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SHOCK LOADS ON PIPING SYSTEMS

Dennis Harold Peters

Naval Postgraduate School
Monterey, California

September 1972

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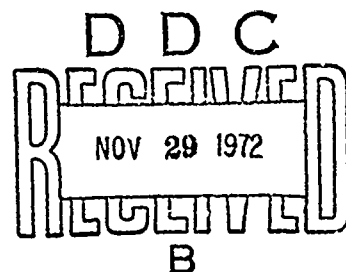
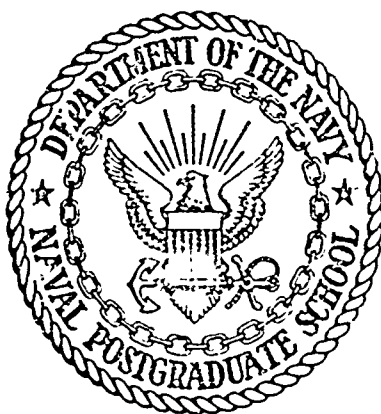
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THESIS

SHOCK LOADS ON PIPING SYSTEMS

by

Dennis Harold Peters

Thesis Advisor:

R.E. Newton

September 1972

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE Shock Loads on Piping Systems			
4. DESCRIPTIVE NOTES (Type of report and, inclusive dates) Master's Thesis; September 1972			
5. AUTHOR(S) (First name, middle initial, last name) Dennis Harold Peters			
6. REPORT DATE September 1972		7a. TOTAL NO. OF PAGES 87	7b. NO. OF REFS 15
8a. CONTRACT OR GRANT NO		9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO			
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940	
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Shock Loads on Piping Systems

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the
NAVAL POSTGRADUATE SCHOOL
September 1972

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ABSTRACT

This thesis describes the development of a Fortran IV computer program for finding shock-induced stresses in a three-dimensional piping system. Discretized equations of motion are formed by the finite element method. Input motions are support translations specified by response shock spectra. Maximum responses in individual modes and resulting octahedral shearing stresses at selected points are found for shock motions in three orthogonal directions. Extreme stresses, based on the square root of the sum of the squares of the modal stresses, are estimated for each input direction. An example problem is analyzed to demonstrate the use of the program.

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LIST OF SYMBOLS

A single underline on a capital letter denotes a rectangular matrix, and a single underline on a lower case letter denotes a column vector. Superior dots denote time derivatives. The symbols used in the computer program are described in Appendix E.

A	Element cross-sectional area
b_r	Mode participation factor, mode r
C	A constant
D	Pipe outside diameter
E	Young's modulus
$\underline{f}^e$	Element generalized force vector
f_i	Components of the generalized force vector
G	Shear modulus
I	Second moment of the pipe cross-sectional area about a diameter
$\underline{I}$	Identity matrix
J	Mass moment of inertia per unit length about pipe axis
$\underline{K}$	Assembled stiffness matrix
$\underline{K}^e$	Element stiffness matrix
ℓ	Length of an element
$\underline{M}$	Assembled inertia matrix
$\underline{M}^e$	Element inertia matrix
$\underline{M}_{B12}^e$	Element inertia submatrix, bending 1-2 plane
$\underline{M}_{B13}^e$	Element inertia submatrix, bending 1-3 plane
$\underline{M}_L^e$	Element inertia submatrix, longitudinal motion

$\underline{M}_T^e$	Element inertia submatrix, torsional motion
m_r	Modal mass, mode r
m_L	Mass of the lagging per unit length
m_P	Mass of the pipe per unit length
$\underline{N}$	Row vector of shape functions
$\underline{p}$	Vector of principal coordinates
p_r	Principal coordinate, mode r
Q	Moment of pipe cross-sectional area lying on one side of neutral axis
$\underline{q}$	Displacement vector
r	Radius of gyration
s	Base displacement
T^e	Kinetic energy of an element
t	Pipe wall thickness
$\underline{u}$	Vector of absolute displacements corresponding to unit base displacement
u_i	Components of displacement vector
$\underline{V}$	Modal matrix
$\tilde{V}_r$	Spectrum velocity, mode r
$\underline{v}_r$	Eigenvector, mode r
W_L	Weight of lagging per unit length
W_P	Weight of pipe per unit length
$\underline{w}$	Absolute displacement vector
z	One degree-of-freedom system coordinate
γ_m	Modified specific weight
ξ	Dimensionless length coordinate
ρ	Density
σ	Modal stress
τ	Shearing stress

τ_{oct}	Octahedral shearing stress
$\underline{\Omega^2}$	Spectral (diagonal) matrix
ω	Natural circular frequency, one degree-of-freedom system
ω_r	Circular frequency of mode r

Superscripts

T	Transpose of matrix
(r)	Mode designator for eigenvectors (r=1,2,...,n)

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my advisor, Professor Robert E. Newton, for his invaluable assistance and constructive supervision in the preparation of this thesis, and to Professor Gilles Cantin for his assistance in the computer work.

I would also like to express my thanks to the staff of the W.R. Church Computer Center, Naval Postgraduate School.

I. INTRODUCTION

With the greater demand for electrical power, and the diminishing fossil fuel supply, there has been an increase in the construction and use of nuclear power generating plants. Correspondingly, there has been greater concern for the safety of the power plant during an earthquake.

Also, the reduction in the size of the Navy has led to an increased emphasis on the integrity of the internal systems of a naval vessel under shock loads. Thus, there has been a growing engineering interest in finding a rapid and accurate method of analysis to determine the shock-induced stresses in a complex continuous piping system. This thesis describes and presents a computer program, written in Fortran IV computer language, to find the stresses in a piping system responding to shock.

Complex piping systems can be analyzed by using discretized models. In using the discretization technique, the continuous piping system is modeled by finite size elements connected at nodes. After the system has been subdivided, the elastic and inertial matrices of each element can be found and assembled to form the elastic and inertial matrices of the system [1,2].

A considerable volume of material is available to assist in analyzing structures and systems responding to earthquakes [3,4,5]. Two of the techniques used in earthquake response analysis are modal analysis with a

discretized model and transfer functions [4,5]. The shock input for earthquakes can be specified by using time history [3], or shock spectrum [4,5].

The Navy uses a technique called the Dynamic Design-Analysis Method (DDAM) to determine the shock response of shipboard equipment and systems [6]. The DDAM is a modal analysis technique using shock spectra to specify the shock inputs.

The shock spectrum presents, as a function of the system natural frequency, the maximum response of a one degree-of-freedom system responding to a shock motion. The shock spectrum is generally presented in terms of response velocity or acceleration.

Several graduates of the Naval Postgraduate School have written theses on determining natural frequencies and mode shapes for piping systems. Fink [7] developed a program to analyze planar piping systems, including out-of-plane bending, using transfer matrices. Baird [8] presented the necessary theory to expand Fink's work to a three-dimensional piping system. Rudolf [9] developed a program that determines the frequencies of a general three-dimensional piping system. Because the transfer matrix does not yield a discretized model of the structure, there is no ready means for using the frequency and mode shape data to find shock-induced modal responses. On the other hand, the finite element technique provides a consistent discretized model

which may be used for finding frequencies, mode shapes, modal responses to shock inputs, and resulting stresses. For this reason the finite element method was chosen for this thesis.

Shock spectra and mode participation factors are used to determine the modal responses. At selected points the modal octahedral shearing stresses are combined by scalar addition of the distortion energy to estimate extreme stresses.

II. THEORY

Material and structural linearity and material local homogeneity and isotropy are assumed in developing the mathematical model.

A. MODEL LIMITATIONS

There are few inherent restrictions on the capabilities of the finite element method to model complex details of piping configurations. Considerations of the quantity of input and output data, program length, core storage capacity, computing time, and cost do impose practical limitations. The limited time available in developing this thesis has necessitated the following restrictions on the model used here.

The system consists of straight lengths of constant-section pipe (elements). Each element centerline is parallel to one of the three mutually orthogonal global reference axes, and 90° bends are replaced by fictitious extensions of the tangent sections to the intersection point of the centerlines. Effects of added mass contributed by external lagging are represented, but no provision is made for added mass due to valves or fittings. Pipe hangers furnishing uniaxial restraint in a global direction may also be represented. Bending action is described by the Euler-Bernoulli beam theory, neglecting shear deformation.

and rotatory inertia. All ends of the configuration are treated as fixed. The shock input motion is a translation of the base¹ along a global axis.

B. FINITE ELEMENT METHOD

Once the system has been subdivided into elements, the elastic and inertial characteristics are determined. The element stiffness matrix can be determined by many different techniques, whereas the inertial matrix is generally determined by using shape functions and integrating along the length, [1,2].

1. The Element Displacement Vector

Consider an element with displacement components at the nodes (ends) as shown in Fig. 1.

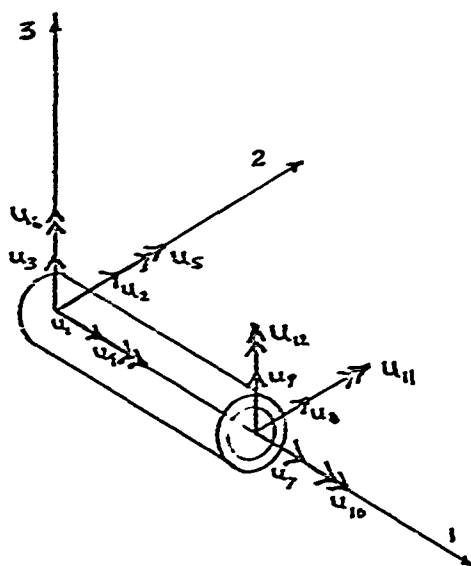


FIG. 1

ELEMENT GENERALIZED DISPLACEMENTS

¹The clamped ends of the configuration are treated as joined to a rigid base.

Here, the double arrowhead vectors are positive rotations in accordance with the right-hand rule. The displacement vector is

$$\underline{q} = [u_1 \ u_2 \ \dots \ u_{12}]^T$$

From Fig. 1, components u_1 and u_7 are longitudinal displacements, components $u_2, u_3, u_5, u_6, u_8, u_9, u_{11}$ and u_{12} are bending displacements and rotations in the 1-2 and 2-3 planes, and components u_4 and u_{10} are twisting rotations.

2. Element Stiffness and Inertial Matrices

Przemieniecki [2] forms the element stiffness matrix by solving the differential equations of the element displacements. Appendix A reproduces the element stiffness matrix with Przemieniecki's transverse shear deflection factor (ψ) set equal to zero.

To determine the element inertia matrix, an expression for the element kinetic energy T^e is formed, rotatory inertia due to bending being neglected.

$$T^e = \frac{1}{2} C \ell \int_0^1 \underline{\dot{q}}^T \underline{N}^T \underline{N} \underline{\dot{q}} \, d\xi = \frac{1}{2} \underline{\dot{q}}^T \underline{K}^e \underline{\dot{q}}$$

where ℓ is the element length, C is a constant, $\underline{K}^e$ is the element inertia matrix, $\underline{N}$ is the shape function row vector, and ξ is a dimensionless length coordinate.

Therefore

$$\underline{M}^e = C \ell \int_0^1 \underline{N}^T \underline{N} d\xi \quad (1)$$

Since the local element axes coincide with the cross section principal axes, the inertia matrix may be determined from 2x2 and 4x4 element sub-matrices. Consider the following motions of the element:

a) longitudinal:

$$\underline{q}_L = [u_1 \ u_7]^T, \quad N_1 = 1 - \xi, \quad N_7 = \xi$$

and $C = \rho A$ where A is the cross-sectional area of the element and ρ is the density. From Eq. 1

$$\underline{M}_L^e = \frac{\rho A \ell}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \quad (1a)$$

b) twist:

$$\underline{q}_T = [u_4 \ u_{10}]^T, \quad N_4 = (1 - \xi)\ell, \quad N_{10} = \xi\ell$$

and $C = J$ where J is the mass moment of inertia per unit length about the pipe axis. From Eq. 1

$$\underline{M}_T^e = \frac{J \ell}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \quad (1b)$$

c) bending in the 1-2 plane:

$$\underline{q}_{B12} = [u_2 \ u_6 \ u_8 \ u_{12}]^T, \quad N_2 = 1 - 3\xi^2 + 2\xi^3, \\ N_6 = \ell(\xi - 2\xi^2 + \xi^3), \quad N_8 = 3\xi^2 - 2\xi^3, \quad N_{12} = \ell(-\xi^2 + \xi^3),$$

and $C = \rho A$. From Eq. 1

$$\underline{M}_{B12}^e = \frac{\rho A \ell}{420} \begin{bmatrix} 156 & 22\ell & 54 & -13\ell \\ 22\ell & 4\ell^2 & 13\ell & -3\ell^2 \\ 54 & 13\ell & 156 & -22\ell \\ -13\ell & -3\ell^2 & -22\ell & 4\ell^2 \end{bmatrix} \quad (1c)$$

Bending in plane 1-3 results in the same numerical coefficients as $\underline{M}_{B12}^e$. Because the positive senses for the rotation angles are reversed, rows 2 and 4 and columns 2 and 4 are multiplied by minus one. These submatrices are assembled to form the element inertia matrix. This matrix is displayed in Appendix A.

C. ASSEMBLED EQUATIONS OF MOTION

The governing equations of motion, in matrix notation, for undamped free vibration [2] with a fixed base are

$$\underline{M} \ddot{\underline{q}} + \underline{K} \underline{q} = 0 \quad (2)$$

where $\underline{q}$ is the assembled displacement vector and $\underline{M}$ and $\underline{K}$ are the assembled inertial and stiffness matrices. $\underline{M}$ and $\underline{K}$ are referred to a global coordinate system and $\underline{M}^e$ and $\underline{K}^e$ are referred to local coordinates. The assembly process consists of realigning the local system to the global system and building the $\underline{M}$ and $\underline{K}$ matrices. Reference [2] gives sample assembly techniques.

D. MODAL ANALYSIS

Modal analysis is the process of finding the response motion of a many degree-of-freedom system by superposition of the response motions in the principal (or natural) modes. This technique is advantageous because the motions in the principal modes are independent of one another (uncoupled). To use the method, it is first necessary to find the natural frequencies and mode shapes for the free motions governed by Eq. 2, i.e., to solve the eigenvalue problem $\underline{K} \underline{v} = \omega^2 \underline{M} \underline{v}$.

Finding eigenvalues (ω^2) and eigenvectors ($\underline{v}$) is a standard problem of numerical analysis. The first step is a transformation to a single-matrix problem. Details of the transformation used here, which requires a Cholesky decomposition of the inertia matrix, are given on p. 349 of reference [1]. Following this, Jacobi rotations [15] are used to find the spectral and modal matrices ($\underline{\Omega}^2$ and $\underline{V}$). The modal matrix is normalized with respect to the inertia matrix, i.e., $\underline{V}^T \underline{M} \underline{V} = \underline{I}$, where $\underline{I}$ is the nth order identity matrix.

The shock analysis is based on using velocity shock spectra to characterize the input motion and mode participation factors to determine the responses. Although both shock spectra and mode participation factors have been extensively used in earlier studies [6], the finite element

discretization necessitates a new development of working formulas. Details of this development are given in Appendix B.

Each shock input motion consists of base translation parallel to a global axis. It is shown in Appendix B that the mode participation factor b_r for mode r is

$$b_r = \underline{v}^{(r)T} \underline{M} \underline{u} \quad (B.5)$$

where $\underline{v}^{(r)}$ is the modal eigenvector and $\underline{u}$ is the vector of absolute displacements corresponding to unit base displacement. The maximum relative displacements due to mode r response are

$$\underline{q}_{\max} = \underline{v}^{(r)} b_r \tilde{V}_r / \omega_r \quad (B.6a)$$

where ω_r is the modal circular frequency and $\tilde{V}_r$ is the spectrum velocity at that frequency.

Since responses to shock inputs in each of the three global directions are separately determined, the vector $\underline{u}$ and the mode participation factors b_r must be evaluated separately for each direction. The modal masses m_r (see Appendix B) are likewise different for each input direction.

E. GENERALIZED FORCES AND STRESSES

The subvector $\underline{q}^e$ of element peak modal displacements may be found from the system vector, taking into account the

orientation of the local reference axes. From this the element generalized force vector $\underline{f}^e$ is determined. This force vector consists of the elastic and inertial contributions for each element.

$$\underline{f}^e = (\underline{K}^e - \omega_r^2 \underline{M}^e) \underline{q}^e \quad (3)$$

Fig. 2 shows the positive directions for the components of the generalized force vector.

$$\underline{f}^e = [f_1 \ f_2 \ \dots \ f_{12}]^T$$

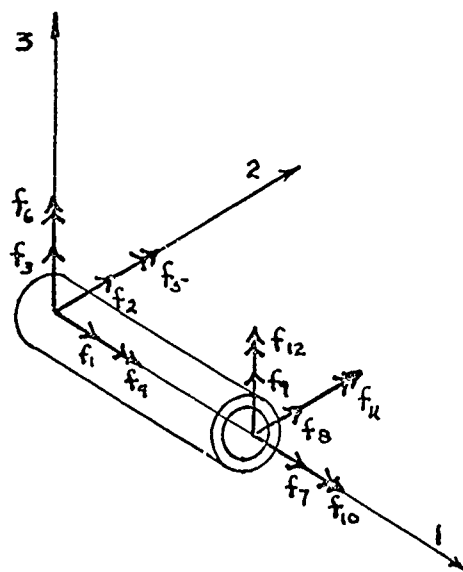


FIG. 2
ELEMENT GENERALIZED FORCES

The stresses at the nodal points of the element can be determined from the generalized forces by standard methods of solid mechanics [10].

III. PROGRAM DEVELOPMENT

The computer program was written in Fortran IV computer language using double-precision arithmetic on an IBM 360/67 digital computer. It consists of a main calling program and seven subroutines. The main program calls the subroutines, where the actual calculations occur, in the necessary order. Information is passed between the main program and the subroutines by the use of a common storage core. Appendix E contains the program listing.

A. SYSTEM DESCRIPTION

After the piping system has been modeled and subdivided, subroutine INPUT is used to read the data input of the geometry and material properties of the system. The geometry of the piping system model is determined by the global coordinates of the nodes of the model. The global system is a right-handed orthogonal coordinate system. Each pipe segment must be parallel to a global axis, but there are no restrictions on the placement of the origin of the global system. The parameters from the subdivision of the system are read. For each node the global coordinates and boundary conditions are read. If the node is fixed, the stiffness and inertial matrix components due to the node displacements are not assembled into the system matrices.

The numbering of nodes and elements is arbitrary. There are two nodes per element and six degrees of freedom per node. For each element, the node numbers and pipe group are read. A pipe group includes all elements that have the same Young's modulus, Poisson's ratio, specific weight, radius of gyration, and cross-sectional dimensions. Appendix D shows the method used to calculate the effect of lagging on the specific weight and the radius of gyration.

B. STIFFNESS AND INERTIAL MATRIX FORMULATION

Subroutine FORM generates the element stiffness and inertia matrices as shown in Appendix A. Rotatory inertia and shear deformation due to bending are neglected. The orientation of the element is determined with respect to the global coordinate system and the correspondence between local and global degrees of freedom is established. After determining the correspondence between the local and global degrees of freedom, the element stiffness and inertia matrices are assembled to form the system stiffness and inertia matrices. If pipe hangers are present, the corresponding (uniaxial) hanger stiffnesses are added to the appropriate diagonal elements of the system stiffness matrix.

C. FREE VIBRATION MODE SHAPES AND FREQUENCIES

Subroutine CHMOD uses Cholesky decomposition of the system inertia matrix and coordinate transformation to form

a single symmetric matrix for which eigenvalues and eigenvectors are found. Subroutine JACROT is a modification of a program originally coded by Professor G. Cantin. It uses the Jacobi variable threshold method to find eigenvalues and eigenvectors of a real symmetric matrix. The modal matrix, when transformed back to system coordinates, is normalized with respect to the system inertia matrix.

Since the system matrices increase in size with finer subdivisions or more complex systems, an economizing technique, to reduce the number of degrees of freedom in the eigenvalue problem, was investigated during the program development. The component mode synthesis method as used by Benfield and Hrudá [11] was studied. It was established that the constrained component branch technique [11], with interface loading, with no node suppression gave results identical with those obtained by the direct method described above when applied to planar vibration of a clamped-clamped beam represented by six elements. Despite the success of this trial, it was concluded that the added program complexity accompanying the use of component mode synthesis would offset the potential economies. Another standard economizer technique [14] was considered, but ultimately rejected for the same reason.

D. MODAL RESPONSE

The number of modes to be used in the stress analysis and the specification of the shock spectrum are input data

for subroutine SPCYRM. There are three choices available to select the number of modes to be used: a designated upper frequency limit, an upper limit which is a multiple of the fundamental frequency, and an option for any method the user desires. Three choices are also available for specifying the shock spectrum: a spectrum defined by straight-line segments; a constant velocity, then constant acceleration shock spectrum; and an option for any method the user desires. The shock input is restricted to a translation of the base along a global axis and is specified by one shock spectrum and three scaling factors for the three input directions. Subroutine WQDE modifies the spectrum velocity for modal mass, if desired. There are three choices available: no correction, log of the modal weight correction, and an option for any method the user desires. This subroutine also calculates the mode participation factors.

E. STRESSES

Subroutine STRESS calculates stresses at the nodes of the elements. The element peak displacements are determined and realigned from global degrees of freedom back to the local element degrees of freedom. The element generalized force vector is then calculated. Consider the action of the generalized force vector on the element shown in Fig. 3.

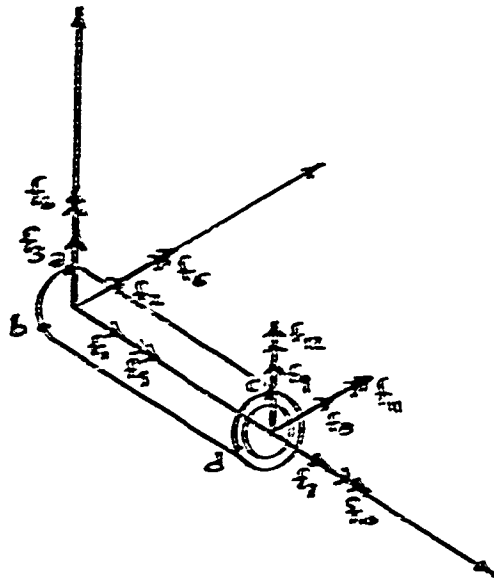


FIG. 3
STRESS LOCATION POINTS

At locations a, b, c, and d, the stress vector acting on the cross-section may be resolved into normal and shearing stresses. Fig. 4 shows the positive sign convention used for the normal and shearing stresses.

The normal stress σ and the shearing stress τ at each point shown in Fig. 3 are given by:

1. at location a)

$$\sigma = -f_1/A - f_5 D/2I$$

$$\tau = -f_4 D/4I + f_2 Q/2It$$

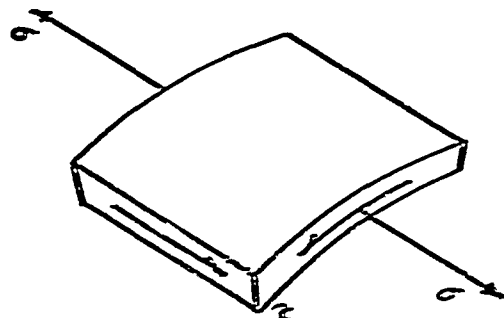


FIG. 4
POSITIVE STRESS CONVENTION

where I is the second moment of cross-sectional area about a diameter, D is the outside diameter, Q is the first moment, about a diameter, of the portion of the cross-sectional area lying on one side of the diameter, and t is the pipe wall thickness.

2. at location c)

$$\sigma = f_7/A + f_{11} D/2I$$

$$\tau = f_{10} D/4I - f_8 Q/2It$$

3. at location b)

$$\sigma = -f_1/A - f_6 D/2I$$

$$\tau = -f_4 D/4I + f_3 Q/2It$$

4. at location d)

$$\sigma = - f_7/A - f_{12} D/2I$$

$$\tau = f_{10} D/4I - f_9 Q/2It$$

These normal and shearing stresses are then used to find the octahedral shearing stresses [12], which are given by

$$\tau_{oct} = 1/3 (2\sigma^2 + 6\tau^2)^{\frac{1}{2}} \quad (4)$$

For each element the above calculations are performed for each mode. At each of the four points, the shearing stresses for the individual modes are then combined by determining the square root of the sum of their squares. This process is accomplished for each input direction. This is done for each element in turn, starting with the first.

F. PROGRAM OUTPUT

All input information is echo-checked. The square of the mode frequency and the mode shape are printed for each mode. The spectrum velocities and mode participation factors are also printed. The octahedral shearing stresses at points a, b, c, and d (Fig. 3) of each element are printed for the three shock input directions.

IV. PROGRAM TESTING

In order to explore the capabilities of the program and verify its integrity, a number of plane test configurations were studied. These are described in the following sections.

A. TEST PROBLEM 1

The configuration shown in Fig. 5 has three identical uniform runs of equal length between the central junction and the clamped edges.

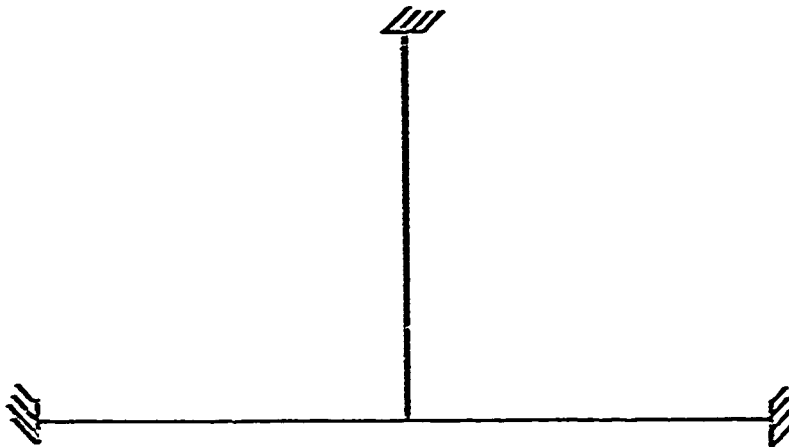


FIG. 5
TEST PIPING SYSTEM 1

The mode shapes and frequencies for in-plane vibration of this system were studied extensively with a developmental program. The present program gave identical results for the

in-plane modes. The out-of-plane modes exhibited the required symmetric or anti-symmetric form.

Additional program tests on this configuration involved different element numbering and node numbering and six different orientations of the global axes relative to the structure. Mode shapes and frequencies were unaffected by these changes.

B. TEST PROBLEM 2

This system, shown in Fig. 6, consisted of a straight uniform pipe clamped at the ends and represented by four elements.



FIG. 6

TEST PIPING SYSTEM 2

The frequencies found for the lower modes showed good agreement with exact results. Table I shows the comparison of the first three bending frequencies of the finite element solution with exact results [13]. All the eigenvectors showed the required symmetric or anti-symmetric form. Bending modes occurred in pairs having equal eigenvalues and with the corresponding eigenvectors representing deflections in orthogonal planes.

Stresses found for this system were studied in detail. At each node, the stresses are calculated at two points of the cross-section. Except at the clamped ends, there are two adjacent elements sharing each node, so that stresses at these sections are calculated twice. Complete agreement was found between these two sets of stress evaluations. Also, identical stresses resulted from shocks in the two directions perpendicular to the length.

TABLE I

COMPARISON OF FIRST THREE BENDING FREQUENCIES OF TEST
PIPING SYSTEM 2 WITH EXACT RESULTS

Mode	Exact (Hz)	Finite Element (Hz)	Percent Difference
1	422.32	422.65	0.08
2	1164.15	1174.26	0.9
3	2282.20	2329.64	2.1

C. TEST PROBLEM 3

The equal-legged configuration of Fig. 7 consists of uniform pipe throughout. Mode shapes of this system again showed the required symmetric or anti-symmetric form. Likewise, the shock-induced stresses exhibited the expected symmetry properties.

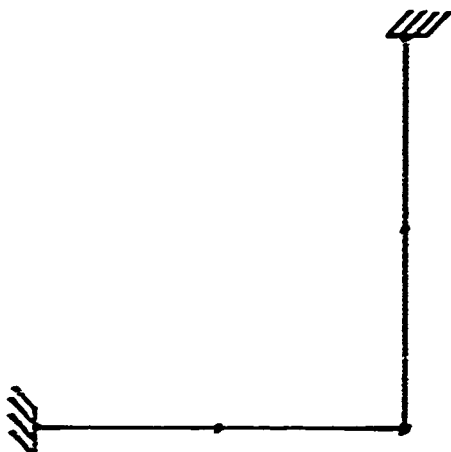


FIG. 7

TEST PIPING SYSTEM 3

V. EXAMPLE PROBLEM

A. PIPING SYSTEM

The example system analyzed is a model of the main steam piping system on a modern naval vessel. The main steam piping from the boiler to the rigid cross-connect anchor assembly is modeled. The ends of the piping system are clamped, and there are two hangers. The system is three-dimensional with no branches. The pipe properties are:

outside diameter	7.625 inches
inside diameter	6.011 inches
Poisson's ratio	0.300
Young's modulus	30×10^6 psi
specific weight	0.327 lb/in^3
radius of gyration	4.04 inches

The specific weight is a fictitious value which accounts for the weight of five inches of lagging bonded to the pipe.

Fig. 2 is a schematic of the piping system. The piping section P1 is 84 inches long, P2 is 264 inches long, P3 is 108 inches long, and P4 is 288 inches long.

B. DATA INPUT AND OUTPUT

The input data cards are punched in accordance with the instructions contained in Appendix E. The echo-check of the data is shown in Table II and is arranged as it would appear at the end of the program deck. The system

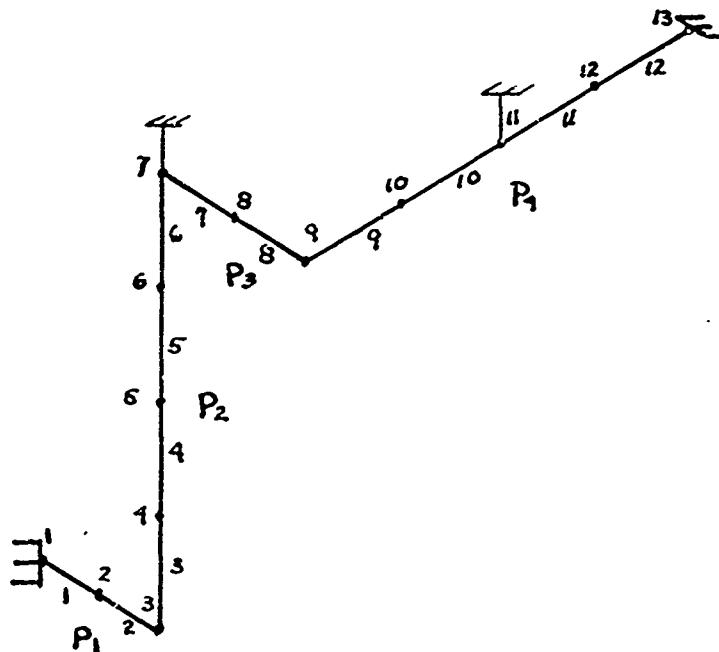


FIG. 8

EXAMPLE PIPING SYSTEM

eigenvalues and eigenvectors are listed in Appendix C, Table VIII. Tables III and IV show the modal velocities and the mode participation factors. The stress output is given in Table V.

This problem required a storage capacity of 174K bytes, and 2.67 minutes of computer time.

TABLE II DATA INPUT, EXAMPLE PROBLEM

PROBLEM NUMBER: 1

NUMBER OF PROBLEMS TO BE SOLVED 1

TOTAL ELEMENTS	TOTAL NODES	DEG OF FREEDOM PER NODE	DEG OF FREEDOM PER ELEMENT	TOTAL GROUPS	SYSTEM TOTAL DEG OF FREEDOM
12	13	6	12	1	66

NODE	X COORD INCHES	Y COORD INCHES	Z COORD INCHES	NODAL BOUNDARY CONDITIONS
1	0.0	0.0	0.0	1
2	42.00	0.0	0.0	0
3	84.00	0.0	0.0	0
4	84.00	0.0	66.00	0
5	84.00	0.0	132.00	0
6	84.00	0.0	198.00	0
7	84.00	0.0	264.00	0
8	138.00	0.0	264.00	0
9	192.00	0.0	264.00	0
10	192.00	72.00	264.00	0
11	192.00	144.00	264.00	0
12	192.00	216.00	264.00	0
13	192.00	288.00	264.00	1

ELEMENT NUMBER	LEFT NODE	RIGHT NODE	GROUP NUMBER
1	1	2	1
2	2	3	1
3	3	4	1
4	4	5	1
5	5	6	1
6	6	7	1
7	7	8	1
8	8	9	1
9	9	10	1
10	10	11	1
11	11	12	1
12	12	13	1

OUTSIDE DIAMETER IN.	INSIDE DIAMETER IN.	POISSONS RATIO	SPECIFIC WEIGHT LB/CU. IN.	YOUNGS MODULUS PSI	SHEAR MODULUS PSI
7.625	6.011	0.300	0.327	3.000D 07	1.154D 07

PIPE GROUP	RADIUS OF GYRATION INCHES
1	4.04

NUMBER OF HANGERS: 2

GLOBAL DOF	1ADOF	HANGER STIFFNESS LB/IN.
7	3	9.817477D 05
11	3	9.817477D 05

SPECTRUM TYPE	FREQUENCY TYPE
1	-1

BREAK FREQUENCY HERTZ	CONSTANT VELOCITY INCHES/SEC.
50.00	100.00

SHOCK INPUT FACTORS		
X	Y	Z
1.000	1.000	1.000

MODE WEIGHT CORRECTION TYPE 0

TABLE III. MODE VELOCITIES EXAMPLE, PROBLEM

MODE	SPECTRUM VELOCITY INCHES/SEC.
1	100.00
2	100.00
3	100.00
4	100.00
5	100.00
6	100.00
7	100.00
8	100.00
9	100.00
10	88.87
11	84.49
12	75.10
13	71.39
14	58.88
15	53.46
16	47.11
17	42.75
18	42.19
19	32.52
20	30.30
21	29.92
22	29.23
23	27.07
24	26.08
25	25.76
26	25.43
27	22.07
28	21.76
29	17.29
30	17.04
31	16.10
32	15.18
33	14.34
34	14.14
35	13.84
36	12.24
37	12.16
38	12.08
39	10.67
40	10.29
41	10.08
42	9.65
43	9.32
44	8.85
45	8.35
46	8.31
47	8.02
48	7.82
49	7.53
50	7.14
51	6.91
52	6.61
53	6.51
54	5.94
55	5.80
56	5.48
57	5.27
58	4.74
59	4.58
60	4.47
61	4.30
62	3.91
63	3.68
64	3.43
65	2.97
66	2.73

TABLE IV MODE PARTICIPATION FACTORS, EXAMPLE PROBLEM

MODE	MODE PARTICIPATION FACTORS		
	X	Y	Z
1	2.4200-01	-5.4330-01	-2.3760-01
2	8.8810-01	1.9360-00	-8.5790-03
3	6.7490-01	-2.1510-01	1.3660-00
4	1.9830-01	-8.6390-01	-2.7390-01
5	1.8130-01	3.6810-02	4.4490-01
6	1.0020-01	2.9530-02	-4.5250-01
7	-2.0020-01	8.8470-01	-5.9830-02
8	1.3420-01	2.9090-02	-4.1320-01
9	3.2810-01	7.3940-02	-1.4520-01
10	-5.3720-01	2.0870-02	-2.2340-01
11	-1.7600-01	-2.7650-02	3.7010-01
12	-1.4610-01	1.7600-02	-4.3580-01
13	-2.4360-02	-2.0570-02	-2.5810-00
14	2.1010-01	6.4130-01	-2.7710-02
15	2.1200-01	3.6170-02	6.2730-02
16	2.4140-01	-4.2060-01	-5.3080-02
17	-1.5570-01	-1.8360-01	-8.9290-03
18	-2.9990-01	2.7700-01	-9.8480-02
19	-2.5230-03	-1.5750-00	2.7830-02
20	3.7280-02	3.9690-01	4.6230-01
21	-7.0010-02	-7.5210-01	1.8320-01
22	5.6800-02	-2.8310-03	3.3900-01
23	2.7300-02	3.0590-02	1.1220-01
24	1.3720-02	-1.4560-01	-7.4960-02
25	2.0960-01	3.5980-02	5.7760-02
26	-5.2840-02	1.7100-01	-2.9510-03
27	3.0180-01	1.8490-02	-2.0460-01
28	6.8570-02	-4.1390-01	3.6120-02
29	1.5020-01	1.9650-02	2.4860-01
30	1.3430-01	-3.7780-02	5.7400-02
31	1.7410-01	-5.5900-02	-1.2860-01
32	8.7360-02	-7.8550-03	-2.3340-01
33	3.2080-01	-3.3680-02	-1.1430-01
34	2.0570-01	1.0940-01	-7.9530-02
35	-1.8320-02	1.4720-03	-1.7040-01
36	-5.6530-02	-2.6610-01	3.9710-02
37	-2.7680-01	-2.8490-02	-1.5850-01
38	-1.3380-01	4.8110-02	1.0380-01
39	5.2820-01	1.8430-02	-1.1140-01
40	-3.8480-01	-1.9360-01	-4.5490-02
41	3.2170-01	-4.5550-01	1.7640-03
42	-9.8130-02	-2.3620-01	5.5900-02
43	1.8100-01	9.5520-02	8.5750-02
44	-4.9230-01	-6.4730-03	-6.5880-02
45	-1.5170-01	4.6710-03	-9.2750-02
46	4.5190-02	2.3120-01	6.8950-03
47	-3.7150-02	8.8880-04	-4.6700-02
48	-7.1100-02	2.7250-02	-1.0660-01
49	-8.7440-02	4.0900-02	2.8070-02
50	-5.4890-02	-6.5710-02	-1.5690-02
51	3.3890-02	4.8980-02	-3.5650-02
52	8.8510-02	-1.2770-01	5.8380-02
53	-5.3290-02	-6.4960-02	-1.2310-01
54	5.0540-02	1.6870-01	8.0280-03
55	6.4810-04	-2.6370-02	-1.6450-02
56	-2.0470-02	2.8140-01	-7.3650-03
57	-2.7480-03	-5.7720-02	-3.5830-03
58	1.9600-02	-2.5910-02	-1.7730-02
59	-1.5410-01	1.0490-02	8.5290-02
60	-1.5460-01	-1.8900-02	1.1470-01
61	-8.0590-03	2.6220-02	4.9190-02
62	1.9480-03	-1.5460-01	2.3570-03
63	8.5170-05	-1.3750-01	1.0660-04
64	-3.4050-02	-5.9190-03	-3.0030-02
65	5.4040-03	-7.4280-03	6.0630-03
66	2.5240-01	4.6170-05	3.8080-02

TABLE V OCTAHEDRAL SHEARING STRESSES, EXAMPLE PROBLEM, PSI

ELEMENT 1			ELEMENT 7		
9.271550 03	6.508980 03	8.408350 03	1.055150 04	3.195620 03	7.845430 03
6.674260 03	1.687530 04	6.482560 03	4.203340 03	5.395320 03	2.892360 03
6.699590 03	6.198620 03	2.617210 03	5.836870 03	3.140230 03	3.869220 03
4.588570 03	8.645530 03	3.095510 03	4.372620 03	5.551520 03	3.620040 03
ELEMENT 2			ELEMENT 8		
6.609590 03	6.192620 03	2.617210 03	5.836870 03	3.140230 03	3.869220 03
4.588570 03	8.645530 03	3.095510 03	4.372620 03	5.550520 03	3.620040 03
1.879580 04	7.527770 03	7.714060 03	2.656300 03	3.213450 03	3.567750 03
4.960030 03	7.392360 03	1.948060 03	7.424390 03	1.316900 04	4.405200 03
ELEMENT 3			ELEMENT 9		
5.764590 03	7.612430 03	1.776200 03	7.592110 03	1.272420 04	4.365370 03
1.888130 04	6.471280 03	7.523990 03	2.469200 03	2.811240 03	3.508090 03
4.458580 03	5.761720 03	3.633880 03	5.776440 03	1.013420 04	3.201110 03
1.114120 04	4.914690 03	2.673220 03	4.857170 03	2.053100 03	8.551300 03
ELEMENT 4			ELEMENT 10		
4.458580 03	5.761720 03	3.633880 03	5.776440 03	1.010420 04	3.201110 03
1.114120 04	4.914680 03	2.673220 03	4.857170 03	2.063100 03	8.551300 03
4.561880 03	9.146560 03	3.568610 03	7.218960 03	6.128630 03	4.520530 03
7.499480 03	4.300960 03	6.189240 03	9.868170 03	3.488530 03	1.570740 04
ELEMENT 5			ELEMENT 11		
4.561880 03	9.146560 03	3.568610 03	6.940940 03	6.053360 03	4.586790 03
7.499480 03	4.300960 03	6.189240 03	9.868170 03	3.488530 03	1.570740 04
4.543860 03	7.596550 03	4.765240 03	1.043000 04	4.379220 03	2.335750 03
6.252800 03	4.330590 03	7.081600 03	3.535350 03	2.305370 03	9.552940 03
ELEMENT 6			ELEMENT 12		
4.543860 03	7.596560 03	4.765240 03	1.043000 04	4.379220 03	2.335750 03
6.252800 03	4.330590 03	7.081600 03	3.535340 03	2.305370 03	9.553940 03
3.613900 03	4.921470 03	2.472250 03	1.769770 04	1.275160 04	6.004770 03
1.086730 04	4.381410 03	7.711130 03	6.153500 03	2.751500 03	1.630620 04

VI. DISCUSSION

Some of the limitations of the capabilities of the program developed above are considered here.

A. CONFIGURATION LIMITATIONS

The restrictions that pipe axes must be parallel to a global axis and that finite radius bends are not represented provide the principal limitations on the configurations that can be modeled. There are no inherent limitations on allowable topological complexity.

Certain additional features of real piping systems that are not represented in the present modeling include added mass due to fittings and pipe contents, and partial fixity or elastic restraint at ends or intermediate points.

Despite these limitations, it is believed that a significant fraction of current piping systems can be adequately modeled using the present program.

B. SIZE LIMITATIONS

For the present purpose, the appropriate measure of system size is the number of degrees of freedom of the system model. This number n , which bears no direct relation to physical size, determines the core storage requirements and execution time of the program. For approximate estimation, storage requirements are proportional to n^2 and execution time is proportional to n^3 . Using the data from the example problem, one can estimate that a 100

degree-of-freedom system would require about 400K bytes of core storage and about 9 minutes execution time.

Increasing the problem size also increases the round-off errors. Because double-precision arithmetic (56 bit mantissa) is used throughout, observed round-off effects have been found negligible (a maximum of 1 unit in the 6th significant digit for $n = 66$) in all applications to date. The very small errors detected are attributed to the residual eigenvector errors present when the Jacobi rotations are terminated.

In view of the foregoing considerations, it is believed that the practical upper limit on problem size (with the IBM 360/57) is about $n = 110$ and is determined by core storage capacity.

VII. CONCLUSIONS

It is concluded that an effective program has been developed for determining shock-induced stresses in piping systems. The principal limitations of the present version can be removed by adding features that are clearly within the current state-of-the-art. Recommended additions are listed below:

1. Remove the pipe axis orientation restriction so that a general piping system can be analyzed.
2. Develop element stiffness and inertia matrices for bends.
3. Modify the program so that partial fixity and elastic restraint at the ends or intermediate points may be included in the boundary conditions.
4. Include the mass effects of valves, fittings, and pipe contents.
5. Replace the Jacobi rotation method by a more efficient eigenvalue-eigenvector algorithm.

APPENDIX A

ELEMENT STIFFNESS AND INERTIA MATRICES

TABLE VI Element Stiffness Matrix

$$\underline{\underline{K}}^e = \begin{bmatrix}
 \frac{EA}{l} & 0 & 0 & 0 & 0 & 0 & \frac{EA}{l} & 0 & 0 & 0 & 0 \\
 0 & \frac{12EI}{l^3} & 0 & 0 & 0 & 0 & 0 & \frac{12EI}{l^3} & 0 & 0 & 0 \\
 0 & 0 & \frac{12EI}{l^3} & 0 & 0 & 0 & 0 & 0 & \frac{12EI}{l^3} & 0 & 0 \\
 0 & 0 & 0 & \frac{2GI}{l} & 0 & 0 & 0 & 0 & 0 & \frac{2GI}{l} & 0 \\
 0 & 0 & \frac{-6EI}{l^2} & 0 & \frac{4EI}{l} & 0 & 0 & 0 & \frac{6EI}{l^2} & 0 & \frac{4EI}{l} \\
 0 & \frac{6EI}{l^2} & 0 & 0 & 0 & \frac{4EI}{l} & 0 & 0 & 0 & 0 & 0 \\
 \frac{EA}{l} & 0 & 0 & 0 & 0 & 0 & \frac{EA}{l} & 0 & 0 & 0 & 0 \\
 0 & \frac{12EI}{l^3} & 0 & 0 & 0 & \frac{6EI}{l^2} & 0 & \frac{12EI}{l^3} & 0 & 0 & 0 \\
 0 & 0 & \frac{12EI}{l^3} & 0 & \frac{6EI}{l^2} & 0 & 0 & 0 & \frac{12EI}{l^3} & 0 & 0 \\
 0 & 0 & 0 & \frac{2GI}{l} & 0 & 0 & 0 & 0 & 0 & \frac{2GI}{l} & 0 \\
 0 & 0 & \frac{6EI}{l^2} & 0 & \frac{2EI}{l} & 0 & 0 & 0 & \frac{6EI}{l^2} & 0 & \frac{4EI}{l} \\
 0 & \frac{6EI}{l^2} & 0 & 0 & 0 & \frac{2EI}{l} & 0 & \frac{6EI}{l^2} & 0 & 0 & 0 & \frac{4EI}{l}
 \end{bmatrix}$$

Symmetric

TABLE VII Element Thoria Molyb

[illegible]

APPENDIX B: VELOCITY SHOCK SPECTRA AND MODAL RESPONSE¹

A shock spectrum exhibits the maximum response displacement of a single degree-of-freedom system whose base is subjected to the shock motion. Consider a single degree-of-freedom whose base has a shock displacement s , and whose displacement relative to the base is z . The equation of motion is

$$\ddot{z} + \omega^2 z = -\ddot{s} \quad (\text{B.1})$$

where ω is the natural circular frequency of free vibration with the base fixed ($s = 0$). If $z_{\max}$ represents the extreme value of z in response to the shock motion s , then the displacement shock spectrum for that shock motion is a plot of $z_{\max}$ versus ω . Equivalent information can be given in the form of a velocity shock spectrum. In this form, the spectrum velocity $\dot{V}$ is related to the maximum displacement $z_{\max}$ by

$$\dot{V} = \omega z_{\max} \quad (\text{B.2})$$

To develop the equations for finding modal response from shock spectrum data, let $\underline{w}$ be the vector of absolute

¹This Appendix is based on material presented by Prof. R.E. Newton in the course ME4522, September 1971.

displacements in the system degrees-of-freedom. For a uniaxial translation s of the base, this may be expressed as

$$\underline{w} = \underline{q} + \underline{u}s \quad (\text{B.3})$$

where $\underline{q}$ is the vector of displacements relative to the base, and $\underline{u}$ is a vector of constants. To illustrate the meanings of these vectors, consider the beam element of Fig. 9.

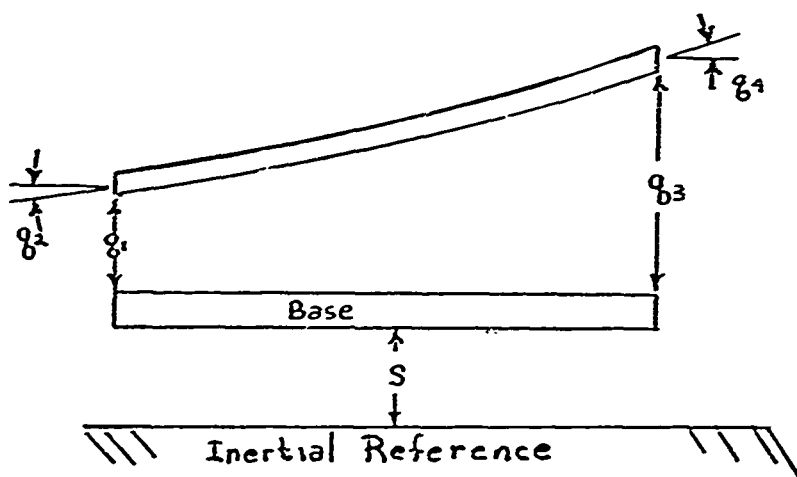


FIG. 9

BEAM ELEMENT COORDINATES

For this example, $\underline{q} = [q_1 \ q_2 \ q_3 \ q_4]^T$, $\underline{w} = [q_1 + s \ q_2 \ q_3 + s \ q_4]^T$, and $\underline{u} = [1 \ 0 \ 1 \ 0]$. It can be seen that $\underline{u}$ represents the

absolute displacements resulting from unit base translation.

The equations of motion of an n degree-of-freedom system with base motion may be written

$$\underline{\underline{M}} \ddot{\underline{\underline{w}}} + \underline{\underline{K}} \underline{\underline{q}} = 0$$

Using Eq. B.3, this becomes

$$\underline{\underline{M}} \ddot{\underline{\underline{q}}} + \underline{\underline{K}} \underline{\underline{q}} = - \underline{\underline{M}} \underline{\underline{u}} \ddot{\underline{\underline{s}}}$$

Using the substitution $\underline{\underline{q}} = \underline{\underline{V}} \underline{\underline{p}}$ where $\underline{\underline{p}}$ is the vector of principal coordinates, this may be rewritten as

$$\underline{\underline{V}}^T \underline{\underline{M}} \underline{\underline{V}} \ddot{\underline{\underline{p}}} + \underline{\underline{V}}^T \underline{\underline{K}} \underline{\underline{V}} \underline{\underline{p}} = - \underline{\underline{V}}^T \underline{\underline{M}} \underline{\underline{u}} \ddot{\underline{\underline{s}}}$$

or

$$\ddot{\underline{\underline{p}}} + \underline{\underline{\Omega}}^2 \underline{\underline{p}} = - \underline{\underline{b}} \ddot{\underline{\underline{s}}} \quad (\text{B.4})$$

where $\underline{\underline{b}} = \underline{\underline{V}}^T \underline{\underline{M}} \underline{\underline{u}}$. Eq. B.4 is equivalent to the scalar equations

$$\ddot{p}_r + \omega_r^2 p_r = - b_r \ddot{s}, \quad (r=1,2,\dots,n) \quad (\text{B.4a})$$

where p_r and b_r are the r th components of $\underline{\underline{p}}$ and $\underline{\underline{b}}$, respectively, and ω_r is the circular frequency of mode r .

The component b_r is called the mode participation factor for mode r . It is given by

$$b_r = \underline{v}^{(r)T} \underline{M} \underline{u} \quad (\text{B.5})$$

where $\underline{v}^{(r)}$ is the eigenvector for mode r (r th column of $\underline{V}$).

Comparing Eq. B.4a with Eq. B.1, and using Eq. B.2, the maximum response in mode r may be expressed as

$$(p_r)_{\max} = b_r \tilde{V}_r / \omega_r \quad (\text{B.6})$$

where $\tilde{V}_r$ is the spectrum velocity at frequency ω_r . Using Eq. B.6, the corresponding extremum for the relative displacement vector $\underline{q}$ is

$$\underline{q}_{\max} = \underline{v}^{(r)} b_r \tilde{V}_r / \omega_r \quad (\text{B.6a})$$

Eq. B.6a is used for calculating peak modal responses in order to find stresses.

In shipboard shock studies, it has been found that massive equipment may partially suppress the base motion [6]. This may be taken into account by appropriate modification of the spectrum velocity $\tilde{V}_r$. Such a correction requires apportionment of the system mass among the modes. The modal mass for the r th mode is taken to be

$$m_r = b_r^2 \quad (\text{B.7})$$

APPENDIX C: EXAMPLE PROBLEM EIGENVALUES AND EIGENVECTORS

Table VIII shows the first six eigenvalues and the corresponding eigenvectors of the example problem. The eigenvalue (square of the circular frequency) appears at the head of a column followed by the components of the eigenvector grouped by nodes. The remaining eigenvalues and eigenvectors are omitted. Spacing of the eigenvalues remains approximately uniform throughout the remainder of the set. The largest eigenvalue is 1.32×10^8 .

TABLE VIII

EXAMPLE PROBLEM EIGENVALUES AND EIGENVECTORS

3.202100 02	1.768220 03	4.283940 03	7.284420 03	1.366430 04	1.936940 04
3.734190-05	1.346630-05	2.084720-04	-1.140300-04	-4.651040-04	9.202400-04
2.419560-03	1.090030-02	-2.656940-02	-1.284070-01	8.533350-02	5.243660-02
4.498290-03	1.041630-03	1.106640-02	-5.213800-03	-1.597670-02	2.803910-02
2.613170-04	-1.297640-03	4.111110-04	1.334410-03	1.670380-04	3.876080-04
-9.722550-05	-2.247990-05	-2.557670-04	1.123570-04	3.099150-04	-5.483340-04
1.227360-04	3.964450-04	-1.134310-03	-5.432470-03	3.613510-03	2.206790-03
7.468300-05	2.693140-05	4.169000-04	-2.280180-04	-9.298920-04	1.839590-03
1.094290-02	2.303660-02	-8.449300-02	-4.007280-01	2.678550-01	1.628400-01
-1.656710-03	-3.865930-04	-1.211330-03	1.910950-03	1.144910-02	-1.906140-02
5.226180-04	-2.594880-03	8.219070-04	2.667080-03	3.336680-04	7.738690-04
5.072280-04	1.175200-04	1.109210-03	-5.856580-04	-2.056210-03	3.551720-03
2.937380-04	6.000790-05	-1.500320-03	-6.912510-03	4.702150-03	2.824790-03
7.586450-02	1.665440-02	1.461590-01	-7.412730-02	-2.396660-01	3.935970-01
-3.272250-02	2.268140-01	-1.378830-01	-5.514730-01	2.053020-01	8.261260-02
-1.502070-03	-3.508370-04	-8.567620-04	1.733630-03	1.086020-02	-1.804080-02
7.817170-04	-3.299150-03	5.612880-04	9.105430-04	1.877230-03	1.713970-03
1.680460-03	3.475920-04	2.712830-03	-1.334510-03	-3.910450-03	5.854290-03
6.803640-04	-1.369440-03	-1.504380-03	-6.234990-03	4.765840-03	2.827700-03
2.077980-01	4.113490-02	2.873100-01	-1.404710-01	-3.879600-01	5.383140-01
-8.986820-02	4.263500-01	-1.358610-01	-4.479070-01	2.053020-01	-4.128320-02
-1.347380-03	-3.150070-04	-5.017450-04	1.554770-03	1.025300-02	-1.697730-02
9.335880-04	-2.558230-03	-7.254990-04	-4.148180-03	3.312280-03	-1.745820-03
2.214390-03	3.624590-04	1.113250-03	-4.794290-04	-4.396840-05	-2.271960-03
1.069920-03	-2.797810-03	-1.505580-03	-5.537350-03	4.800720-03	2.806380-03
3.554280-01	6.127200-02	2.505250-01	-1.256530-01	-2.500440-01	1.421630-01
-1.541720-01	5.499210-01	-3.754620-02	-4.379060-02	-1.789320-01	-1.135150-01
-1.192630-03	-2.791370-04	-1.464640-04	1.374510-03	9.628570-03	-1.587330-02
1.005280-03	-1.168140-03	-2.229600-03	-7.483740-03	2.470720-03	3.151950-04
2.171520-03	2.325480-04	-2.408720-03	8.999310-04	3.612420-03	-8.321710-03
1.459330-03	-4.223990-03	-1.503930-03	-4.821860-03	4.806570-03	2.761020-03
4.844370-01	7.136440-02	-3.727910-02	-3.999870-02	-5.137650-02	-3.036070-01
-2.019640-01	5.922980-01	1.513220-01	4.441130-01	-2.818790-01	-9.597510-02
-1.037840-03	-2.431470-04	-2.088940-04	1.193020-03	8.987980-03	-1.473150-02
1.050640-03	-3.187010-04	-3.438590-03	-6.623490-03	8.151150-04	-5.005620-04
1.676140-03	8.266200-05	-6.263850-03	1.465560-03	1.029980-03	-3.163490-03
1.848530-03	-5.646860-03	-1.499420-03	-4.090820-03	4.783360-03	2.692010-03
4.844510-01	7.134930-02	-3.730900-02	-3.986070-02	-5.067870-02	-3.040550-01
-1.159680-01	2.764270-01	7.101190-02	2.253770-01	-5.032210-02	2.482560-02
-7.857740-02	-2.704960-03	3.940520-01	-7.170640-02	7.375440-02	-3.788760-02
1.111580-02	-1.873420-04	-4.581830-03	-3.766730-03	3.146250-06	-7.118030-06
1.227640-03	1.566670-05	-7.876010-03	1.203200-03	-2.844290-03	3.160610-03
2.067390-03	-5.781560-03	-1.448660-03	-4.120900-03	3.231510-03	1.327770-03
4.844510-01	7.132310-02	-3.732580-02	-3.969890-02	-4.992390-02	-3.040190-01
-5.323830-05	1.192160-03	2.462120-04	4.440830-04	-2.334730-03	-1.372800-03
1.372120-01	-2.735590-03	8.116120-01	-1.282270-01	2.579220-01	-2.657550-01
1.172420-03	-5.588410-05	-5.719250-03	9.022450-04	-8.088350-04	4.863670-04
9.790640-04	6.817380-06	-7.355270-03	-9.235360-04	-3.532320-03	4.543460-03
2.211200-03	-4.079800-03	-1.107360-03	-4.114530-03	-2.122720-03	-2.715950-03
3.223770-01	2.421760-01	1.778870-02	2.072240-01	3.027290-01	6.348150-02
-3.993090-05	9.943870-04	1.847940-04	3.334770-04	-1.755140-03	-1.033020-03
-5.555850-02	-2.962940-03	3.684660-01	-1.034650-01	1.527310-01	-1.749390-01
1.023740-03	3.440720-05	-6.240510-03	1.293160-03	-2.121270-03	2.211040-03
7.344430-04	-5.118530-06	-5.531030-03	6.957710-04	-2.671720-03	3.448750-03
2.254460-03	-7.879040-04	-4.405480-04	-2.320910-03	-5.611510-03	-6.110440-03
1.674890-01	2.105480-01	2.932840-02	2.586930-01	5.251100-01	3.673960-01
-2.662160-05	5.963870-04	1.232610-04	2.225160-04	-1.172050-03	-6.903080-04
-6.529060-04	-8.495620-05	5.640670-03	-2.713260-03	3.420560-03	-4.391680-03
4.239510-04	2.892450-05	-3.012320-03	9.956980-04	-1.428070-03	-1.732520-03
4.896970-04	-3.415200-06	-3.694300-03	4.653360-04	-1.791900-03	-2.188990-03
1.980800-03	1.424270-03	8.409130-05	8.950440-04	3.088030-04	-1.287430-03
4.818110-02	8.043060-02	1.346290-02	1.178810-01	2.769850-01	2.298260-01
-1.331100-05	2.982320-04	6.164940-05	1.113170-04	-5.866110-04	-3.456440-04
7.315500-03	4.820690-04	-5.242910-02	1.714040-02	-2.559000-02	3.178660-02
-9.921070-05	-6.354490-06	6.954800-04	-2.219140-04	3.246660-04	-3.929370-04
2.448690-04	-1.708410-06	-1.849240-03	2.331150-04	-8.991850-04	1.165380-03
1.249900-03	1.840420-03	2.856850-04	2.488810-03	5.464770-03	4.226120-03

APPENDIX D: CALCULATION OF MODIFIED SPECIFIC WEIGHT
AND RADIUS OF GYRATION

There is negligible effect on the stiffness of the pipe element from the lagging on the pipe; however, the lagging does contribute significantly to the mass of the element. By appropriately modifying the pipe element specific weight and radius of gyration, the mass effect of the lagging can be included. The modified specific weight is

$$\gamma_m = (W_p + W_L)/A \quad (C.1)$$

where γ_m is the modified specific weight of the pipe element, and the sum $(W_p + W_L)$ is the combined weight of the lagging and pipe per unit length. The radius of gyration is given by the relation

$$J_p + J_L = (m_p + m_L) r^2 \quad (C.2)$$

where J_p and J_L are the mass moment of inertia per unit length of the pipe and lagging, respectively, $(m_p + m_L)$ is the combined mass of the pipe and lagging per unit length, and r is the radius of gyration.

APPENDIX E: PROGRAM LISTING

LIST OF SYMBOLS USED IN PROGRAM SHOKPI

BX(I).....MODE PARTICIPATION FACTOR I, X AXIS SHOCK INPUT
 BY(I).....MODE PARTICIPATION FACTOR I, Y AXIS SHOCK INPUT
 BZ(I).....MODE PARTICIPATION FACTOR I, Z AXIS SHOCK INPUT
 BMOWTE.....END COORDINATE OF LOG MODAL WEIGHT VS CORRECTED
 SPECTRUM VELOCITY CURVE
 BMDWTS.....STARTING COORDINATE OF LOG MODAL WEIGHT VS CORRECTED
 SPECTRUM VELOCITY CURVE
 DQ(I).....OUTSIDE DIAMETER, PIPE MATERIAL GROUP I, INCHES
 DI(I).....INSIDE PIPE DIAMETER, PIPE MATERIAL GROUP I, INCHES
 DE(I).....YOUNG'S MODULUS, PIPE MATERIAL GROUP I, LB/IN.**2
 EFRAD.....EFFECTIVE RADIUS, OF GYRATION, INCHES
 EIVUCO.....MODAL COLUMN VECTOR
 EIVR.....FREQUENCY CUTOFF VALUE FOR STRESS ANALYSIS, HERTZ
 FSES(I).....MODAL MATRIX AT BEGINNING OF SEGMENT I OF VELOCITY
 SPECTRUM, HERTZ
 G(I).....SHEAR MODULUS, PIPE MATERIAL GROUP I, LB/IN.**2
 HSTIF.....HANGER STIFFNESS
 IADOF.....DEGREE OF FREEDOM INDEX FOR HANGER
 1: HANGER DIRECTION X GLOBAL
 2: HANGER DIRECTION Y GLOBAL
 3: HANGER DIRECTION Z GLOBAL
 IEL.....ELEMENT NUMBER
 IEL3LO.....ADDRESS MATR TO SPECIFY METHOD OF ANALYZING THE SHOCK
 IFRQTY.....INDEX USED TO SPECIFY METHOD OF ANALYZING THE SHOCK
 NUMBER OF MODAL FREQUENCIES FOR STRESS ANALYSIS
 -1: METHOD TO BE DETERMINED BY USER
 0: CUTOFF FREQUENCY IS DESIGNATED BY USER
 1: CUTOFF FREQUENCY IS DESIGNATED BY USER
 IGVN.....GLOBAL NODE NUMBER AND SIZE GROUP MATRIX
 IGRP(I).....ELEMENT MATERIAL GROUPS
 IGRP1.....TOTAL NUMBER OF GROUPS
 ISPECTY.....INDEX USED TO SPECIFY METHOD OF ANALYZING THE SHOCK
 VELOCITY SPECTRUM
 -1: METHOD TO BE DETERMINED BY USER
 0: SHOCK SPECTRUM APPROXIMATED BY STRAIGHT
 LINE SEGMENTS
 1: SHOCK SPECTRUM IS CONSTANT VELOCITY TO
 FN, THEN CONSTANT ACCELERATION
 JSEG.....NUMBER OF STRAIGHT PLUS 1
 THE SHOCK SPECTRUM
 MOWTTY.....INDEX USED TO SPECIFY MODAL EIGHT CORRECTION TO

```

SPECTRUM VELOCITY BE DETERMINED BY USER
-1: TO CORRECTION TO BE APPLIED
0: SPECTRUM VELOCITY CORRECTED USING LOG
1: OF MODAL WEIGHT I

NBCN(I)....BOUNDARY CONDITION ON NODE I
NDQFT.....TOTAL NUMBER OF FREEDOM OF SYSTEM
NHANG.....NUMBER OF DEGREES OF FREEDOM OF SYSTEM
NN(1,K)....FIRST NODE NUMBER ELEMENT K
NV(2,K)....SECOND NODE NUMBER ELEMENT K
NNA.....ADDRESS MATRIX GLOBAL NODES FROM GLOBAL NODES
NNG.....NUMBER OF PIPE ELEMENTS FROM ASSEMBLED NODES
NPROB.....TOTAL NUMBER OF PIPE ELEMENTS TO BE ANALYZED BY PROGRAM
NNT(I)....POISSON'S RATIO, PIPE MATERIAL GROUP I
SPHT(I)....SPECIFIC WEIGHT, PIPE MATERIAL GROUP I
VOVTE.....VELOCITY RATIO AT END OF MODAL WEIGHT CORRECTION
VOVTS.....VELOCITY RATIO AT START OF MODAL WEIGHT CORRECTION
VSEG(I)....VELOCITY AT BEGINNING OF SEGMENT I OF VELOCITY
X(I).....SPECTRUM, INCHES/SEC. NODE I, INCHES
Y(I).....GLOBAL X COORDINATE, NODE I, INCHES
Z(I).....GLOBAL Y COORDINATE, NODE I, INCHES
XSPCER.....SPECTRUM SCALING FACTOR X DIRECTION INPUT
YSPCER.....SPECTRUM SCALING FACTOR Y DIRECTION INPUT
ZSPCER.....SPECTRUM SCALING FACTOR Z DIRECTION INPUT

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B. THE SEQUENCE IN NUMBERING THE NODAL POINTS OF THE SYSTEM IS ARBITRARY

D. PIPING MATERIAL AND SIZE AND PROPERTIES ELEMENT THE PIPING ELEMENT SIZE AND ON THE MATERIALS PROPERTIES ARE THE ELEMENT IS ASSIGNED TO A PIPE AND INSIDE DIAMETERS THE TWO NODAL POINTS ON THE ELEMENT. EACH PIPE INFORMATION:

DI. HANGERS
THAN PER
THE HAD
PLACED
SUBP
SUBP

THE PROGRAMMER HAS TO DETERMINE THE EFFECTIVE SPECIFIC WEIGHT OF THE PIPE AND THE LAGGING, AND ALSO THE EFFECTIVE RADIUS OF CYRATATION FOR TORSIONAL INERTIA.

E) DATA	1-5	ONLY ONE SYSTEMS TO BE ANALYZED (NPROD)	15
1) CARD	1-5	NUMBER OF SYSTEMS (NET)	15
2) CARD	1-5	TOTAL NUMBER OF DEGREES OF FREEDOM PER NODE	15
3) SUCCEEDING	1-5	NUMBER OF DEGREES OF FREEDOM (NDOFT)	15
4) CARD	1-5	PIPE MATERIAL GROUPS (IGRPT)	15
5) CARD	1-5	PIPE MATERIAL GROUPS (NDOFT)	15
6) CARD	1-5	COORDINATE, INCHES	15
7) CARD	1-5	COORDINATE, INCHES	15
8) CARD	1-5	COORDINATE, INCHES	15
9) CARD	1-5	COORDINATE, INCHES	15
10) CARD	1-5	COORDINATE, INCHES	15
11) CARD	1-5	COORDINATE, INCHES	15
12) CARD	1-5	COORDINATE, INCHES	15
13) CARD	1-5	COORDINATE, INCHES	15
14) CARD	1-5	COORDINATE, INCHES	15
15) CARD	1-5	COORDINATE, INCHES	15
16) CARD	1-5	COORDINATE, INCHES	15
17) CARD	1-5	COORDINATE, INCHES	15
18) CARD	1-5	COORDINATE, INCHES	15
19) CARD	1-5	COORDINATE, INCHES	15
20) CARD	1-5	COORDINATE, INCHES	15
21) CARD	1-5	COORDINATE, INCHES	15
22) CARD	1-5	COORDINATE, INCHES	15
23) CARD	1-5	COORDINATE, INCHES	15
24) CARD	1-5	COORDINATE, INCHES	15
25) CARD	1-5	COORDINATE, INCHES	15
26) CARD	1-5	COORDINATE, INCHES	15
27) CARD	1-5	COORDINATE, INCHES	15
28) CARD	1-5	COORDINATE, INCHES	15
29) CARD	1-5	COORDINATE, INCHES	15
30) CARD	1-5	COORDINATE, INCHES	15
31) CARD	1-5	COORDINATE, INCHES	15
32) CARD	1-5	COORDINATE, INCHES	15
33) CARD	1-5	COORDINATE, INCHES	15
34) CARD	1-5	COORDINATE, INCHES	15
35) CARD	1-5	COORDINATE, INCHES	15
36) CARD	1-5	COORDINATE, INCHES	15
37) CARD	1-5	COORDINATE, INCHES	15
38) CARD	1-5	COORDINATE, INCHES	15
39) CARD	1-5	COORDINATE, INCHES	15
40) CARD	1-5	COORDINATE, INCHES	15
41) CARD	1-5	COORDINATE, INCHES	15
42) CARD	1-5	COORDINATE, INCHES	15
43) CARD	1-5	COORDINATE, INCHES	15
44) CARD	1-5	COORDINATE, INCHES	15
45) CARD	1-5	COORDINATE, INCHES	15
46) CARD	1-5	COORDINATE, INCHES	15
47) CARD	1-5	COORDINATE, INCHES	15
48) CARD	1-5	COORDINATE, INCHES	15
49) CARD	1-5	COORDINATE, INCHES	15
50) CARD	1-5	COORDINATE, INCHES	15
51) CARD	1-5	COORDINATE, INCHES	15
52) CARD	1-5	COORDINATE, INCHES	15
53) CARD	1-5	COORDINATE, INCHES	15
54) CARD	1-5	COORDINATE, INCHES	15
55) CARD	1-5	COORDINATE, INCHES	15
56) CARD	1-5	COORDINATE, INCHES	15
57) CARD	1-5	COORDINATE, INCHES	15
58) CARD	1-5	COORDINATE, INCHES	15
59) CARD	1-5	COORDINATE, INCHES	15
60) CARD	1-5	COORDINATE, INCHES	15
61) CARD	1-5	COORDINATE, INCHES	15
62) CARD	1-5	COORDINATE, INCHES	15
63) CARD	1-5	COORDINATE, INCHES	15
64) CARD	1-5	COORDINATE, INCHES	15
65) CARD	1-5	COORDINATE, INCHES	15
66) CARD	1-5	COORDINATE, INCHES	15
67) CARD	1-5	COORDINATE, INCHES	15
68) CARD	1-5	COORDINATE, INCHES	15
69) CARD	1-5	COORDINATE, INCHES	15
70) CARD	1-5	COORDINATE, INCHES	15
71) CARD	1-5	COORDINATE, INCHES	15
72) CARD	1-5	COORDINATE, INCHES	15
73) CARD	1-5	COORDINATE, INCHES	15
74) CARD	1-5	COORDINATE, INCHES	15
75) CARD	1-5	COORDINATE, INCHES	15
76) CARD	1-5	COORDINATE, INCHES	15
77) CARD	1-5	COORDINATE, INCHES	15
78) CARD	1-5	COORDINATE, INCHES	15
79) CARD	1-5	COORDINATE, INCHES	15
80) CARD	1-5	COORDINATE, INCHES	15
81) CARD	1-5	COORDINATE, INCHES	15
82) CARD	1-5	COORDINATE, INCHES	15
83) CARD	1-5	COORDINATE, INCHES	15
84) CARD	1-5	COORDINATE, INCHES	15
85) CARD	1-5	COORDINATE, INCHES	15
86) CARD	1-5	COORDINATE, INCHES	15
87) CARD	1-5	COORDINATE, INCHES	15
88) CARD	1-5	COORDINATE, INCHES	15
89) CARD	1-5	COORDINATE, INCHES	15
90) CARD	1-5	COORDINATE, INCHES	15
91) CARD	1-5	COORDINATE, INCHES	15
92) CARD	1-5	COORDINATE, INCHES	15
93) CARD	1-5	COORDINATE, INCHES	15
94) CARD	1-5	COORDINATE, INCHES	15
95) CARD	1-5	COORDINATE, INCHES	15
96) CARD	1-5	COORDINATE, INCHES	15
97) CARD	1-5	COORDINATE, INCHES	15
98) CARD	1-5	COORDINATE, INCHES	15
99) CARD	1-5	COORDINATE, INCHES	15
100) CARD	1-5	COORDINATE, INCHES	15

```

COL 6-10 FREQUENCY TYPE INDEX (IFRQTY) 15
-1: USE ALL MODES
-0: USE FUNDAMENTAL FREQUENCY
1: CUTOFF FREQUENCY IS DEFINED
1: CUTOFF FREQUENCY IS DEFINED (JSEG) 15
REPRESENTING SPECTRUM +1 REPRESENTATION
O: OTHER IS HERTZ
O: OTHER IS HERTZ
CARD C1) IF AND ONLY IF FREQUENCY IS 3 (ONE CARD FOR EACH COORD) 01:1:4
COL 11-15 NUMBER OF STRAIGHT LINE SEGMENTS (JSEG) 15
CARD C11) IF AND ONLY IF IS STARTING COORD OF ST. LINE 01:1:4
COL 1-9 REPRESENTATION (VSEG)
SPECTRUM VELOCITY (VSEG) STARTING COORD OF ST. 01:1:4
COL 10-18 REPRESENTATION (VSEG)
SPECTRUM VELOCITY (VSEG) STARTING COORD OF ST. 01:1:4
CARD C12) IF AND ONLY IF IS WHICH CONSTANT ACCELERATION 01:1:4
COL 1-10 FREQUENCY (FSEG) VALUE (VSEG(1)) 01:1:4
CONSTANT VELOCITY (FSEG(1)) VALUE (VSEG(1)) 01:1:4
7) CARD D) (USE ONLY ONCE FOR EACH SYSTEM) 01:1:4
COL 11-20 SPECTRUM SCALING FACTOR X DIRECTION 01:1:4
COL 1-10 SPECTRUM SCALING FACTOR Y DIRECTION 01:1:4
COL 11-20 SPECTRUM SCALING FACTOR Z DIRECTION 01:1:4
COL 21-30 SPECTRUM SCALING FACTOR Z DIRECTION 01:1:4
8) CARD E) (USE ONLY ONCE FOR EACH SYSTEM) 15
COL 1-5 INDEX -1: NO CORRECTION DESIRED
-0: NO CORRECTION DESIRED
CARD E1) IF AND ONLY IF LOG MODAL WEIGHT CORRECTION APPLIED 01:1:4
COL 1-10 STARTING COORD VELOCITY RATIO ('/OTS) 01:1:4
COL 11-20 ENDING COORD VELOCITY RATIO ('/OTS) 01:1:4
COL 21-30 STARTING COORD LOG MODAL WEIGHT ('/OTS) 01:1:4
COL 31-40 ENDING COORD LOG MODAL WEIGHT ('/OTS) 01:1:4

```

THE A CARD IS USED ONLY ONCE, THE REMAINDER OF THE CARDS ARE PRODUCED FOR EACH SYSTEM OF THE PROGRAM. THE PROGRAM ARE INCHES-SECONDS-POUNDS, HOWEVER ANY CONSISTENT SET OF UNITS CAN BE USED. THE GRAVITATIONAL ACCELERATION IN THE PROGRAM MUST BE CHANGED IF THE UNITS ARE CHANGED.

```

SUBROUTINE INPUT
IMPLICIT REAL*8(A-H,O-Z)
COMMON X(13),Y(13),Z(13),DO(1),DI(1),POI(1),SPWT(1),E(1),G(1),DUM(
160),DUM1(66),DUME(66),DUME1(66),SKE(12,12),SME(12,12),G(1),DUM(
2(66,66),GV,PI,EIVU(66),EIVR(66),BX(66),BY(66),Z(66),ZSPCPR,SMUX
3VSEG(1),FACITR(66),FACITR2(66),XSPCPR,YSPCPR,ZSPCPR,SMUX
4(66),SMUY(66),SMUZ(66),EFRAD(1),NNG(1),NNCN(13),NDOFPE,NDOFPN,IGRP
5NPRD2,NNT,NET,NN(2,12),NNA(13),JSEG,JSEG6N,KOUNT,MOWTY,IELGLO(6,6)
6I,IGRP(12),NNDPE,IEL(12),NDOFT,NDOFPN,IGRP(12),NDOFT,IELGLO(6,6)

```

THIS SUBROUTINE READS THE SYSTEM DATA NECESSARY TO SOLVE THE
EIGENVALUE PROBLEM

READ BASIC SYSTEM PARAMETERS AND ECHO CHECK

```

READ(5,180) NET,NNT,NDOFPN,IGRPT,NDOFT
NNPE=2
NDOFPE=NNPE*NDOFPN
WRITE(6,190) NET,NNT,NDOFPN,NDOFPE,IGRPT,NDOFT

```

SET THE PROGRAM CONSTANTS

```

PI=3.141592653589793D0
CV=386.0D0

```

READ GLOBAL COORDINATES OF NODES AND ECHO CHECK

```

WRITE(6,191)
DO 120 I=1,NNT
  READ(5,181) X(I),Y(I),Z(I),NBCN(I)
  WRITE(6,192) I,X(I),Y(I),Z(I),NBCN(I)

```

READ GLOBAL NODE AND ELEMENT DATA AND ECHO CHECK

```

WRITE(6,193)
DO 140 K=1,NET
  READ(5,182) IEL(K),NN(1,K),NN(2,K),IGRP(K)
  WRITE(6,194) IEL(K),NN(1,K),NN(2,K),IGRP(K)

```

READ MATERIAL AND SIZE GROUP DATA AND ECHO CHECK

```

WRITE(6,195)
DO 160 J=1,IGRPT
  READ(5,183) DI(J),POI(J),SPWT(J),E(J)
  WRITE(6,196) J,DI(J),POI(J),SPWT(J),E(J)

```



```

212 LC=1
    LI=2
    GO TO 219
215 IF(DZ.LT.O.O.OO0) GO TO 216
C
C    LOCAL AXES  ALIGNED WITH +Z GLOBAL
    LO=1
    LI=2
    L2=3
    GO TO 239
C
C    LOCAL AXES  ALIGNED WITH -Z GLOBAL
    LO=1
    LI=3
    GO TO 219
C
C    ASSEMBLE THE SYSTEM STIFFNESS AND MASS MATRICES
219 DO 225 K=1,4
    K3N=3*(K-1)
    DO 220 J=1,NDJFPE
        DUME(J)=SME(J,LO+K3M)
        SKE(J,LO+K3M)=SKE(J,L1+K3M)
        SME(J,LO+K3M)=SME(J,L1+K3M)
        SKE(J,L1+K3M)=DUME(J)
        SME(J,L1+K3M)=DUME(J)
    DO 221 J=1,NDJFPE
        DUME1(J)=SKE(LO+K3M,J)
        DUME1(J)=SME(LO+K3M,J)
        SKE(LO+K3M,J)=SKE(L1+K3M,J)
        SME(LO+K3M,J)=SME(L1+K3M,J)
        SKE(L1+K3M,J)=DUME1(J)
        SME(L1+K3M,J)=DUME1(J)
    CONTINUE
225 GO TO 350
239 K3M=3*(K-1)
    DO 235 J=1,NDJFPE
        DUME(J)=SKE(J,LO+K3M)
        SKE(J,LO+K3M)=SKE(J,L1+K3M)
        SME(J,LO+K3M)=SME(J,L1+K3M)
        SKE(J,L1+K3M)=SME(J,L2+K3M)
        SME(J,L1+K3M)=SME(J,L2+K3M)
        SKE(J,L2+K3M)=DUME(J)

```

```

235 SME(J,L2+K3M)=DUME(J)
DO 236 J=1,NDJFPE
DUME1(J)=SKE(LO+K3M,J)
DUME1(J)=SME(LO+K3M,J)
SKE(LO+K3M,J)=SKE(L1+K3M,J)
SME(LO+K3M,J)=SME(L1+K3M,J)
SKE(L1+K3M,J)=SKE(L2+K3M,J)
SME(L1+K3M,J)=SME(L2+K3M,J)
SKE(L2+K3M,J)=DUME1(J)
SME(L2+K3M,J)=DUME1(J)
CONTINUE
236 IF(NNA(NN(1,L)).EQ.0) GO TO 380
240 IF(NNA(NN(2,L)).EQ.0) GO TO 390
350 DO 370 I=1,NNPE
INN=NDJFPN*(I-1)
DO 365 J=1,NDJFPN
INP=NDJFPN*(NNA(NN(1,L))-1)
SMUX(INP+J)=SMUX(INP+J)+(SME(INN+J,1)+SME(INN+J,7))
SMUY(INP+J)=SMUY(INP+J)+(SME(INN+J,2)+SME(INN+J,8))
SMUZ(INP+J)=SMUZ(INP+J)+(SME(INN+J,3)+SME(INN+J,9))
365 CONTINUE
370 GO TO 395
380 INP=NDJFPN*(NNA(NN(2,L))-1)
DO 385 I=1,NDJFPN
NPI=NDJFPN+I
SMUX(INP+I)=SMUX(INP+I)+(SME(NPI,1)+SME(NPI,7))
SMUY(INP+I)=SMUY(INP+I)+(SME(NPI,2)+SME(NPI,8))
SMUZ(INP+I)=SMUZ(INP+I)+(SME(NPI,3)+SME(NPI,9))
385 GO TO 395
390 INP=NDJFPN*(NNA(NN(1,L))-1)
DO 394 I=1,NDJFPN
SMUX(INP+I)=SMUX(INP+I)+(SME(I,1)+SME(I,7))
SMUY(INP+I)=SMUY(INP+I)+(SME(I,2)+SME(I,8))
SMUZ(INP+I)=SMUZ(INP+I)+(SME(I,3)+SME(I,9))
394 CONTINUE
395 IF(NNA(NN(1,L)).EQ.0) GO TO 400
IF(NNA(NN(2,L)).EQ.0) GO TO 405
DO 420 I=1,NNPE
II=NDJFPN*(NNA(NN(1,L))-1)
DO 420 J=1,NNPE
JJ=NDJFPN*(NNA(NN(2,L))-1)
DO 410 KI=1,NDJFPN
KI=NDJFPN*(I-1)+KI
DO 410 K2=1,NDJFPN
KJ=NDJFPN*(J-1)+K2
SK(II+K1,JJ+K2)=SK(II+K1,JJ+K2)+SKE(KI,KJ)
SM(II+K1,JJ+K2)=SM(II+K1,JJ+K2)+SME(KI,KJ)
410 CONTINUE
420 CONTINUE

```

```

400 J TO 450
    KZ=NDOPFN
    II=NDOPFN*(NNA(NN(2,L))-1)
    GO TO 408
405 KZ=0
    II=NDOPFN*(NNA(NN(1,L))-1)
408 DO 409 I=1,NDOPFN
    DC 409 J=1,NDOPFN
    SK(I+I,I+J)=SK(I+I,I+J)+SKE(I+KZ,J+KZ)
    SM(I+I,I+J)=SM(I+I,I+J)+SME(I+KZ,J+KZ)
409 CONTINUE
450

CCCCC
IF THE PIPING SYSTEM INCLUDES PIPE HANGERS, INSERT THE SEGMENT FOR
ADDING THE HANGER STIFFNESS TO THE SYSTEM STIFFNESS MATRIX

READ THE NUMBER OF HANGERS IN THE SYSTEM

READ(5,440) NHANG
WRITE(6,441) NHANG

READ THE GLOBAL NODE AT THE HANGER, HANGER GLOBAL DIRECTION INDEX,
AND AXIAL STIFFNESS
ADD HANGER STIFFNESS TO THE SYSTEM MATRIX

WRITE(6,444)
DO 445 I=1,NHANG
    READ(5,442) IGNN,IADOF,HSTIF
    LAZ=NDOPFN*(NNA(IGNN)-1)+IADOF
    WRITE(6,443) IGNN,IADOF,HSTIF
    SK(LAZ,LAZ)=SK(LAZ,LAZ)+HSTIF
445 FORMAT(I5),/,10X,'NUMBER OF HANGERS:',I5,/,/
440 FORMAT(2I5,D11.6)
442 FORMAT(I5,I5,I5,7X,I5,7X,1PD13.6)
443 FORMAT(I5,I5,I5,7X,I5,7X,10X,'GLOBAL DOF:',5X,'IADOF:',5X,'HANGER STIFFNESS:',/,/
444 135X,'LB/IN.',/,/
    RETURN
END

```



```

DUM(K)=0.D0
DO 702 J=1,K
DUM(K)=DUM(K)+SK(I,J)*SM(K,J)
DO 703 ID=1,NDOFT
SK(I,ID)=DUM(ID)
DO 704 K=1,NDOFT
DUM(K)=0.D0
DO 704 J=1,K
DUM(K)=DUM(K)+SM(K,J)*SK(J,I)
DO 705 ID=1,NDOFT
SK(ID,I)=DUM(ID)
709 RETURN
END

```

```

SUBROUTINE JACROT
  IMPLICIT REAL*8(A-H,O-Z)
  COMMON X(13),Y(13),Z(13),DO(1),DI(1),POI(1),SPWT(1),E(1),G(1),DUM(
166),DUM1(66),DUME1(66),DUME1(66),SKE(12,12),SME(12,12),SK(66,66),SM
2(66,66),GV,PI,EIVU(66),EIVR(66),BX(66),BY(66),BZ(66),FSEG(1),
3VSEG(1),FACTRX(66),FACTRY(66),FACTRZ(66),XSPCFR,YSPCFR,ZSPCFR,SMUX
4(66),SYJY(66),SMUZ(66),FFRAD(1),NNG(1),NBCN(13),NDOFPE,NDOFPN,IGRP
5NPRGR,NNT,NET,NN(2,12),NNA(13),JSEG,JSEGM,KOUNT,MOWTY,IELGLO(6,6)
6T,IGPP(12),NNPE,IEL(12),NDOFT,NDOFTT,IELGLO(6,6)

```

THIS SUBROUTINE USES THE JACOBI V.T. METHOD TO SOLVE THE
EIGENVALUE PROBLEM

SET THE MODE SHAPE MATRIX TO ZERO

```

DO 710 J=1,NDOFT
  DO 739 I=1,NDOFT
    EIVR(I,J)=0.00
  709 EIVR(J,J)=1.00
  710 ATOP=0.00

```

TEST THE NEW STIFFNESS MATRIX FOR SYMMETRY

```

DO 720 J=1,NDOFT
  DO 719 I=1,J
    IF(SK(I,J)-SK(J,I)) 712,715,712
  712 SK(I,J)=0.5*(SK(I,J)+SK(J,I))
  715 CONTINUE
  ATEMP2=DABS(SK(1,J))
  IF(ATOP-ATEMP2) 716,719,719
  716 ATOP=ATEMP2
  719 CONTINUE
  EIVU(J)=SK(J,J)
  720 AVGF=DFLOAT(NDOFT*(NDOFT-1))*0.55
  D=0.00

```

```

DO 730 JJ=2,NDOFT
  DO 730 II=2,JJ
    S=SK(II-1,JJ)/ATOP
  730 D=S*S+D

```

```

DSTOP=(1.D-06)*D
  THRESH=DSQRT(D/AVGF)*ATOP
  732 IFLAG=0
  DO 800 JCOL=2,NDOFT
    JCOL1=JCOL-1

```

```

734 DC 800 IROW=1, JCOL1
    SKPIJ=SK(IROW, JCOL)
    IF(DABS(SKPIJ)-THRESH) 800,800,734
    SKPII=SK(IROW, IROW)
    SKPJJ=SK(JCOL, JCOL)
    S=SKPJJ-SKPII
    IF(DABS(SKPIJ)-1.D-09*DABS(S)) 800,800,736
    IFLAG=1
    IF(1.D-10*DABS(SKPIJ)-DABS(S)) 740,738,738
    S=0.7071067811865475
    GO TO 742
740 T=SKPIJ/S
    S=J.25/DSQRT(J.25+T*T)
    C=DSQRT(0.5+S)
    S=2.0*T*S/C
    DO 750 I=1, IROW
    T=SK(I, IROW)
    U=SK(I, JCOL)
    SK(I, IROW)=C*T-S*U
    SK(I, JCOL)=S*T+C*U
    I2=IROW+2
    IF(I2-JCOL) 752,752,754
752 CONTINUE
    I=I2, JCOL
    DO 753 I=1, JCOL
    T=SK(I-1, JCOL)
    U=SK(IROW, I-1)
    SK(I-1, JCOL)=S*U+C*T
    SK(IROW, I-1)=C*U-S*T
    SK(JCOL, JCOL)=S*SKPIJ+C*SKPJJ
    SK(IROW, IROW)=C*SK(IROW, IROW)-S*(C*SKPIJ-S*SKPJJ)
    DO 760 J=JCOL, NDOFT
    T=SK(IROW, J)
    U=SK(JCOL, J)
    SK(IROW, J)=C*T-S*U
    SK(JCOL, J)=S*T+C*U
    DO 762 I=1, NDOFT
    T=EIVR(I, IROW)
    U=EIVR(I, JCOL)=C*T-EIVR(I, JCOL)*S
    EIVR(I, IROW)=S*T+EIVR(I, JCOL)*C
    S=SKPIJ/ATOP
    D=D-S*STOP
    IF(D-STOP) 764,766,766
764 D=0.D0
    DO 765 JJ=2, NDOFT
    DO 765 II=2, JJ
    S=SK(II-1, JJ)/ATOP
    D=S*S+D
765

```

```

766  DSTOP=(1.D-06)*D
800  THRESH=DSQRT(D/AVGF)*ATOP
      CONTINUE
810  IF(IFLAG) 732,810,732
      T=SK(1,1)
      SK(1,1)=EIVU(1)
      EIVU(1)=T
      DO 820 J=2,NDJFT
      T=SK(J,J)
      SK(J,J)=EIVU(J)
      EIVU(J)=T
      DO 820 I=2,J
      SK(I-1,J)=SK(J,I-1)
820  SK(I-1,J)=SK(J,I-1)
CC
      TRANSFORMING MODIFIED COORDINATES TO THE ORIGINAL SET
      DO 870 I=1,NDJFT
      DO 860 K=1,NDJFT
      DUM(K)=0.D0
      DO 860 J=1,NDJFT
      DUM(K)=DUM(K)+SM(J,I)*EIVR(J,K)
860  DUM(K)=DUM(K)+SM(J,I)*EIVR(J,K)
      DO 870 IA=1,NDJFT
      EIVR(I,IA)=DUM(IA)
870  EIVR(I,IA)=DUM(IA)
CC
      SORTING EIGENVECTORS AND EIGENVALUES
      DO 900 I=1,NDJFT
      DO 900 J=1,NDJFT
      IF(EIVU(I).LE.EIVU(J)) GO TO 900
      AMAP=EIVU(I)
      EIVU(I)=EIVU(J)
      EIVU(J)=AMAP
      DO 885 K=1,NDJFT
      AMAP=EIVR(K,I)
      EIVR(K,I)=EIVR(K,J)
      EIVR(K,J)=AMAP
885  EIVR(K,J)=AMAP
900  CONTINUE
      WRITE(6,1015)
      NDIV=NDJFT/NDJFPN
      DO 1025 I=1,NDIV
      NMP=NDJFPN*(I-1)+1
      IT3=NDJFPN*I
      WRITE(6,1040)(EIVU(N),N=NMP,IT3)
      DO 1020 N=1,NDIV
      IOP=NDJFPN*(N-1)+1
      IDP=NDJFPN*N
      DO 1019 L=1,1045(EIVR(L,K),K=NMP,IT3)
1019  WRITE(6,1045)(EIVR(L,K),K=NMP,IT3)

```

```

1020 WRITE(6,1043)
      CONTINUE
1025 WRITE(6,1044)
      CONTINUE
1015 FORMAT('1',//,30X,'EIGENVALUES AND EIGENVECTORS',//)
1040 FORMAT(' ',10X,6(1X,1PD13.5),//)
1044 FORMAT(' ',//)
1043 FORMAT(' ',//)
1045 FORMAT(' ',10X,6(1X,1PD13.5))
      RETURN
      END

```

```

SUBROUTINE SPCTRM
IMPLICIT REAL*8(A-H,O-Z)
COMMON X(13),Y(13),Z(13),DO(1),DI(1),POI(1),SPWT(1),E(1),G(1),DUM(
166),DUM1(66),DUME(66),DUMEL(66),SKE(12,12),SME(12,12),SK(66,66),SM
2(66,66),GV,PI,EIVU(66),EIVR(66),BX(66),BY(66),BZ(66),FSEG(1),
3VSEG(1),FACTRX(66),FACTRY(66),FACTRZ(66),XSPCFR,YSPCFR,ZSPCFR,SMUX
4(66),SMUY(66),SMUZ(66),EFRAD(1),NNG(11),NBCN(13),NDOFPE,NDOFPN,IGRP
5NPROB,NNT,NET,NN(2,12),NNA(13),JSEG,JSEGM,KOUNT,MOWTTY,IELGLO(6,6)
6T,IGRP(12),NNPE,IEL(12),NDOFT,JSEG,JSEGM,KOUNT,MOWTTY,IELGLO(6,6)

THIS SUBROUTINE DETERMINES THE SHOCK SPECTRUM AND NUMBER OF MODES
TO BE USED IN THE STRESS ANALYSIS

READ(5,991) ISPCTY,IFRQTY,JSEG
WRITE(6,996) ISPCTY,IFRQTY

CHANGE RADIAN FREQUENCY TO HERTZ

DO 905 J=1,NDOFT
EIVU(J)=DSQRT(EIVU(J))
EIVU(J)=EIVU(J)/(2.0D0*PI)

DETERMINE THE NUMBER OF MODES TO BE USED IN THE ANALYSIS

KOUNT=0
IF(IFRQTY) 910,920,930
KOUNT=NDOFT
GO TO 939

THE CUTOFF FREQUENCY IS 10X THE FUNDAMENTAL FREQUENCY

920 EIVUCO=10.0D0*EIVU(1)
DO 925 I=1,NDOFT
IF(EIVU(I).LE.EIVUCO) KOUNT=KOUNT+1
CONTINUE
GO TO 939

CUTOFF FREQUENCY IS PREDETERMINED AND READ

930 READ(5,992) EIVUCO
WRITE(6,997) EIVUCO
DO 935 I=1,NDOFT
IF(EIVU(I).LE.EIVUCO) KOUNT=KOUNT+1
CONTINUE

935 CONTINUE

DETERMINE THE TYPE OF SHOCK SPECTRUM TO BE USED

```

```

C 939 JSEGM=JSEG-1
940 IF(IISPCY) 943,963,970
940 GO TO 980

C SHOCK SPECTRUM REPRESENTED BY STRAIGHT LINES

C 963 WRITE(6,982) JSEGM
READ(5,993)(FSEG(J),VSEG(J),J=1,JSEG)
WRITE(6,998)(J,FSEG(J),VSEG(J),J=1,JSEG)
DO 966 J=1,KOUNT
DO 965 J=1,JSEGM
IF((FSEG(J)).LE.EIVU(I)).AND.(EIVU(I).LE.FSEG(J+1))) GO TO 963
GO TO 965
963 DUM(J)=(VSEG(J+1)-VSEG(J))/(FSEG(J+1)-FSEG(J))*(EIVU(I)-FSEG(J))
1+VSEG(J)
965 CONTINUE
966 GO TO 980

C SHOCK SPECTRUM CONSTANT VELOCITY TO F, THEN CONSTANT ACCELERATION

C 970 READ(5,994) FSEG(1),VSEG(1)
WRITE(6,999) FSEG(1),VSEG(1)
DO 975 J=1,KOUNT
IF(EIVU(J).LE.FSEG(1)) GO TO 977
DUM(J)=(VSEG(1)-FSEG(1))/EIVU(J)
GO TO 975
977 DUM(J)=VSEG(1)
975 CONTINUE
980 READ(5,995) XSPCFR,YSPCFR,ZSPCFR
WRITE(6,990) XSPCFR,YSPCFR,ZSPCFR
WRITE(6,991)(J,DUM(J),J=1,KOUNT)
991 FORMAT(3I5)
996 FORMAT(1I,10X,SPECTRUM,10X,FREQUENCY,/,10X,TYPE',14X,TYP
1E,/(10X,14,14X,15))
982 FORMAT(1I,10X,NUMBER OF STRAIGHT LINE SEGMENTS',15)
992 FORMAT(1I,10X,CUTOFF FREQUENCY,/,10X,HERTZ,/,12X,1PD10.3)
997 FORMAT(1I,10X,SEGMENT,5X,STARTING FREQUENCY,5X,STARTING
998 1VELOCITY,/,32X,HERTZ,18X,INCHES/SEC.,/(22X,14,10X,F8.2,15X,
2F8.2))
993 FORMAT(2D9.2)
994 FORMAT(2D10.3)
999 FORMAT(1I,10X,BREAK FREQUENCY,5X,CONSTANT VELOCITY,/,10X,
1HERTZ,15X,INCHES/SEC.,/(12X,F8.2,13X,F8.2))
995 FORMAT(3D10.3)
990 FORMAT(1I,10X,SHOCK INPUT FACTORS,/,10X,X',10X,Y',10X,Z',

```

```
1//((7X,F8.3,3X,F8.3,3X,F8.3))  
981 FORMAT(1.1,/,10X,MODE',10X,SPECTRUM VELOCITY',/,24X,INCHES/SEC  
1.1,/,10X,14,15X,F8.2))  
RETURN  
END
```

```

SUBROUTINE MODE
IMPLICIT REAL*8(A-H,O-Z)
COMMON X(13),Y(13),Z(13),DO(1),DI(1),POI(1),SPWT(1),E(1),G(1),DUM(
166),DUM1(66),DUME1(66),SKE(12,12),SME(12,12),SK(66,66),SM
2(66,66),GV,PI,EIVU(66),EIVR(66),BX(66),BY(66),FSEG(1),X
3VSEG(1),FACTRX(66),FACTRY(66),FACTORZ(66),XSPCFR,YSPCFR,ZSPCFR,SMUX
4(66),SMUY(66),SMUZ(66),EFRAD(1),NNG(11),NBCN(13),NDOFFPE,NDOFPN,IGRP
5NPRCB,NNT,NET,NN(2,12),NNA(13),JSEG,JSEGM,KOUNT,MOWTTY,IELGLO(6,6)
6T,IGRP(12),NNPE,IEL(12),NOOFT,NOOFFPE,NDOFFPE,NDOFPN,IGRP

```

THIS SUBROUTINE COMPUTES THE MODE PARTICIPATION FACTORS AND CORRECTS THE SPECTRUM VELOCITY FOR MODAL MASS

```

DO 2100 I=1,KOUNT
  BX(I)=0.0D0
  BY(I)=0.0D0
  BZ(I)=0.0D0
DO 2100 J=1,NDOFT
  BX(I)+=EIVR(J,I)
  BY(I)=BXY(I)+EIVR(J,I)
  BZ(I)=BZ(I)+EIVR(J,I)
  SMUX(J,I)
  SMUY(J,I)
  SMUZ(J,I)

```

CALCULATE CORRECTIONS TO SPECTRUM VELOCITY

```

READ(5,2111) MOWTTY
WRITE(6,2112) MCWTTY
IF(MCWTTY) 220,2240,2260
GO TO 2280

```

NO CORRECTION DESIRED

GO TO 2280

CORRECTION PREDICTED BY STRAIGHT LINE ON CORRECTED VELOCITY VS LOG MODAL WEIGHT CURVE

```

READ(5,2113) VOVOTS,VOVOTE,BMWTS,BMWTE
WRITE(6,2114) VOVOTS,VOVOTE,BMWTS,BMWTE
SLOPE=(VOVOTS-VOVOTS)/(DLOG10(BMWTE)-DLOG10(BMWTS))
VCEP=VOVOTS-SLOPE*DLOG10(BMWTS)
DO 2300 I=1,KOUNT
  DUM1(I)=(SLOPE*DLOG10((BX(I)**2)*GV))+VCEP)*DUM(I)
  DUM2(I)=(SLOPE*DLOG10((BY(I)**2)*GV))+VCEP)*DUM(I)
  DUM3(I)=(SLOPE*DLOG10((BZ(I)**2)*GV))+VCEP)*DUM(I)
CONTINUE
WRITE(6,2115)(I,BX(I),BY(I),BZ(I),I=1,KOUNT)

```

```

2283 IF(MOWITY) 2290,2283,2285
2285 GO TO 2290
2285 WRITE(6,2116)(DUM1(J),DUME(J),DUME1(J),J=1,KOUNT)
2290 CONTINUE
2111 FFORMAT(15),,,10X,'MODE WEIGHT CORRECTION TYPE',I4)
2112 FFORMAT(40),,,10X,'START V COORD',1X,'END V COORD',1X,'START MO WT
2113 FFORMAT(15),,,10X,'START V COORD',1X,'END V COORD',1X,'START MO WT
2114 1 COORD',1X,'END MO WT COORD',,,12X,1PD10.3,2X,1PD10.3,7X,1PD10.3,
2115 26X,1PD10.3)
2115 FFORMAT(15),,,10X,'MODE PARTICIPATION FACTORS',/,24X,'X
2116 1,11X,'Y',12X,'Z',/(9X,14,6X,1PD10.3,2X,1PD10.3,3X,1PD10.3)}
2116 FFORMAT(15),,,10X,'CORRECTED SPECTRUM VELOCITY',/,10X,'INCHES/SEC.
1,/,3(1X,1PD10.3))
RETURN
END

```

```

SUBROUTINE STRESS
IMPLICIT REAL*8(A-H,O-Z)
COMMON X(13),Y(13),Z(13),DO(1),DI(1),POI(1),SPWT(1),E(1),G(1),DUM(
166),DUM1(66),DUME(66),DUME1(66),SKE(12,12),SME(12,12),SK(66,66),SM
2(66,66),GV,P IVU(66),EIVR(66,66),BX(66),BY(66),BZ(66),FSEG(1),SMUX
3VSEG(1),FACTR(66),FACTRZ(66),XSPCFR,YSPCFR,ZSPCFR,SMUX
4(66),SMUY(66),SMUZ(66),EFRAD(1),NNPE,IEL(12),NDOFT,JSEG,JSEGM,KOUNT,MOWTY,IELGLO(6,6)
5NPROB,NNT,NET,NV(2,12),NNA(13),NNG(11),NBCN(13),NDOFPE,NDOFPN,IGRP
6T,IGRP(12),NNPE,IEL(12),NDOFT,JSEG,JSEGM,KOUNT,MOWTY,IELGLO(6,6)

```

CC
CC
CC
CC
CC

THIS SUBROUTINE COMPUTES THE OCTAHEDRAL SHEARING STRESS AT EACH
NODE FOR AN ELEMENT FIBER AT THE TOP AND 90 DEGREES TO THE SIDE
FOR EACH ELEMENT IN EACH MODE

DETERMINE THE MAXIMUM DISPLACEMENTS FOR EACH ELEMENT

```

DO 3255 I=1,NDOFT
DC 3255 J=1,NDOFT
SM(I,J)=0.0D0
3255 SK(I,J)=0.0D0
IF(MOWTY) 2600,2700,2780
2600 GO TO 2800

```

CC
CC

NO MODAL MASS CORRECTIONS TO SPECTRUM VELOCITY

```

2700 DC 2750 I=1,KOUNT
FACTRX(I)=((BX(I)*DUM(I))/(2.0D0*PI*EIVU(I)))*XSPCFR
FACTRY(I)=((BY(I)*DUM(I))/(2.0D0*PI*EIVU(I)))*YSPCFR
FACTRZ(I)=((BZ(I)*DUM(I))/(2.0D0*PI*EIVU(I)))*ZSPCFR
2750 GO TO 2800

```

CC
CC

MODAL MASS CORRECTIONS APPLIED TO SPECTRUM VELOCITY

```

2780 DC 2790 I=1,KOUNT
FACTRX(I)=((BX(I)*DUM1(I))/(2.0D0*PI*EIVU(I)))*XSPCFR
FACTRY(I)=((BY(I)*DUM1(I))/(2.0D0*PI*EIVU(I)))*YSPCFR
FACTRZ(I)=((BZ(I)*DUM1(I))/(2.0D0*PI*EIVU(I)))*ZSPCFR
2790 CONTINUE
2800

```

CC
CC

GENERATE THE ELEMENT AND GLOBAL ADDRESS ARRAY

```

DO 2850 I=1,3
DO 2850 J=1,3
KK=3
KM=I-1
IELGLO(J,I)=J+KM

```


[illegible]

```

2910 GO TO 3050
2915 KCUL=4
2920 GO TO 3050
2925 IF (TOY.LT.1.0D-3) GO TO 2940
2930 IF (CY.LT.0.000) GO TO 2930
2935 KCUL=2
2940 GO TO 3050
2945 KCUL=5
2950 GO TO 3050
2955 IF (DZ.LT.0.000) GO TO 2950
2960 KCUL=3
2965 GO TO 3050
2970 KCUL=6
2975 GO TO 3050
2980 N=1, KOUNT
2985 N=1, NNPE
2990 NEX=NDOPFN*(K-1)-1)*NDOPFN
2995 IEZ=(NNA(T.O)IEZ=0
3000 IF (IEZ.LT.0) J=1, NDOPFN
3005 J=1, NDOPFN
3010 J=1, NDOPFN
3015 J=1, NDOPFN
3020 J=1, NDOPFN
3025 J=1, NDOPFN
3030 J=1, NDOPFN
3035 J=1, NDOPFN
3040 J=1, NDOPFN
3045 J=1, NDOPFN
3050 J=1, NDOPFN
3055 J=1, NDOPFN
3060 J=1, NDOPFN
3065 J=1, NDOPFN
3070 J=1, NDOPFN
3075 J=1, NDOPFN
3080 J=1, NDOPFN
3085 J=1, NDOPFN
3090 J=1, NDOPFN
3095 J=1, NDOPFN
3100 J=1, NDOPFN
3105 J=1, NDOPFN
3110 J=1, NDOPFN
3115 J=1, NDOPFN
3120 J=1, NDOPFN
3125 J=1, NDOPFN
3130 J=1, NDOPFN
3135 J=1, NDOPFN
3140 J=1, NDOPFN
3145 J=1, NDOPFN
3150 J=1, NDOPFN
3155 J=1, NDOPFN
3160 J=1, NDOPFN
3165 J=1, NDOPFN
3170 J=1, NDOPFN
3175 J=1, NDOPFN
3180 J=1, NDOPFN
3185 J=1, NDOPFN
3190 J=1, NDOPFN
3195 J=1, NDOPFN
3200 J=1, NDOPFN
3205 J=1, NDOPFN
3210 J=1, NDOPFN
3215 J=1, NDOPFN
3220 J=1, NDOPFN
3225 J=1, NDOPFN
3230 J=1, NDOPFN
3235 J=1, NDOPFN
3240 J=1, NDOPFN
3245 J=1, NDOPFN
3250 J=1, NDOPFN
3255 J=1, NDOPFN
3260 J=1, NDOPFN
3265 J=1, NDOPFN
3270 J=1, NDOPFN
3275 J=1, NDOPFN
3280 J=1, NDOPFN
3285 J=1, NDOPFN
3290 J=1, NDOPFN
3295 J=1, NDOPFN
3300 J=1, NDOPFN
3305 J=1, NDOPFN
3310 J=1, NDOPFN
3315 J=1, NDOPFN
3320 J=1, NDOPFN
3325 J=1, NDOPFN
3330 J=1, NDOPFN
3335 J=1, NDOPFN
3340 J=1, NDOPFN
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3360 J=1, NDOPFN
3365 J=1, NDOPFN
3370 J=1, NDOPFN
3375 J=1, NDOPFN
3380 J=1, NDOPFN
3385 J=1, NDOPFN
3390 J=1, NDOPFN
3395 J=1, NDOPFN
3400 J=1, NDOPFN
3405 J=1, NDOPFN
3410 J=1, NDOPFN
3415 J=1, NDOPFN
3420 J=1, NDOPFN
3425 J=1, NDOPFN
3430 J=1, NDOPFN
3435 J=1, NDOPFN
3440 J=1, NDOPFN
3445 J=1, NDOPFN
3450 J=1, NDOPFN
3455 J=1, NDOPFN
3460 J=1, NDOPFN
3465 J=1, NDOPFN
3470 J=1, NDOPFN
3475 J=1, NDOPFN
3480 J=1, NDOPFN
3485 J=1, NDOPFN
3490 J=1, NDOPFN
3495 J=1, NDOPFN
3500 J=1, NDOPFN
3505 J=1, NDOPFN
3510 J=1, NDOPFN
3515 J=1, NDOPFN
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3525 J=1, NDOPFN
3530 J=1, NDOPFN
3535 J=1, NDOPFN
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3545 J=1, NDOPFN
3550 J=1, NDOPFN
3555 J=1, NDOPFN
3560 J=1, NDOPFN
3565 J=1, NDOPFN
3570 J=1, NDOPFN
3575 J=1, NDOPFN
3580 J=1, NDOPFN
3585 J=1, NDOPFN
3590 J=1, NDOPFN
3595 J=1, NDOPFN
3600 J=1, NDOPFN
3605 J=1, NDOPFN
3610 J=1, NDOPFN
3615 J=1, NDOPFN
3620 J=1, NDOPFN
3625 J=1, NDOPFN
3630 J=1, NDOPFN
3635 J=1, NDOPFN
3640 J=1, NDOPFN
3645 J=1, NDOPFN
3650 J=1, NDOPFN
3655 J=1, NDOPFN
3660 J=1, NDOPFN
3665 J=1, NDOPFN
3670 J=1, NDOPFN
3675 J=1, NDOPFN
3680 J=1, NDOPFN
3685 J=1, NDOPFN
3690 J=1, NDOPFN
3695 J=1, NDOPFN
3700 J=1, NDOPFN
3705 J=1, NDOPFN
3710 J=1, NDOPFN
3715 J=1, NDOPFN
3720 J=1, NDOPFN
3725 J=1, NDOPFN
3730 J=1, NDOPFN
3735 J=1, NDOPFN
3740 J=1, NDOPFN
3745 J=1, NDOPFN
3750 J=1, NDOPFN
3755 J=1, NDOPFN
3760 J=1, NDOPFN
3765 J=1, NDOPFN
3770 J=1, NDOPFN
3775 J=1, NDOPFN
3780 J=1, NDOPFN
3785 J=1, NDOPFN
3790 J=1, NDOPFN
3795 J=1, NDOPFN
3800 J=1, NDOPFN
3805 J=1, NDOPFN
3810 J=1, NDOPFN
3815 J=1, NDOPFN
3820 J=1, NDOPFN
3825 J=1, NDOPFN
3830 J=1, NDOPFN
3835 J=1, NDOPFN
3840 J=1, NDOPFN
3845 J=1, NDOPFN
3850 J=1, NDOPFN
3855 J=1, NDOPFN
3860 J=1, NDOPFN
3865 J=1, NDOPFN
3870 J=1, NDOPFN
3875 J=1, NDOPFN
3880 J=1, NDOPFN
3885 J=1, NDOPFN
3890 J=1, NDOPFN
3895 J=1, NDOPFN
3900 J=1, NDOPFN
3905 J=1, NDOPFN
3910 J=1, NDOPFN
3915 J=1, NDOPFN
3920 J=1, NDOPFN
3925 J=1, NDOPFN
3930 J=1, NDOPFN
3935 J=1, NDOPFN
3940 J=1, NDOPFN
3945 J=1, NDOPFN
3950 J=1, NDOPFN
3955 J=1, NDOPFN
3960 J=1, NDOPFN
3965 J=1, NDOPFN
3970 J=1, NDOPFN
3975 J=1, NDOPFN
3980 J=1, NDOPFN
3985 J=1, NDOPFN
3990 J=1, NDOPFN
3995 J=1, NDOPFN
4000 J=1, NDOPFN

```

[illegible]

CC

STORE THE OCTAHEDRAL SHEARING STRESSES

```

DO 3300 I=1,4
  IL2=3*L-2
  IL1=3*L-1
  SK(I,IL2)=SK(I,IL2)+(DUM(I)**2)
  SK(I,IL1)=SK(I,IL1)+(DUM1(I)**2)
  SK(I,IL)=SK(I,IL)+(DUME(I)**2)
3300 CONTINUE
DO 3550 I=1,LOP
  J=1,4
  SK(J,I)=DSQRT(SK(J,I))
  WAIT(6,4006)
  WRITF(6,4008) I
  NTJ=3*(I-1)+1
  DO 3659 J=1,4
    SK(J,K),K=NMD,NTJ)
  WRITF(6,4005)
  CONTINUE 4010
3659 CONTINUE
3660 CONTINUE
4005 FORMAT(' ',/(9X,3(1X,1PUI2.5)))
4006 FORMAT(' ',//,10X,'COMBINED OCTAHEDRAL SHEARING STRESSES EACH ELEM
  ENT',//)
4008 FORMAT(' ',//,10X,'ELEMENT',15)
4010 FORMAT(' ',//)
  RETURN
END

```

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