make much difference. Data on newer model trucks and automobiles is very scarce. The Germans, however, have published a survey of the vibration levels measured in major German manufacturer's vehicles. Because of the emphasis on ride comfort, a significant amount of acoustic data is available. Infrasound (below 20 Hz) in vehicles can cause increased fatigue on drivers. Several researchers are carrying out fundamental studies in this area.

PHENOMENOLOGY

Damping

Damping is a significant mechanism for controlling both vibration or shock amplitudes. It is also very significant in that damping properties must be considered to assure reasonably accurate results from structural response calculations. Aside from internal damping, which is very low, structural damping comes mostly from the energy loss due to the Coulomb friction in the structural joints. Some progress has been made in the development of techniques for predicting the overall damping in such assembled structures, but far more information is needed. The lack of sufficiently accurate techniques for predicting structural damping can cause errors in the estimation of large scale parameters, such as the internal acoustic environment in a spacecraft, flutter instabilities in aircraft, or machine tool chatter. Much better design information is needed on the damping of joints before structures such as machine tools can be optimized at the design state from mechanical drawings. Many researchers are studying this problem and better design information on the damping of characteristics of joints should become available soon. Dr. R.S.H. Richardson has already provided a number of contributions from Australia, although his work in this area is currently somewhat diminished. Professor Jean-Guy Beliveau of the Universite De Sherbrooke, Quebec is studying joint characterization for damping synthesis for civil engineering applications. Some engineers are already exploiting friction damping as a design aid. Welded and epoxied joints have also been investigated. A limited amount of data are available on the damping characteristics of clamped joints in missiles. Progress has been made in the design and development of passive nutation or ring dampers for satellites; good design and selection information is available.

Special high damping alloys are now available which were developed for special applications such as noise reduction in ship propellers. The application of layers of viscoelastic material to surfaces to reduce vibration and noise is a widespread useful technique, especially for reducing acoustic fatigure in high noise areas on aircraft. Design information is somewhat lacking on the placement and sizing of acoustic damping panels, but some literature reviews are available on the subjects. Layered damping treatments have been used to control wind-induced vibrations in buildings, fuel sloshing, acoustic fatigue, noise emission and vibrations in fluid-conveying pipes. Care must be exercised in the use of viscoelastic materials, however, due to their strong temperature dependence and their deterioration with time due to exposure to harmful environments. High temperature enamels have been developed which have good damping properties and which can be applied to turbine blades to optimize their dynamic characteristics.

Many damping devices have been developed to handle shock and vibration problems for special applications, such as dampers to control the earthquake response of large spherical fuel tanks and damping rings which can be easily added to gears. The development of powerful Cobalt permanent magnets has caused an improvement in the performance characteristics of boring bars which have internal electromagnetic dampers. There has been, and there will continue to be, rapid development of both active and passive dampers to control self-excited vibrations in machine tools. The work of Dr. Kazuto Seto of the National Defense Academy in Japan provides a good example. Dr. Seto has developed a variable stiffness-type dynamic absorber which is adaptable to the improvement of the damping properties of a vibrating system with changing natural frequency. He is presently studying methods of applying this absorber to hand tools, such as rock drills and chain saws. Another problem encountered is the in-service fatigue failure of vibration dampers which have energy continuously pumped into them. Torsional dampers on large reciprocating engines are susceptible to this type of failure.

Significant advancements have taken place in both instrumentation and procedures for the laboratory determination of the damping properties (complex modulus) of viscoelastic materials, especially with respect to the temperature dependence. Dr. R.D. Adams of the University of Bristol has made some progress in the study of the dynamic damping characteristics of materials at cryogenic temperatures (4°K) for applications such as superconducting electrical machines. Still it is evident that much more research is required on damping at extreme temperatures.

During the dynamic analysis of structures which are partially made up of viscoelastic materials, it is common practice to assume some simple analytical spring-mass damper model to represent the dynamic behavior of the material, e.g., the Kelvin or Voigt models. The assumption of these simple models greatly eases the burden of finding a solution to the equations of motion, but the assumption may be an oversimplification. Additional research on rheological models could provide some useful answers.

There is a need for much better information on the structural damping of spacecraft made of new composites. A number of investigators have pursued the study of damping in high-performance composites, including Dr. R.D. Adams who was mentioned earlier. The research efforts should be intensified, however, to provide design information to support the rapidly growing requirements for the use of these new materials in system development. In a similar light, active dampers and active controls will be used to reduce both transient and steady state vibration, especially in large flexible space structures. As the research efforts in these areas increase,, as they surely will, perhaps investigators may profit from work on active control for other applications. Drs. Peter C. Muller and K. Popp of the Technical University in Munich have studied combined active/passive vibration control on high-speed ground vehicles, and are already looking at applications on large flexible space structures. Prof. H. Leipholz of the University of Waterloo, Canada is working on automatic control of civil engineering structures and is the organizer for a symposium on "Structural Control" to be held in July 1979. During the next few years, many new developments are expected which will bridge the gap between theory and application to specific systems.

Fatigue

Research and development on the fatigue properties of metallic and composite materials is being conducted world-wide. Miner's rule for estimating cumulative fatigue damage is still heavily used. It has been contended that it can be used for stochastic inputs, as it is for sinusoidal inputs. There is some controversy in this area. Other major analysis efforts have generated crack propagation models which, in some cases, are used in lieu of Miner's rule. Newer theories are under development but some have not been validated or widely used. Professor Leipholz, mentioned earlier, is among the researchers studying fatigue due to stochastic loading of materials.

Developments in fatigue testing have kept pace with the analytical predictive methods. Many test laboratories are now using random loadings as well as sinusoidal. Using random loading and Monte Carlo simulation methods, it is now possible to reduce the amount of experimental data needed to establish the fatigue life of the test item. Research is being done to establish a dependable technique for accelerated vibration life testing, as typified by the work of Dr. H.S. Blanks of the University of New South Wales in Australia. Dr. Blanks has shown that, as far as fatigue failures are concerned, life prediction from accelerated vibration testing is feasible as long as the extrapolation equations are understood and correctly used. The digital computer is being used extensively in connection with testing for predicting the fatigue life of test samples. The computer also assists the test personnel in running the test, making measurements and analyzing the data.

Recent efforts have been aimed at predicting and measuring the fatigue life of asphalt, solder joints in electric circuits, and more importantly, composites. As the use of composites increases in aircraft and spacecraft, their fatigue properties must be predicted and measured. It is not clear that present methods are adequate. Research on the problem is continuing. In the field of acoustic fatigue testing, some large acoustic fatigue test facilities have been shut down, while others have greatly reduced the number of tests performed. The reasons for this are not clear. One would guess that it is a combination of economic pressure and the increased availability of improved analysis/design methods.

Elasticity

Methods are available for calculating the propagation of waves in elastic, nonlinear plastic, or viscoelastic structures. Elastic wave propagation has been studied for homogeneous and non-homogeneous media, and for almost any shape. The propagation of Rayleigh waves, spherical waves and cylindrical waves in elastic media have all been studied. The propagation of waves in viscoelastic material, especially rods, can now be predicted. There is even a method which predicts the build-up of a shock wave in a viscoelastic rod. Mathematical models of viscoelastic materials are available which allow for the prediction of energy dissipation. In general, the level of understanding of elastic theory seems to keep pace with dynamic design analysis requirements.

Composites

The use of composite by the aerospace industry and the defense establishments is increasing. Aircraft manufacturers were quick to realize the cost benefits of reducing the weight of an aircraft by using high strength fiber-reinforced composites. Graphite-epoxy is now becoming a very popular construction material for some satellites, but the long term stability of some of its material properties (damping, stiffness, fatigue life, etc.) are still not well defined. In the military arena, composite materials are used for armor (Kevlar-epoxy), helicopter structures, and missile structures, as well as for other applictions. The use of metal-metal composites is on the increase, but the cost is still prohibitive. With fiber-reinforced composites, it is currently possible to construct a material with unique structural properties. The composite designer can choose the tiers, ply angle, resin and number of plys. Computer programs have been written to aid in this process. There are also viscoelastic composites available. The propagation of waves in viscoelastic composite rods and bars can be predicted. New methods are under development for the testing of the fatigue life and impact resistance of composites.

There is an area relating to the use of composite materials which, in the past, appears not to have been given much attention. The area of application is crack patching which, in a larger sense, requires a look at the broader problems of repaired structures and their response to dynamic loads. Dr. R.H.Y.S. Jones of the Aeronautical Research Laboratories in Melbourne is taking such a look with his work on the static and dynamic behavior of repaired structures. In the statics area he has already completed what appears to be the first exact analysis of an adhesive layer. Further success in the dynamics area would be an important contribution to our field.

Fluids

As shown in Chapter 5, there are four main subject areas in fluid research which relate strongly to shock and vibration; fluid structure interaction, fluid-induced excitation, dynamics of contained fluids, and aerodynamic or wind-induced excitation. Some progress has been made with fluid-structure interaction problems which are still difficult to model. New methods are available for computing the interaction of shock waves with structures based on the Doubly Asymptotic Approximation. Because of these developments, it is possible to do a better job of modeling sound radiation from hulls, propeller forces and hull-slamming. Using these improved methods, it should now be easier to design more reliable off-shore structures, perhaps at reduced cost.

Flow-induced vibration problems have occurred in many sea systems such as sonar domes, pilings, towed cables, mooring lines and hydrofoils. Many flow-induced vibration failures have occurred in nuclear reactors. The knowledge gained in solving these problems has been put into design guidelines to help prevent further failures. Other instabilities have occurred in the elastic components of large power generation equipment, such as turbine blades, guide vanes and heat exchanger tubes. The problems have not all been solved, but design engineers have a better understanding of the basic vibration generation mechanism of vortex shedding. Recent studies have centered on the excitation of downstream bluff bodies by the vortex shedding action of upstream bodies.

The dynamics of contained fluids is important to the designers of fuel tanks. Pioneering efforts were made by members of the aerospace community who were faced with the problems caused by fuel sloshing in the tanks of launch vehicles. Improvements in numerical analysis methods have been made, which has allowed for the more accurate treatment of the structural (finite element) and the fluid (finite difference) modes. Other analytical advancements have been made in the theory of fluid-filled shells and the coupling between fluid (slosh) modes and structural modes. These techniques have been applied to oil tankers, LNG tanks, wing-tip fuel tanks, dams, reservoirs and large spherical and cylindrical petroleum storage tanks. Better information for the aseismic design of large fuel tanks has been developed as a result. The basic phenomenology has now been applied to a wide range of human shock and vibration problems including blood flow, motion of the brain (fluid) in the skull and the response of the eye, which is fluid-filled. The treatment or prevention of POGO effects in launch vehicles can now be handled due to the advancement of this technology.

The basic characteristics of aerodynamic/wind induced excitation have been thoroughly researched. Basic information on the excitation mechanisms such as vortex shedding, boundary layer attachment/re-attachment, turbulent flow and noise generation is readily available to the design engineer. The effects of galloping, flutter, stall, noise and acoustic fatigue are well understood. The victims of wind-induced excitation include such exposed structures as bridges (Tacoma Narrows), flexible buildings, overhung roofs, towers, transmission lines and hyperbolic cooling towers. Design methods for eliminating the problems at an early stage are becoming more widely used. Many cures are available for eliminating cable vibration, especially power cables. These include the addition of spoilers and dampers or by surrounding the cable with smoother aerodynamic/hydrodynamic shapes. For cylindrical towers, such as chimneys, it has been found that the Scruton spiral developed in West Germany provides a very effective method of damping vortex-induced vibration.

Soils

One of the most frequently researched soil-related dynamics problems is the interaction of the soil with the structure in building foundations. Progress has been made in modeling this problem using both continuum methods and finite element methods. The main excitation mechanisms considered have been earthquakes, nuclear ground shock and conventional explosions. Nuclear reactors and underground strategic structures have been extensively studied with respect to ground-induced excitation. Excellent design guides have been written and are now available to assist the design engineer. Other studies have led to a better understanding of the dynamic behavior of soils, including nonlinear behavior. The foundations of off-shore structures can also be analyzed with these methods. A number of studies have been made on the use of vibration to aid in soil penetration. Vibration can be used to assist the driving of piles and the cutting of soil with metallic blades. In the United States, a major contributor to soil research is the U.S. Army Waterways Experiment Station in Vicksburg, Mississippi.

EXPERIMENTATION

Measurement and Analysis

The basic principals of transducer operation and the techniques for their use have remained the same for the last several years. Advancements have been made in transducer reliability, size reduction, and temperature operating range. New transducers have been developed for the measurement of blast-induced shock in buried structures, forces and moments on wheels, and the low frequency acceleration of rail vehicles. Acoustic holography is being used to locate sound sources in machinery and optical holograms are being used for modal analysis and transient response measurements. A laser instrument has been developed which is capable of making a non-contact measurement of the torsional vibration of a rotating shaft. Other advancements have taken place in proximity probes, which are commonly used for machinery diagnostics.

As with other research areas, reliable measurements are an essential part of experimental investigations in dynamics. Accuracy is a must, if results are to be believed and if correlations with analytical predictions are to be meaningful. In Australia, the importance of measurement is emphasized by their laboratory accreditation organization, the National Association of Testing Authorities (NATA). Acoustics and Vibration Measurement is one of nine broad fields of testing in which NATA provides an accreditation service. This type of activity, along with assured accuracy in calibration, contributes to greater confidence in measurements.

Some of the advancements discussed earlier clearly indicate that research efforts often deman new measurement methods. In the area of acoustics, for example, Dr. F.J. Fahy of the Institute of Sound and Vibraton Research in England has worked on the problem of measuring sound intensity directly. Professor John M. Dewey of the University of Victoria, Canada is concerned with the measurement of shock and blast waves using high speed photogrammetric techniques. The analysis of these measurements can provide information on the spacially and temporally resolved particle velocity, density, hydrostatic pressure and dynamic pressure throughout the waves. These examples illustrate the potential benefits of advancing measurement technology.

The development of small portable measurement and recording equipment has progressed rather slowly, considering the advanced miniature solid state electronics available. There have been some advancements, however, including a new digital crash recorder. Sometime ago, a miniaturized shipping shock recorder was developed incorporating advanced technology, but cost has prevented further development. Cost tradeoffs in this case were not favorable with respect to the benefits. In any event, special developments of this kind are spurred by special needs; the cost must be justified.

Major advances have taken place in signal processing electronics, especially in the areas of high gain operational amplifiers, integrated circuits, and mini-computers. Digital control and analysis are coming into use in many countries. "Bispectral" analysis techniques are starting to be used. The increase in world activity in noise control has been another cause for the rapid increase in digital data analysis equipment. The applications are expected to increase.

Dynamic Testing

With the increased capability for digital test control and analysis, a number of new modal survey techniques have been developed. There are still problems related to the nonlinearity of structures and the noise levels in the measured data, but progress has been significant. Budget constraints often make the decision "to test or not to test" a difficult one. The tests are carefully chosen to be cost effective. It is not an uncommon practice to test some parts of a system and analyze the rest, then to combine the results. The strength of our dynamic test capability seems to lie in our ability to perform any required test. Whatever weaknesses there are relate to our ability to understand the test results. Dr. Fahy of ISVR pointed out a need for experimental work directed towards an empirical evaluation of confidence levels to be used in conjunction with Statistical Energy Analysis of coupled multi-mode vibrating systems. How can we experimentally determine the relationship of response variances to perturbations of system parameters? There are many questions of this type that need answers and it is to that end that our test research efforts should be directed.

It is worthwhile to call attention to the importance of accelerated vibration lifetesting and to the significant work of Dr. H.S. Blanks who was mentioned earlier for his work in fatigue. Dr. Blanks has developed a new method of vibration testing which is called exponential excitation expansion. The method involves increasing the excitation level exponentially with time, and offers several important advantages, including compressed scatter of failure times, less need for prior knowledge of the item's vibration resistance, and the ability to test simultaneously various points within one product. The method appears to be an important contribution to the field of accelerated testing.

With respect to test facilities, there hasn't been much change in the basic shock and vibration test equipment. As might be expected, new facility developments are brought forth mostly for special purposes such as sonic boom simulation, seismic testing, pyrotechnic shock simulation and other requirements. There has been an increase in the use of electrodynamic shakers to simulate transient (shock) events. Special techniques, such as using two amplifiers with one shaker, are sometimes required to do this, but our test engineers seem to be up to the challenge.

As to the future of dynamic testing, it is felt that test requirements will be heavily influenced by the Space Shuttle and the new programs that it makes possible. The challenges may be to perform dynamic tests in a simulated zero-g environment. It also seems safe to predict that there will be a significant increase in the testing of scale models.

Diagnostics

Mechanical signature analysis is a nondestructive testing technique that was developed to use the mechanical vibration signatures of rotating machinery as an indicator of their overall mechanical condition. Using this technique, it is also possible to diagnose faulty components such as bearings and gears in rotating machinery or blades in turbomachinery. The "petro-chemical" industry has made the most extensive use of mechanical signature analysis. They have shown that cost savings are possible due to a reduction in unscheduled repairs and maintenance. Other machinery monitoring applications include rotating machinery in steam or hydroelectric powerplants, main propulsion machinery and principal auxiliaries on naval vessels, and power trains on helicopters, trucks and earth moving equipment. Some of the more unique applications of mechanical signature analysis include the vibration monitoring of a nuclear reactor's internal structure, detection of defects in sealed electronics packages and detecting change in the quality of mechanical components.

Two acoustic monitoring techniques have been developed. Acoustic signature analysis is also a nondestructive testing technique to detect hidden flaws by comparing the test article's emitted spectrum with a reference spectrum of an article that is known to be sound. This technique has proved to be feasible for detecting cracks in railroad car wheels in situ. Acoustic emission is another monitoring technique that is used to detect the presence of and the growth of hidden flaws in materials. It has been used to determine the structural integrity of pressure vessels and submarine hulls, and to monitor concrete test specimens for impending failure.

Machine diagnostics may be considered analogous to regular physical checkups to detect potential health problems. In fact, it is sometimes called machinery health monitoring. The importance of diagnostic techniques should not be underestimated. Cost savings can be great when, because of advance knowledge of impending failure, simple maintenance can prevent a catastrophic loss.

Scaling and Modeling

A comprehensive text has been written on the subject of scaling and modeling, and scaling laws were developed for strong shock and for the combination of transient ground winds and the nonlinear acoustic fields that surround a launch vehicle. Similarity laws for the blade passage sound of centrifugal fans were epxerimentally verified.

Dynamic tests have been performed on a wide variety of scale model structures and they have proved to be highly cost effective. Tests have been conducted for many purposes including the determination of the dynamic characteristics of large structures, the determination of flutter characteristics of suspension bridges, the simulation of water entry loads on the Space Shuttle Solid Rocket Booster, the determination of the dynamic characteristics of full size aircraft structural components, and the prediction of the structureborne noise transmission through shipboard structures.

The use of scale models for testing, rather than full-size items, is expected to increase as scaling and modeling techniques gain wider understanding. Model tests are already used extensively in Japan, particularly in relation to seismic testing. West Germany has produced results of investigations to verify similarity laws. Aircraft models have been used in wind tunnel tests for a long time. Dr. N. Popplewell at the University of Manitoba in Canada is considering small scale modeling techniques for vibro-impact machinery studies. With the limitations on some of the available dynamic test equipment, it may be that if a test is conducted at all for a large item, it will have to be on a scale model.

COMPONENTS

Electrical

Very few studies on the dynamics of electrical components have been reported in the literature. The few studies that were found presented methods for solving printed circuit board vibration problems, guidelines for the design of mechanical failure resistant electric motors, and a program to develop earthquake-resistant circuit breakers. Such a program is much in order, since circuit breakers have been reported for years among the most troublesome electrical components with respect to dynamic loads. Shock loads produce the greatest problems, whether they originate from seismic events or from the effects of underwater explosions on ships and submarines.

It is clear that electrical and electronic components are susceptible to damage from dynamic loads. It is not completely clear why investigations on the design and protection of such devices is not widely reported in the literature. We do know that often these components are assessed as a part of a much larger system and that the results are buried in the report on the systems study. We also know that such components are often not "designed" for dynamic loads; rather they are tested and used if they are acceptable. The test reports are usually internal documents not available in the open literature. Finally, the authors may be guilty of missing some meaningful work by not scanning appropriate electrically-oriented journals.

Mechanical

Absorbers and Isolators

Several novel dynamic absorbers were developed. One consisted of a circular or annular damped plate loaded at its outer perimeter by a rigid annular mass. Other absorbers were also developed to protect structures against earthquakes or to minimize the transient vibrations of thin plates. The variable stiffness dynamic absorber developed by Dr. Seto in Japan has interesting applications for machine tools. Combined isolator and dynamic absorber systems have on occasion found application for specific problems.

The application of isolators for mitigating shock and vibration effects is a reasonably routine process, except for particularly troublesome problems. Elastomeric materials are most frequently used in isolation mounts. There are many interesting applications of energy absorption devices (as opposed to isolation), such as crash absorbers and aerial delivery protection devices. Some unusual concepts were studied by P. Hernalsteen and L.C. Leblois of TRACTIONEL in Belgium, for application to pipe-whipping restraints in nuclear power plants. The concepts were the plastic extension of stainless steel rods, plastic compression of copper bumpers, and punching of lightweight concrete. The possibilities in this area are endless, since any action that requires work can be used to absorb energy.

Blades

Blades are used in many types of machinery such as compressors, turbines and fans, as well as in aircraft engines. The most significant areas of interest with regard to fans has been in the dynamics of blade flutter and the reduction of noise. Significant progress has been made in the study of blade transonic flutter, a phenomenon occurring at the high tip speeds that are necessary for increased performance. The disturbance occurs when the flow velocity is supersonic in the trip region and subsonic near the hub, i.e., mixed subsonic/supersonic flow. In spite of the progress, many effects remain to be investigated in order to avoid unpleasant flutter incidents in this speed regime. Among the areas in need of study are blade thickness and camber effects, and shock/boundary layer and rotor/stator interactions.

A great deal of work has been done related to aerodynamic excitation of blades. Most studies have been to understand the nature of the excitation, its effects on blades, and the interaction between adjacent blade rows. Many fundamental studies have been performed to understand the behavior of blades, to develop optimal design techniques, and predict their mode shapes and natural frequencies. The finite element technique is frequently used in the analyses. Experimental techniques have been developed for studying turbine blade vibrations, determining the condition of turbine blades and determining the mechanisms of failure during an impact with a containment structure. Composite materials have been used to develop fan blades that are more resistant to foreign object impacts and to reduce vibration in high tip speed applications.

Bearings

Research on gas-lubricated bearings is being conducted to determine their dynamic characteristics and establish methods for predicting their whirl stability. Studies of the stability of hydrodynamically-lubricated bearings are also being carried out to determine how various factors affect operating stability and to develop methods for stabilizing bearing rotor systems. Many investigations of the dynamics of bearings have been carried out to determine their dynamic characteristics for specific applications such as machine tools. Research studies have involved the use of the finite element method and mobility concepts.

Research on bearings can be quite varied, as illustrated by information furnished by Mr. Abraham Francken of the Institute for Mechanical Constructions (TNO) in the Netherlands. Their work involves applications, the improvement of propeller-shaft aftermost bearing behavior - computational capability, development of a computer program for calculating stiffness and damping coefficients of turbulent film bearings - and new bearing materials, the theoretical and experimental investigation of compliant surface bearings (e.g. rubber bearings). Bearing dynamics is still a lucrative area for further study.

Ducts

The study of fluid-flow in ducts has been related to noise-generation mechanisms and methods for attenuating the sound. Investigations of the former related to the effect of duct cross sectional geometry and any barriers or baffles, whereas the latter studies concern the properties of duct lining materials and design modifications for noise reduction.

Linkages and Gears

The dynamics of cams and other mechanical linkages is extremely important to the manufacturers of such devices, as well as the users of the machinery of which they are a part. Problems solved related to efficient mechanical operation, reduction of wear rate, and noise reduction, among others. The problem solving involves the use of the latest technology, including transfer matrix analysis and special computer programs to deal with torsional and translational vibrations. The PLANET II code, for example, was developed to simulate the dynamic behavior of mechanisms that employ linkages.

Two interesting communictions from the UK illustrate the breadth of dynamics investigations related to gears. Mr. G.C. Mudd, Director of Engineering at David Brown Gear Industries, Ltd., described, among other items, trouble shooting situations involving mathematical modeling techniques to examine transient conditions at start-up or other points of discontinuity. His company also uses telemetry to investigate torsional vibration and, in particular, to measure the stresses in the roots of gear teeth in mesh to derive the dynamic increment of gear tooth loading. Mr. D.B. Welbourn of the University of Cambridge conducts seminars on gear noise. His associate, Dr. J.D. Smith is doing promising work on geared systems involving the measurement of transmission loss at speed under load. For his doctoral thesis, Dr. M.L.W. Salzer studied gearbox dynamics and successfully modeled manufacturing errors in addition to the design parameters. Obviously, there are many interesting and challenging problems in this area.

Pipes, Tubes and Valves

A review of the dynamic modeling of pressure vessels and piping systems provided insight into the advantages and limitations of modeling and analysis techniques. Numerous studies on the seismic response of pipelines indicate the concern in this area. Many studies on the vibration of heat exchangers have been undertaken, including the determination of tube-baffle contact forces and the solution of acoustic problems. The stability of pipes and tubes conveying fluid and the external flow-induced vibration of pipes and banks of multiple tubes are other areas of extensive investigation. Some computer programs are available for piping analysis. The greatest need seems to be for improved modeling techniques.

Structural

By far the greatest abundance of learned papers related to dynamics concerns the mathematical analysis of the basic structural shapes, designated herein as structual components. This is particularly true for beams, plates, shells and cylinders. There are seemingly endless solutions on the response of ideal structural elements with different boundary conditions to a number of different types of loads. The importance of these efforts relative to the solution of "real" structural response problems should not be underestimated. Without these analyses as a departure point, the present capability to study physical structures mathematically would be substantially nonexistant. A tribute is due to the mathematical analysts who have paved the way to progress in structural dynamics.

Beams

The development of methods of predicting the transient response of beams is a very important area of structural dynamics. The beams may be loaded by impact, blast, underwater explosion or repeated moving loads. As might be expected there are a number of studies in this area. Nonlinear beam problems relate to transient loads, and several studies on the plastic response of beams have been made. It is possible to analyze many structures as beams, hence methods for determining their natural frequencies and mode shapes are important. Studies have included the analysis of periodically supported beams, multi-span beams, box beams, and laminated beams. One study concerned the use of mobility data to predict the natural frequencies and mode shapes of connected beams.

Cables

The dynamic behavior of cable systems is important for a number of applications. Studies of cable dynamics in towing or marine salvage applications have been performed. Vibration of overhead power conductors has also been extensively researched. Studies have included aerodynamically-excited overhead powerlines and the dynamic interaction between a locomotive's current collector and the overhead power cables. Cables are used to support many types of structures. Studies have been performed to determine their dynamic behavior in such diverse applications as supports for long span roofs in buildings, and booms for suspending sensors from spacecraft.

Cylinders

Literature reviews on the dynamics of cylinders are available. Much of the interest in the vibration of cylinders has concerned problems related to fluid-induced or aerodynamic excitations. Typical applications have included excitation of floating structures, establishment of design criteria for marine piles, and the analysis of wind-resistant stacks. Studies of shock loads on cylinders have been made to support submarine design efforts.

Frames and Arches

Frames and arches are basic elements in a number of physical structures. Some of the important problems that have been treated relate to the transient analysis of frames in connection with such applications as the design of the earthquake-resistant structures. Most recent are the problems related to the response of frame members of large space structures. Additional work is needed in this area, particularly dealing with problems of large displacements and small strains.

Films and Membranes

Studies of membranes have been related to frequency response analysis, nonlinear vibrations, and response to traveling ring loads (on circular membranes). Approximate expressions for free vibration of membranes are available. Membranes with holes, as well as membranes made from composites, have been analyzed. Future work is needed on the study of nonlinear membranes, especially with noncircular geometry. More experimental work would be desirable.

Panels

Panels are geometrically similar to plates. The term seems to be applied to particular structural applications. Sandwich and composite panels, for example, are very popular structural members. Their light weight, high strength, and, in some cases, sound absorption qualities make such panels useful in a number of structures and vehicles. Consequently, many studies related to vibration response, damping properties, buckling, and other dynamic phenomena have been made. More attention should be given to optimal design procedures for panels, considering the criteria of stresses under various loadings, buckling load, and panel flutter speeds. The interaction of stiffness, damping and fatigue strength should be studied. More experimental verifications of dynamic analyses are needed.

An interesting study in Switzerland by Mr. Peter P. Degen of Motor Columbus deals with the perforation of reinforced concrete slabs (composite panels) by rigid missiles. The application is for containment or barrier walls. Analytical and experimental studies produced a new method for calculation of perforation thickness, useful in establishing design requirements for specific containment or protective structures.

Plates

The vibration of plates is an active area of research which continues to result in the development of techniques for solving specific problems, as well as general analytical techniques. It is instructive to note some of the more specific studies. For example, simplified techniques were developed to predict the response of window panes and wall panels to sonic booms. Plate-like structures are often subjected to explosions. Techniques have been developed to predict the stress wave propagation in and the damage to plates due to the detonation of surface rings of explosives. The SPAN computer code was developed to aid in the static and dynamic analysis of grillages. Flat resonance frequencies of damped, stiffened sandwich plates were determined using a combination of periodic structure theory and the theory of damped, forced normal modes. Floors, decks and platforms are other examples of structures that are modeled as plates to study their dynamic behavior.

Many general analytical methods have been developed. Liapunov's second method was used to determine the stability of elastic plates. Several studies have addressed the problem of large amplitude vibrations of plates. In other efforts, solutions to the problem of vibration of orthotropic plates are being determined, the effects of shear deformation and rotary inertia on the response of plates has been studied, and the finite element method is being applied to the solution of plate vibration problems.

Shells

Many structures can be modeled as shells and the research efforts on the vibration of shells are extensive. Several literature reviews that deal with this topic have been written.

Studies that are oriented to specific applications or that have potential applications are many and varied. The response of shells with attaches masses has been studied. The effects of different loads such as explosions or aerodynamic excitation, on shell response have been investigated. Analytical techniques have been developed to predict the stability of pressure vessels, and oil tanks have been studied as shell models. Other analyses have treated such problems distorted cylindrical shells and the coupleed flexural-rotational motion of cantilevered cylinders.

Applications of shell theory are widely used in structural analysis, therefore the development of general shell analysis techniques is of great interest. The use of the finite element method to solve shell vibration problems has been studied. Studies of the vibration of stiffened shells have addressed the effects of imperfections, loading conditions and restraint conditions. Several applications of the Donnell type equations to the solution of shell vibration problems were made, including the vibration of stiffened shells and the dynamic stability of shells. Much additional research work is needed on nonlinear problems related to the response of shells to dynamic loads.

SYSTEMS

A properly functioning system, operating reliably in performance of its mission, is the technological end product of all ressearch and development efforts. From the standpoint of shock and vibration, the dynamic loads that potentially can negate or interfere with system performance must be considered in the design development phase. In some cases methods of energy mitigation or absorption must be employed. All aspects of dynamics discussed earlier play a part. The dynamic environments must be measured or defined and this data introduced into the design. Considering dynamic characteristics of materials, one then may use available analytical design tools. The design can be verified by test or analysis based on criteria established from a systems performance profile. In the following sections, highlights of work on different systems will be offered as indicators of present capabilities and, in some cases, research needs will be mentioned.

Air Systems

Aircraft

The prediction and measurement of aircraft vibration environments is an active area of work. Efforts have included the definition of the vibration environment in newer and larger transport aircraft, special studies to define the environment for vibration sensitive equipment, and the prediction of full-scale dynamic environments from scale model test results. The response of aircraft to taxi loads induced by uneven runways is of concern. The load produced are sometimes defined in terms of stochastic data. Methods have been developed to design landing gear to minimize the effects of this environment.

Aircraft noise poses a problem to the structural integrity of the airframe and to the community. Many studies have made it possible to better understand the noise generating mechanisms and to find methods for reducing its effects. In addition, an assessment of the state-of-the-art in airframe self-noise was performed. The noise requirements for future aircra. power plants is of major concern. Concepts for noise reduction in aircraft therefore continue to be explored. The advent of the Supersonic Transport has spurred studies of silencing techniques, as well as studies of sonic boom effects, aimed at meeting noise level guidelines. The propulsion system for VSTOL aircraft presents a unique noise problem. Studies have identified noise sources, and noise prediction techniques and silencing methods are available.

Aircraft flutter research is very active, as indicated by a review of the literature concerning the recent trends. Methods for minimizing flutter, either by design or by the use of a variety of active control systems, have been developed. The active control area seems to have been studied more extensively. A number of flutter calculation techniques have been investigated. These include the use of the finite element technique in the analysis of a multi-web aircraft wing, calculation techniques using a reduced number of degrees-of-freedom, and the use of stochastic methods for determining modal parameters in flutter analyses. There are active investigations of vibration and flutter related to external weapons stores. Typical studies are on the relationship between vibration levels and dynamic pressure, the identifcation of parameters that influence the flutter speed of wings with attached weapons stores, and the prediction and measurement of aerodynamic loads on oscillating wing/store configurations. Ground vibration test data are also used in flutter analysis. The results of one study displayed the nonlinear behavior of an aircraft, while another depicted the status of testing aircraft using system identification techniques. Aircraft safety inspires a significant amount of research. Typical efforts are related to improving the crash-worthiness of general aviation aircraft and studying the effects of bird strikes on windshields.

Progress has been significant in research on the deformation of structurally elastic bodies in response to aerodynamic loads, commonly called aeroelasticity. The progress is evident when we consider the high performance capabilities of present day aircraft. Requirements continue to arise for ever increasing performance, thereby calling for high performance materials and increased analytical capability. There are still many unsolved problems today, particularly with respect to nonlinear effects. Research on dynamics related to aircraft is expected to be extensive in the years ahead.

Helicopters

The severity of the vibration environment in helicopters is responsible for the continuing extensive efforts to alleviate its effects. Capabilities exist for measuring vibration levels and these levels are reasonably well defined. Fatigue loads have been studied and life prediction methods have been developed. Methods for isolating the airframe from the vibration source have been studied and isolation methods have been developed. Helicopters also produce severe noise environments. Current studies in this area concern the identification of the noise sources and the development of techniques for reducing the cabin and cockpit noise levels. Future studies should continue the trend towards lower vibration levels by improving methods for isolating the rotor from the fuselage.

Missiles

Missile dynamic loads are generated by various sources and studies of the effects of these loads on the performance and the structural integrity of new or uprated missiles is continuing. The development of sophisticated modal analyses techniques makes it possible to rapidly verify mathematical models of missiles and as well as to establish their dynamic characteristics.

Sea Systems

Surface Ships

The principal dynamic considerations for ships are vibration and, for naval ships, shock from underwater explosions. This is not to say that other problems such as slamming and collision protection are not important; they are and they have been studied, sometimes, as with collisions, after the fact. Ship vibrations may produce detrimental effects on shipboard equipment or may cause the emission of unwanted sound, i.e., the silencing problem. Ship vibration sources are well-known and techniques for calculating hull vibrations are available. The shock loads on ships from underwater explosions are reasonably well understood and significant progress has been made on methods for designing shipboard equipment to survive these loads. The basic computations involved in the U.S. Navy's Dynamic Design Analysis Method are now programmed and calculable on large scale computers.

Structureborne noise in ships is an active area of study. In both analytical and experimental investigations, techniques have been developed for predictting and measuring the structureborne noise levels. The use of these techniques lead to improved habitability of manned spaces onboard ship, as well as methods for reducing the radiated noise from ships, thus assisting in meeting both environmental and ship silencing objectives.

Shipboard machinery-hull interaction vibration problems still arise in spite of the fact that this area is well documented. As these problems arise, they are solved using a combination of analysis and experimentation. A prime mover in this area has been the Bureau Veritas in France, lead by M. Guy Volcy. This French work relating to machinery/hull vibration interaction problems and related areas is exhaustive, reaching almost every facet of the dynamics of ships and ship's equipment. The results have been major contributions to ship design and troubleshooting techniques. A more extensive discussion of the Bureau Veritas contribution is given in Chapter 8.

Contributions in ship dynamics have come from a number of countries and many useful references are cited in this report. Some work not cited until now is by J.J. Jensen and P.T. Pedersen of Denmark in an upcoming paper on "Wave-Induced Bending Moments in Ships - A Quadratic Theory". They offer a theory to predict the nonlinear vertical response of surface ships in irregular stationary waves. The quadratic terms in their theory arise due to the nonlinearity of the exciting waves, the non-vertical sides of the ship, and the nonliner dydrodynamic forces. Studies of this kind verify the statement from Professor R.E. D. Bishop of University College, London that "...we really cannot distinguish between vibration studies and naval architecture". Professor Bishop is co-author of a book on "The Hydroelasticity of Ships" which will be of wide interest.

Submarines

Many of the problems are the same for submarines as for surface ships. The pressure hull is basically a cylinder and is modeled as such for analysis purposes. Fluid-structure interaction analyses provide the greatest challenge, but significant advancements have been made with the introduction of new hydrocodes and the development of the Doubly Asymptotic Approximation by Dr. T. Geers of Lockheed. New developments are expected to emerge.

Off-Shore Structures

Off-shore structures have received increasing attention because of the potential oil resources under the oceans. Most of the dynamic studies have concerned the response of the structures to ocean waves, however noise control has recently become an important consideration.

Ground Systems

Off-Road Vehicles

This report has examined work on three categories of off-road vehicles. It is evident that dynamic analysis techniques are being used in the design of agricultural vehicles, although the literature does not reflect that this trend is by any means universal. The most severe environments are produced by tracked vehicles and a number of dynamic studies have been conducted on tanks and personnel carriers, both from the standpoint of noise reduction and vibration isolation. Dynamic studies on surface effects vehicles have been to determine the response of these vehicles during overland operation and to develop active control systems for improving the ride quality.

Rail Systems

Rail systems dynamics studies have concerned the response of vehicles to track-generated inputs, motions of freight cars during impact, and the interaction between vehicles and the track and roadbed. The stability of rail vehicles is important and several methods for predicting the onset of an instability called "hunting", as well as methods for controlling it, are available. Magnetically levitated and tracked air cushion vehicles have been included in this category, even though they ride above guideways. They have stability and dynamic behavior problems of their own and studies have been made or are in progress.

Rail vehicle noise has become an important part of rail vehicle dynamics research. The noise emitted by passing trains has been measured for compliance with noise emission regulations. Investigations have been performed to determine the mechanisms of externally-generated railroad noise and how it may be controlled, and to evaluate prediction techniques. The same applies to the internal acoustics of passenger vehicles.

A few items are worth noting as signs of progress in rail systems dynamics. In the United States a full-scale rail vehicle dynamics test facility is about to provide full test capability in the laboratory. Interesting and useful developments are expected as the facility is brought into full use. In Japan, some interesting work related to the dynamics of power collectors for high speed trains has been contributed by Professors Taro Shimugo and Kazuo Yoshida of Keio University. Dr. Hidehiko Abe of the Japanese National Railways described interesting work on upgrading railway structures for earthquake resistance, on the dynamic interactions of bridges and moving trains, and on methods of protecting trains from falling boulders. Mr. A.H. Wickens, Director of Laboratories for the British Railways Board has analyzed stability in a class of multiaxle railway vehicles possessing perfect steering. The wide variety of problems associated with rail systems is illustrated by the short list of impressive contributions listed above.

Road Systems

The design of road vehicle structures has become highly sophisticated in recent years. Automobile structures have been designed using computer graphics techniques, finite element computer programs are used routinely, and systems identification techniques have been used to determine the dynamic characteristics of motor vehicles.

Crashworthiness of motor vehicles continued to be an important problem. Finite element models are used in the dynamic analysis of vehicle structures; in one case nonlinear finite elements were used. Studies have addressed the problems of predicting vehicle collapse modes, determining the ability of vehicles to absorb collision energy, the mitigation of crash severity, and the protection of the occupants.

The ride quality and stability of motor vehicles has been investigated. Factors affecting ride quality include self-generated vehicle vibration and stochastic road inputs. Stability studies relate to the response of vehicles to steering inputs.

Motor vehicle noise studies emphasize the identification of external noise sources in trucks and automobiles and the development of quiet vehicles. Internal noise studies in trucks and automobiles have also been performed and have resulted in the definition of vehicle acoustic characteristics and the development of methods for reducing the noise level.

Reactor Systems

The potential for nuclear accidents has prompted many studies of nuclear reactor components and structures. Pipe whip studies have resulted in the development of methods for predicting input forces and breakage locations, as well as modeling methods for both piping and restraint systems. Dynamic analysis of nuclear reactor containment systems have considered the structural integrity due to internal and external shock loads. An example of the former is the containment of pressure fluctuations due to blowdown. The most common example of the latter is the response of the structure to aircraft impacts. In addition, a method for the reliability-based design of reactor safety containments that would be applicable to seismic, climatic, and both internal and external pressure loads has been proposed.

Earthquakes and chemical explosions pose hazards to nuclear reactor systems. Analyses, and tests where possible, are performed to verify that the nuclear reactor systems are resistant to seismic loads or to identify potential hazards. Many existing dynamic structural analysis techniques and computer programs can be used for seismic analysis of nuclear reactor systems or their components.

Fluid flow past nuclear reactor fuel elements, or in other nuclear reactor components, is a significant source of vibration and techniques for predicting the response of these elements are available. In addition, the problem of vibratory wear of fuel rods has been addressed. Techniques for exploiting a nuclear reactor's characteristic vibration to yield diagnostic information have been developed. The application of such techniques to foretell impending accidents would be a great advancement, potentially offering the greatest contribution in this area.

Various soils, frozen soils and rock have been studied to determine their dynamic characteristics. There are many sources of ground vibrations and the energy transmission mechanisms are quite diverse. Underground blasting is one of the major sources of human-induced ground vibration, and studies of its effects on canal locks and structures have been performed. Seismic events induce ground motion of concern for such items as buried pipelines, foundations and embedded piles. Professor M. Novak of the University of Western Ontario is currently studying all three of these problems, considering the interaction effects.

Soil-structure interaction effects are important in the design of foundations or buried structures. The development of techniques for predicting the stiffness and damping in soils generated by soil-pile interaction, and the resistence of soils to horizontally-vibrating piles allows the dynamic response of footings and structures supported by piles to be predicted. Caissons and piles are often part of machinery foundations. The availability of techniques for predicting the interaction between the soil and piles vibrating vertically or horizontally should make it possible to perform a more accurate analysis of such foundations for predicting the vertical vibration of floating piles. The torsional vibrations of pile foundations are also a subject of study.

Space Systems

Spacecraft

The dynamics requirements of previous major space programs, such as SKYLAB and VIKING, have provided advancements in spacecraft dynamics technology and the SPACE SHUTTLE program promises to continue this trend. Experience with the VIKING program has shown that substructure modal coupling techniques are effective in the dynamic analysis of complex structures. The success of this project has also demonstrated that it is possible to develop valid mathematical models of spacecraft that can be used in a load analyses to determine the forces in primary structures. In another development, coupled-base motion response analysis of payload structures allow complex structural members to be used for various load conditions without having to re-establish the entire coupled structural system modal properties. The determination of the interface dynamics between launch vehicle and payload is an important step in establishing the coupled response of a spacecraft and launch vehicle to launch vehicle dynamic loads. One recently-developed technique in this area makes use of the combination of complex admittance functions measured separately on the payload and the launch vehicle.

Large flexible space structures are now an area of great interest with the expectation of SPACE SHUTTLE capabilities. So far, most of these are in the concept definition phase. Such structures will bring their own dynamic problems, such as control system structural interaction, pointing accuracy requirements, and extreme flexibility. Recent efforts with smaller flexible spacecraft should provide some of the necessary analytical tools. Examples include a free vibration analysis of flexible spinning spacecraft, vibration of spacecraft with momentum exchange controllers, analysis and modal tests of flexible solar arrays, the development of software for the dynamic analysis of solar arrays, and techniques for deriving the equations of motion for large orbiting flexible spacecraft composed of elastic structures with coupled rigid bodies.

In response to a request concerning this survey, Mrs. E. Nellessen of the European Space Agency provided a detailed letter describing the ESA program development since 1970. It was extremely interesting, indicating systematic planning with each step taking advantage of the latest technological developments. The authors also agree with Mrs. Nellessen's personal assessment of needs for further investigations relative to the dynamics of space structures. These include more work in parameter identification, to identify damping and stiffness in particular, for inclusion in mathematical models for dynamic response predictions; advancement in test equipment and methods to achieve greater realism in flight environment simulation; development of methods to verify design analytically, where tests are not possible; and development of methodology for testing ultralight structures to orbital environment.

Launch Vehicles

The sources of launch vehicle dynamic loads range from on-the-pad ground winds to transonic dynamic instability. Problems such as combustion instability, POGO, and longitudinal pressure oscillations have occurred, and techniques for their solution have been developed. The need for dynamic testing of launch vehicles continues, however, cost constraints and the limited availability of development test models of full-scale hardware often dictates the use of scale models. This trend is expected to continue.

There are three developments that have made space flight a reality. They are the large general purpose computer programs for dynamic analysis, the development of high speed digital computers to accomodate the use of large digital programs, and the recent development of sophisticated digital test control and data analysis techniques. This is not to denigrate the essential analytical techniques that have been developed. It is to indicate that without these new capabilities the progress in many of the previous space programs would have been nearly impossible and the progress in future space programs would have been seriously affected.

Human

Dynamically speaking, humans have not changed much since Adam and Eve. What has changed is our ability to describe human beings dynamically and our ability to determine human tolerance to noise, shock and vibration. Mathematical models of the hand-arm system, the head-neck region and human skulls are available. Mechanical impedance techniques have been used to determine the response of the human head to sinusoidal vibration. Experimental studies of human response are evident in several countries. The criteria for judging response may vary. Dr. T. Miwa of the Ministry of Labour in Japan uses sensation response (vascoconstriction) for studying whole body shock motion and physiological reaction for studies of hand-arm vibration. Other investigations in the United States and elsewhere are aimed at determining the factors that are important in evaluating hand-transmitted vibration.

Automotive collision sutdies have resulted in the development of a vehicle-occupant crash simulation model. This has lead to the development of occupant protective systems. While data on human tolerance to shock continue to be collected, the current trend seems to be to develop systems for protecting humans from the effects of shock.

As pointed out earlier, much has been learned about human tolerance to vibration. This has allowed a standard for whole body sinusoidal vibration levels above 1 Hz to be prepared and safe limits of human exposure to blast-induced vibration and helicopter-induced vibration to be suggested. In addition, limits of human exposure to whole body vibration in the 0.1 to 1 Hz frequency range have been proposed. The relationship between vibration and human comfort, or the ability to carry out tasks, is subjective and techniques for assessing the subjective response to vibration have been validated. The subjective response to vibration relies on equivalences. Experimental results that depict the equivalence between sinusoidal and random whole-body vibration, and noise and whole-body vibration are available. It should be noted that International Standard 2631 relates permissible whole-body vibration levels to the duration of exposure.

The fact that excessive audible noise causes permanent hearing damage is well known and this has lead to limitations to its exposure that have the force of law. This area continues to be explored. Noise affects human performance and the factors that influence human performance have been identified. Infrasound is a low frequency inaudible airborne vibration. Limited studies of the effects of this environment have shown that it affects human performance, and can even imapir human health if the levels are high enough. Investigations of the effect of noise on hearing are extensive. Roland Nilsson in Sweden is using acoustic impedance measurement of the ear to try to determine why some go deaf and some do not at the same noise level. Further investigations are needed on the effects of impulse noise.

Isolation and Reduction Systems

Absorbers

Dynamic absorbers are used to suppress unwanted vibration in some systems. Typical applications are the suppression of vibration in machinery and the suppression of chatter in machining operations. A dynamic absorber was successfully used to suppress vibrations in a flexible elastic body to prevent upsetting the performance of its attitude control system. The concept of a dynamic abosrber is an old one, and while many ideas exist, there are few applictions.

The use of shock absorbers on automobiles and aircraft landing gear is well known. Other types of isolation and energy absorption devices have been developed for vehicle occupant restraint systems or to reduce damage due to vehicle collisions.

Noise Isolation and Reduction

Most of the work in this area is applications-oriented, however, some basic studies are being performed, notably on the suppression of sound by the destructive interference of soundwaves and on the performance of mufflers for engine exhaust systems. The technical feasibility of noise control in industry has been assessed; noise problems and noise sources were categorized and solutions were identified.

Noise control may be obtained by retrofit or it may be designed into a new system. The distinction is not clear, since some methods are applicable to either situation. Some noise reduction techniques are applicable to a number of different problems; acoustical barriers are good examples. The ability to predict their effectiveness is well in hand. They have been used to reduce highway noise and in-plant machinery noise, among other applications. The capabilities in noise control technology are such that noise reduction for most systems is feasible. This includes buildings, motor vehicles, aircraft, machinery, and even the muzzle blast from cannons; however none of the above problems have been completely solved. The question is not whether the noise levels can be lowered, but how much? We will continue to struggle to reduce the noise by a few more db until the regulations for occupational and environmental noise levels are satisfied. At the same time, studies will continue to make certain that these regulations are realistic.

Isolation Systems

The technology for passive isolation systems has been extensively explored and research continues. The optimal design of isolation systems is an active area, resulting in isolation systems for rotating shafts and for some systems that are subjected to random excitation. Design criteria and techniques are available for the isolation of equipment on flexible foundations. Messrs. J.A. Macinante and H. Simmons from the National Measurement Laboratory in Australia, for example, have been working to establish a more satisfactory design basis for the isolation of machinery on suspended floors. Isolation systems with dual-phase damping have been developed, and systems have been developed to isolate equipment and missiles in silos from ground motions and nuclear reactor systems from earthquakes.

Active isolation system concepts continue to be explored. Systems have been developed to isolate helicopters from rotor-induced excitations, or to isolate railroad passenger cars and motor vehicles. The trend in application of isolation systems is to use a passive system wherever possible. Active systems are more expensive, they may impose a weight penalty and there is a reluctance to use anything that is required to operate in order to provide protection. In spite of this, there are a number of applications where more precise control may be required. The continued study of active isolation systems is necessary to meet this need.

Machinery Systems

The most active areas of study on machinery systems relate to machine tool dynamics, noise reduction and flow problems, rotor dynamics, and turbomachinery. These are the major topics covered in the following sections. The reader will note that literature citations on materials handling equipment, certain industrial manufacturing equipment, consumer products, and internal combustion engines are not extensive. Even so, such work is considered important and, perhaps, indicative that increased emphasis on dynamics would be advantageous in these areas.

Metal Working and Forming

Machine tool dynamics studies have emphasized the analytical or experimental determination of stability, the onset of chatter between workpiece and cutting tools, methods to increase the material removal rate, and, in general, to improve their dynamic characteristics. Another goal is to reduce noise emission. Techniques are available for mathematically modeling a machining process to predict the onset of instability, and to determine the stability limits of machine tools under actual working conditions. The effects of changes in operating conditions on machine tool stability and the dynamic characteristics of machine tools can also be determined experimentally. The former investigations are also used to develop changes to improve the stability of a machining process; the development of an anti-chatter boring bar is an example. The latter studies have been used to obtain the dynamic characteristics of machine tool systems to support analytical studies of stability.

A number of analytical techniques are available for predicting the stability limits of machine tool operation. Techniques are also available for predicting the dynamic characteristics of machine tool components and structures and the effects of these characteristics on the stability of the machining process. For example, Professor S.A. Tobias of the University of Birmingham in England describes work on the dynamics of grinding machine structures and the stability of the grinding process. Other work in this area related to noise generated by impact forming operations, wherein a finite element analysis of the machine vibrations is performed and modes excited under impulsive loading are predicted. Computer-aided design techniques are available for many types of machine tools and machine tool components; a minimum vibration milling cutter is an example. Some digital computer programs are available to carry out the previously-mentioned analysis tasks and software is being developed for processing experimental data.

Pumps, Turbines, Fans and Compressors

Pulsating flow and surge in flow affect the reliability and efficiency of pumps. In addition, these phenomena produce noise and excite vibration in their associated piping. Studies of these phenomena have lead to a better understanding of their effects, thereby improving pump design. However, there is clearly a need for more research in this area.

Most of the technical effort on fans is aimed at noise reduction, although vibration studies have resulted in design techniques that can be used to reduce fatigue failures. The factors that influence fan noise are reasonably well understood. As a result, techniques are available for reducing the noise of fans used in aircraft turbofan engines, air handling systems, and automotive cooling systems.

Rotating stall or surge are two basic modes of instability in axial-flow compressors. Analytical studies backed up by experimental results make it possible to predict the onset of these instabilities.

Rotor Systems

The reader is referred to reviews by Dr. Neville Rieger for an indication of the state-of-the-art in rotor bearing dynamics and for guidance to computer programs in this area. Dr. Rieger has also prepared a comprehensive treatise on the balancing of rotating machines which will be published as a monograph by the Shock and Vibration Information Center.

Many techniques can be used to solve rotor dynamics problems. Rotor bearing systems can be modeled by using finite elements. The dynamic stiffness matrix concept is one general technique that may be used to calculate the unbalance so as to predict the stability threshold speed of a flexible rotor in damped flexible supports. Another technique makes it possible to calculate the critical speeds of a flexible rotor in either rigid or flexible bearings. Insight has been developed with respect to the vibration of rotors being accelerated through critical speeds. Further light has been shed on the effects of damping flexible mountings, asymmetric pedestals, gyroscopic forces, and fluid film forces on rotor vibrations. A technique is available to detect crack growth in balanced rotor-shaft systems that rotate at critical or sub-critical speeds. Guidelines for selecting balancing techniques for flexible rotors are available.

Rotor-bearing systems stability analysis is an important consideration in rotor dynamics. There are several types of rotor instabilities. Studies continue to emphasize improvements in analytical techniques for predicting the instability threshold speed, including the concern with factors that cause the instabilities to occur. Typical research efforts include the development of a general method for the stability analysis of rotating shafts, a method for simulating transient and steady-state response of flexible rotors supported by incompressible hydrodynamic-film journal bearings, and a method of predicting the linear transient response of flexible rotors supported in gas-lubricated bearings. The effect of bearing lubricants, the influence of journal-bearing clearance, and the effect of the dynamic characteristics of the bearings themselves are factors that lead to the unstable operation of rotor bearing systems; these factors have been, and should continue to be, investigated.

Propellers or helicopter rotors are also grouped in the rotor category. Most of the effort in this area has resulted in a better understanding of their noise generation mechanisms, or in better methods for predicting their vibration and noise characteristics.

Turbomachinery

Traexler has pointed out, in a review article, that vibration is a major source of problems in turbomachinery. Vibrations in turbomachinery can be broadly grouped into rotor dynamics problems or blade dynamics problems. Investigative efforts in the former area have resulted in the development of dampers to suppress unwanted shaft responses and in a method for predicting the lateral forces due to steam leakage that cause self-excited vibrations in steam turbines. The use of the finite element method for determining the vibration modes of a rotating blade-disc system is an example of a study in the latter area. Lightning strikes on power plants can cause abrupt load changes, thereby producing destructive transient torsional vibrations in turbomachinery; a technique for predicting these effects is available.

Noise in turbomachinery is another area of concern. Typical studies have resulted in the identification of the sources of blade cascade noise, as well as the development of a method for predicting the acoustic power emitted from gas turbine exhausts. The method was based partly on fluctuations in the flow from the combustor to the turbine section. As with noise reduction efforts, research must continue to develop improved methods.

Structural Systems

Bridges

Bridge vibrations can be induced by moving loads, earthquakes or wind loads. The response of bridges to randomly-spaced loads moving at a uniform speed can be predicted; the method is based on a technique for modeling the bridge as a beam. Investigations on the aeroelastic stability of bridges have provided methods for predicting the combined vertical and torsional response of a suspension bridge to wind loads.

Although there have been a number of fruitful studies on bridge dynamics, it is the opinion of the authors that this is not enough. Bridge disasters involving loss of life have not been uncommon in recent years, mostly caused by failure of the structure under load. It is fully realized that failures are mostly of older bridges for which modern design methods were not employed. More reliable design methods can eliminate such catastrophies for future bridges and promote an awareness that older bridges should be examined and, if defective, replaced.

Buildings

The current trend in building construction is toward lighter construction and more flexible structures. There are many sources of building vibration. Tools are available for predicting and controlling these vibrations, however it is the feeling of the authors and others that further efforts are needed.

The seismic resistance of buildings is of major concern and, while further research is needed, considerable progress has been made. Seismic design and analysis guidelines for military buildings are available. Techniques are available to predict the seismic response of many types of large buildings for both the linear and the nonlinear cases. Methods for approximating the modes of vibration in buildings are available. Investigations of ground shock and air blast loads on buildings have contributed methods for predicting structural damage, as well as improvements in structural analysis techniques.

Probably the most important area for continued research in building dynamics relates to aseismic design. More exact methods of analysis are needed. Quality control in construction needs to be improved. Design codes should be verified and enforced. Methods are needed to retrofit older buildings to improve their earthquake resistance.

Noise in buildings is actively studied and methods have been developed for determining the noise transmission paths and predicting the noise transmitted through a building. Investigations will continue toward the goal of improving the environment for the building inhabitants.

Towers

Towers and stacks must be designed for dynamic loads such as winds or seismic motion. Seismic design and analysis methods are available which provide greater confidence for the safety of cooling towers. A number of studies on the response of towers to high winds have been made, including work on guyed towers. Research efforts will not diminish in this area.

Dams

The concern for the safety of dams during earthquakes has lead to the development of methods for predicting their dynamic characteristics and seismic response. Tests on scale model dams have shown that it is feasible to use models to determine the dynamic characteristics of full-scale dams, including hydrodynamic pressures at the dam/reservoir interface. There are many problems still to be solved relative to safe dam design. The major research programs in the United States in this area are being conducted by the U.S. Army Waterways Experiment Station.

NATIONAL INTERESTS AND ACCOMPLISHMENTS

United States

It is clear that the United States has a strong interest in almost all shock and vibration subject areas covered in this report. Since interest promotes accomplishment, major advancements have been made in the U.S. in at least some aspect of each of these areas. Developments in the U.S., then, roughly parallel those described in the previous section on the STATE OF THE TECHNOLOGY. No attempt will be made to discuss those developments again in any detail. Rather we will here attempt to highlight only the most outstanding contributions to progress and, in some cases, provide some background on the general sources of these contributions.

In the analytical area, probably the greatest recent progress has been in the area of nonlinear analysis. In particular, new developments have been extensive in numerical or approximation methods for the solution of nonlinear problems. In general, problems to be solved have grown larger, i.e., more degrees-of-freedom. Significant new techniques such as component mode synthesis lead to fewer elements in the model, thereby simplifying the computational effort involved. For the most part the ultimate sources of new analysis methods are the universities, through research programs supported by such organizations as the National Science Foundation and the research arms of other government agencies. However, the contributions from government laboratories and contractors are not insignificant and should not be overlooked, particularly on work related to the application of analytical methods to program needs. With respect to design techniques, the most progress has been made on computer-aided design and design optimization techniques.

The development of general purpose computer programs has been extremely successful, the most notable example being NASTRAN which was created to meet the dynamic analysis requirements of the space programs of the National Aeronautics and Space Administration. NASTRAN and similar finite element programs have been applied to a wide variety of problems. In the versatility of such programs lies their greatest strength. Special purpose computer programs are abundant and most are significant. Ample discussion of these programs has been provided earlier. Again, it is appropriate to note the software related to computer-aided design as one of the more useful contributions.

When one thinks of environments it is usually in terms of data that define those environments. Arguments are frequently put forth that available data is not "realistic" or that it is not offered in terms applicable for the establishment of design or test criteria. In many cases this is probably true. Nevertheless, it is suggested that the greatest contribution of the U.S. in the area of environments is related to data management, a subject not previously covered in any detail. Notable examples come from the aerospace industry, in particular General Dynamics Corporation, for the management of launch vehicle dynamic data; and from Agbabian Associates who manage data from HE shock tests. The problem does not seem to be so much with the data management, as it is with the education of users on how to use the capabilities of the data banks.

The most significant progress in the study of material properties is in the area of damping, even through much work obviously remains to be done. More specifically, it is suggested that the greatest advancements relate to the development of highly-damped materials and in the application of various damping methods in structural design. Notable progress has also been made on "designing" damping into a structure, as in the joints. Composite materials developments have provided the most fruitful contributions to structural design for dynamic loads, primarily because of the increasing requirements for high-strength, light-weight materials.

In the experimental area, it is clear that the greatest contribution has been in the area of digital control of dynamic tests and the associated digital analysis of test data. Tests are being performed today that could not have been done earlier, such as modal survey tests of structures with high density modes. A pioneer in this area was Phil Chapman of the Jet Propulsion Laboratory. His work formed the basis for many of the later developments. We would be remiss if we did not credit diagnostics, particularly mechanical signature analysis, as being an area of major progress. The capability to predict impending mechanical failure through changes in a characteristic vibration signature can result in avoiding catastrophic failure, thereby saving countless dollars and, in some cases, even human life.

Developments on components are difficult to assess as to their relative importance. Looking at the overall contributions, as well as the applications, it is suggested that the greatest benefits have been realized from the studies relating to blades and bearings. The analysis of these components in the setting of their high performance requirements is a difficult process, yet some extremely useful results have been made available.

The most rapidly advancing systems development efforts in the U.S. have been on space systems, air systems and sea systems, in that order. The ranking is made principally on the basis of the complexity of the system mission. There is considerable room for argument about the most significant recent breakthrough in our technology in these or any other areas. We will not attempt that one. Suffice to say that, in each of these major systems areas, extremely complex engineering problems involving a number of complex load conditions have arisen and have been solved. These solutions came about often under tight constraints with respect to space and weight, and at the same time that a number of other adverse environmental conditions and high performance operational requirements had to be considered. The final performance is the true test. One might well wonder how it can all be done.

Australia

Australia has made substantial contributions in the area of defining acoustic environments, this being principally in conjunction with their rather effective noise reduction efforts. A number of fundamental investigations on noise have supported this work. At Monash University, for example, fundamental studies on the effects of different forcing functions on sound radiation are being made. The idea is to be able to control noise at the source. In a closely related area, noteworthy progress on vibration isolation methods has been made, particularly at the National Measurement Laboratory in Sydney. As a result of this work, we can look forward to a book on vibration isolation by Mr. Joseph A. Macinante, principally addressed to practicing engineers and architects.

Contributions are evident toward the understanding and use of damping in structural joints. Composite materials and fracture mechanics are studied analytically in conjunction with their aeronautical research objectives. Simple formulae have been contributed enabling the calculation of frequencies of plates and shallow shells by rapid and accurate hand calculations. In the test area, the Australian laboratory accreditation program operated by the National Association of Testing Authorities is to be lauded. Contributions of substance to the area of accelerated vibration testing have also been made.

United Kingdom

Noteworthy developments have taken place in the UK in the areas of nonlinear analysis, statistical methods and stability analysis. There is considerable interest in linear analysis of non-conservative systems. As a matter of fact, it is fair to say that UK efforts rank rather high in the analytical area. Not a small part of this work is produced by researchers at the Institute of Sound and Vibration Research at Southampton. Certainly, much of all the results of significant acoustic and vibration studies in the UK is published in their Journal of Sound and Vibration, an exceptional publication, drawing as well from the rest of the world. Great strides have also been made in computer programs as typified by the GENESYS system for Civil and Structural Engineering.

As may be expected there is considerable research related to acoustic and vibration environments. Noise reduction efforts are extensive and have met with considerable success in a number of areas, including aircraft noise, industrial noise and community noise. Research on damping and its applications have produced useful results. Outstanding work is evident relative to fluids, particularly as related to fluid-structure interaction and, the dynamics of sloshing. Significant contributions are available related to wind-induced excitations, particularly from the University at Loughborough. Capabilities for measurement are excellent, as indicated by several new developments. Dynamic test advancements are quite good and the UK is among the world leaders in the development of diagnostic techniques. Contributions to non-destructive testing are significant. Of particular interest is a method to locate defects in composites by measuring changes in natural frequencies caused by the defect or its propagation. This work was done at the University of Bristol.

Blades, bearings and gears are the mechanical components studied that have produced the best results. The capability of analyzing structural components goes hand-in-hand with their basic analytical expertise. In systems work, the main interests seem to lie with aircraft, rail systems, machine tools, and rotors. Accomplishments in each area have produced very useful results.

Canada

In the area of analysis, Canada has made significant contributions to nonlinear analysis and, particularly, on stability analysis. Indicative of the interest and progress in this area is a book on "Stability Theory" by Professor H. Leipholz of the University of Waterloo, published by Academic Press. He has another book coming out soon on "Stability of Elastic Systems". Regarding the study of linear structures, an interesting theory was proposed to define the greatest maximum response to incompletely described loads. The simplicity of the theory is that quite reasonable estimates of maximum response are provided, yet less knowledge than previous theories is required.

Ground shock and blast are of considerable interest. Special measurement techniques provide more complete understanding of blast wave phenomena. Response of buried structures, such as pipelines, to seismic shock, soil-structure interaction phenomena, and soil dynamics are all areas with contributions worthy of note. Damping, particularly in joints, and fatigue are subjects of ongoing study. A portable sonic boom simulator is rather a unique contribution to testing. Some pioneering efforts relative to the analysis of flexible spacecraft may be useful to upcoming U.S. programs.

France

France is well-advanced in computer technology, with their own finite element program, TITUS, and a special program to calculate the response of thick structures damped by viscoelastic layers, ASTRE. Progress in noise research is significant, with aircraft noise studies particularly prominent. Major advancements in noise reduction have been achieved. Shock environments and their simulation are of considerable interest and progress is evident. Instrumentation capabilities are excellent; some rather interesting advancements have been made. Contributions to modal survey testing are considered to be very useful, adding to the advancement in this area. Wind tunnel work in France is pushing the state-of-the-art, particularly with respect to control of test variables.

The most significant contributions to component studies are on blades and bearings, with some interesting work on piping network analysis. Research on aircraft, space systems and ships is very active, with commendable results coming from all areas. Flutter studies are particularly prominent. Advanced analysis techniques for spacecraft are being developed, with the expectation of using the U.S. Space Shuttle. Contributions to ship vibration studies from Bureau Veritas are noteworthy. France is the headquarters for AGARD the Advisory Group for Aerospace Research and Development and is closely tied to the European Space Agency (ESA), with headquarters in the Netherlands. These two organizations are the best sources of available information on current European aerospace technology.

India

India is very strong in analytical methods and mathematical modeling, especially the modeling of plates and shells. Advances have been made in nonlinear analysis and numerical techniques. Results of work related to damping treatments for structures is useful. In the experimental area techniques for multipoint excitation of aircraft for ground vibration surveys are noted. Some outstanding research studies on blades, bearings and linkages are evident. In aircraft research flutter studies seem to be the greatest contributions. Some interesting developments related to off-road vehicles have been made, particularly related to rough terrain and vehicle response.

Israel

Some of the more fruitful analytical efforts in Israel relate to optimization, parameter identification and nonlinear analysis. Such problems as aircraft structural optimization for flutter requirements and the development of a random algorithm for the dynamic optimization of gear mechanisms represent typical efforts. The most lucrative study of material properties has related to

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Italy

Analytical techniques suitable for use on strongly nonlinear systems have been developed to analyze response to forced vibration. Plasticity studies are evident, both for perfectly plastic and elasto-plastic structures. A noteworthy computer program EURDYN, was developed to handle transient dynamic problems stemming from fast reactor safety. As indicated by the literature, the environment of most interest seems to be underwater acoustics. Useful works on the response of spacecraft cables to torsional vibration and on vortex shedding are available. Prominent studies of systems relate to aircraft/stores compatibility, pipe whip analysis for nuclear reactor problems, and rotor dynamics.

Greece

Two major areas of work are obvious from the literature. The interest in Greece on the structural analysis of beams seems to be the most prominent, including rather complex problems involving beam-columns with concentrated masses and springs at the support. There is also a special interest in the use of vibration for soil compaction and the analysis that attends this process. Of special note is the control device, employing a laser, which allows for the control of the frequency and force on the compacter to obtain a selected soil density. Greece has also offered an interesting use of the Laplace transform in structural analysis for natural frequency determination.

Japan

Japan has developed advanced methods for using analog computers to simulate nonlinear systems. They are also used for checking theoretical calculations by some members of the Japanese academic community. Some of their analog applications might well prove useful to others. Digital computer programs are also in evidence, such as the general purpose programs, ISTRAN/S, which will handle large deflections.

Japan is quite advanced in the area of machine tool development, and one may easily deduce that their manufacturing technology is superior. Extensive research in such areas as damping in joints and welds supports their technological advancement. They have also made significant advances in computer-aided design, which enhances their industrial capabilities by optimizing the dynamic characteristics of machinery. The use of great quantities of steel, as in the shipbuilding industry, has led to expertise in metallurgical research, especially in welding technology.

Significant advances in noise reduction and control have been made in Japan with respect to a wide range of vehicles and equipment. Examples are automobiles, Diesel engines, ships and machinery. The use of scale models for testing is widespread, for such problems as wind-induced excitation, seismic excitation and sloshing dynamics. Research and development on high speed transportation systems is active, as well as extensive studies of dynamic hazards to present transportation systems.

Understandably, Japan has a strong national program of research in aseismic design. The Earthquake Resistant Structures Research Center in Tokyo is the centralizing activity for these efforts. A wide range of analytical and experimental (often with scale models) programs are underway to support better seismic-resistant designs of nuclear reactors, conventional power plants, rail systems, dams, bridges and buildings, among others. Last but not least, mention should be made of Japan's industrial health program, including biodynamics, in which such subjects as whole-body vibration and shock effects, and hand-arm vibration response are studied.

Netherlands

The central organization in the Netherlands for much of their applied scientific research (TNO) is in Delft. Several subsets of TNO are oriented toward specific application areas such as mechanical constructions, industrial research, and buildings and metals. Ship research administration is now at the Netherlands Maritime Institute in Rotterdam. The European Space Agency, headquartered in the Netherlands is the central point for space research and development in western Europe.

Advances in analysis are principally in the area of numerical methods. Advances in acoustic measurements are prominent at the Institute of Applied Physics, TNO. Dynamics work at the Institute for Mechanical Constructions relates to such areas as condition monitoring of marine diesels and the dynamics of bearings and seals. Research related to aircraft flutter and fatigue has produced interesting contributions. The results of a number of studies related to spacecraft dynamics are available. Noise control is an active area with quite reasonable progress, especially with respect to urban noise problems.

Belgium

Dynamic studies related to nuclear power plants is probably one of the most lucrative areas of work, notably at the Societe de Traction et D'Electricte S.A. in Brussels. A primary area of study is related to accidentally-loaded structures, internally or externally. The loads may come from broken pipes as missiles (internally) or aircraft crashes (externally), for example. Interesting energy absorption techniques for the protection of such structures have been studied. Another area of high interest in Belgium is noise reduction. The most interesting results are from urban noise studies.

Sweden

Sweden is very active in noise control in their industrial environments, as evidenced by their recent strong participation in the INTERNOISE 78 meeting. Of special note was their publication of the "ASF' Handbook. This publication, written in everyday language with no formulas and many excellent illustrations, is an attempt to relate the basic principles of machinery and industrial noise control to the workers who live in the noise environments.

There is progress related to computer program development, the most significant for aerodynamic calculations. Damping of wind-excited structures has been studied with some success. In line with their active acoustics work, acoustic instrumentation developments are commendable. Sweden is active in vibration testing. Their modal survey techniques that have been developed add to the world's capabilities in this field. Very active research programs on aircraft, ships and submarines have produced some valuable results.

Norway

Analytical studies in Norway are not published extensively, but a method of calculating crack propagation in 3-dimensional solids is worthy of note. The most interesting computer program is for ship applications. SESAM-69 employs super elements. Noise-control and ships research are the most productive areas. Efforts in the latter area are lead by Det Norske Veritas. The efforts are aimed principally at vibration problems and noise control, with some significant successes. Of special note is a series of scale model tests, in which the models were exposed to air blast propagation to simulate the effects of explosions in underground ammunitions storage sites. The tests were sponsored by the Norwegian Defense Construction Service.

Denmark

Many of the technical contributions from Denmark are produced by the Technical University of Denmark at Lyngby. The outstanding work of Dr. J.W. Lund and his colleagues on rotor dynamics is recognized on a world-wide basis. Particularly significant contributions have been made in the areas of rotor balancing and unstable whirl. Dr. J.J. Jensen and others in the Department of Ocean Engineering have made significant contributions related to ship dynamics in heavy seas. Professor O.J. Pedersen is an active researcher in psychoacoustics. He participates in many international activities related both to research and standardization. Elsewhere in Denmark, the study of the structural integrity of nuclear reactor containments is pursued. Special contributions have been made on techniques and equipment for real time analysis of vibration data.

Switzerland

Useful nonlinear analysis techniques have been published. Computer programs developed in Switzerland are for the transient analysis of nuclear power plant turbines or for symbolic manipulation. Noise reduction efforts related to aircraft, railways, and machinery have produced useful results. The main other area to be noted, aside from some rather useful work related to civil defense, is the substantial effort related to nuclear reactor safety, particularly on containment structures. Penetration due to impact is the prime consideration.

West Germany

The literature from West Germany indicates excellent capabilities in the analytical area, with particular emphasis on nonlinear analysis, statistical methods, and the use of Fast Fourier Transforms. Some useful work is also evident on parameter identification methods. The real strength of their analyitcal capabilities is reflected in the applications of these techniques to support their extensive system development efforts. They are quite progressive in the development of large, general purpose computer programs. The program, ASKA, is in some respects better than NASTRAN, particularly with respect to nonlinear capabilities. The West Germans are among the world leaders in the use of computer-aided design techniques. Environments given the greatest emphasis for study seem to be acoustics, shock, and to a lesser degree, transportation. Noise measurement and control is active and productive. There is a broad interest in shock. One interesting concept for shock studies, the Shock Polygon, was introduced in W. Germany by Professor K.E. Meier-Dornberg of the Technishe Hochschule, Darmstadt. Attention is paid to the measurement of transportation vehicular vibration.

Damping and fatigue are the major materials properties that are studied, with special emphasis on fatigue. Experimental work is active in all areas with very useful contributions. Special techniques have been developed for torsional testing. Productive studies are available on all components; special note is taken of outstanding work on bearings and gears. In the systems area there are similar broad interests and capabilities. Aerospace technology is strong, both on the dynamics of aircraft and on spacecraft. Spacecraft technology is currently extended to large flexible structures involving the interaction of structural response and control systems. Research results are available related to rail and road systems, principally aimed at vibration problems, noise reduction and vehicle safety. Reactor technology is high, with many noteworthy contributions. The West German machine tool technology is among the front runners in this field. Progress and results in rotor dynamics are excellent. Active pursuit of research in biodynamics has made a permanent place for West Germany in the human response community.

FUTURE TRENDS

Analysis and Design

Future programs or problems, such as the need to design stronger and lighter structures, to reduce cost and to increase safety, will demand a general increase in our analytical capabilities. This will be particularly true with respect to nonlinear problems. The finite element method is now widely used for dynamic, as well as static, analysis. One of the more important aspects of this and other analysis tools is the modeling. By necessity, we will see increased efforts to improve modeling techniques and more research on methods aimed at reducing the number of elements required for the model, such as component mode synthesis. Although a number of very useful statistical analysis techniques are available, the application of these methods are somewhat limited. Future activities are expected to be toward more widespread understanding through better documentation and educatonal mechanisms such as seminars. In general, the trends in analysis are expected to be toward simplification, wherever possible, without attendant loss of accuracy. Increased emphasis on the development of design optimization techniques is also expected.

Computer Programs

As our problems continue to increase in complexity, there will be more requirements to increase performance of computer hardware, as well as for greater capabilities in software. Along this line, as the number of computer programs continues to grow, there will be more emphasis on programs for systematic evaluation of software capabilities, to make this information available to software users. Ever increasing emphasis will be placed on the development of computer-aided design techniques. The use of minicomputers and microcomputers is expected to increase in support of analytical and experimental research.

Environments

The requirements for noise control are expected to grow, and, in this light, there will be requirements for improved noise measurement techniques principally aimed at noise source identification. In general, there should be requirements for increased accuracy in the measurement and prediction of all dynamic environments. Such efforts would support the development of more realistic design criteria and introduce increased confidence in environmental and reliability test criteria. Emphasis is expected on increased understanding of seismic phenomena, including extensive research on seismic prediction techniques. It is reasonable to predict a new look at transportation environments, particularly for the newer forms of transportation.

Phenomenology

Damping investigations will continue, with expected emphasis on high temperature applications, new damping materials, methods of "designing" damping into structures, and better methods for handling damping in analysis. Studies on fatigue will receive increased attention, motivated by more adverse life environments created by new vehicles such as the SPACE SHUTTLE. Research will increase on the development of composites and the understanding of their performance. The newer metal-metal matrix materials are expected to receive special attention. Work will accelerate in the general area of media-structure interaction (air, water, soils) to solve some of the more difficult problems not yet fully understood.

Experimentation

Work will continue to achieve greater accuracy and capabilities in instrumentation. Computer usage will likely continue to enter into more and more phases of the testing process. In general, there will probably be some reduction in the total number of tests performed, as more confidence is gained in analytical procedures. There will likely be more challenges relative to unusual test requirements, such as dynamic tests in a zero-g environment. A rapid increase in the use of scale models for testing is expected. The expected reduction in endurance testing will likely mean even a greater emphasis on modal testing to validate designs.

Components

Computer-oriented analysis techniques for the design and study of mechanical components is expected to continue to increase. Goals are, and will be, to optimize the designs for increased efficiency, reduced wear and longer life. Analysis techniques will place more emphasis on incorporating manufacturing defects and operational parameters into the model. Newer techniques for analysis of structural elements will continue to be developed, contributing significantly to our capabilities to handle applications-oriented problems.

Systems

Systems developments will continue to require greater performance, longer life, higher strength and lighter weight, all at optimum cost. These requirements will continue to test our research and development capabilities. Thus, research efforts in support of all systems areas will continue to expand. Areas worthy of receiving special mention are large flexible space structures with their control/structural response interaction problems, increased requirements for safety and efficiency in reactors, increased performance requirements for rotors, and a better understanding of human response to dynamic loads. The challenge is great, but it is believed that it will be met.

APPENDIX

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Sample Letter

SHOCK AND VIBRATION INFORMATION CENTER

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It is the mission of this Center to collect, analyze, categorize and disseminate technical information generated around the world which is concerned with shock, vibration, acoustics and related dynamic areas. Up until now we have done this principally by scanning the world's journals and abstracting relevant technical papers, then indexing these papers to become a part of our shock and vibration information base. The results of our work are disseminated princiaplly in our monthly Shock and Vibration Digest with which you may be familiar.

Although the efforts described above provide us with considerable useful information, we feel somewhat lacking in our knowledge of ongoing programs and perhaps results of studies completed in the recent past. This letter is to solicit information of this nature.

You are recognized as a key investigator on subjects within our technology. We would be most appreciative if you would provide us with some description(s) of your current work and interests, supplemented perhaps by reprints of recent technical papers you have written. We are also very much interested in your opinions on areas within our technology that are critically in need of further investigation.

We freely admit that this request is very general in nature, not giving specific direction for your response. Please be guided by your own judgment as to any information you are kind enough to furnish, hopefully with minimum labor on your part.

We look forward to hearing from you.

Sincerely,

Henry C. Pusey
Director

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