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DEVELOPMENT OF RANDOM RESPONSE ANALYSIS CAPABILITY FOR THE VAST FINITE ELEMENT PROGRAM - PHASE II

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DEVELOPMENT OF RANDOM RESPONSE ANALYSIS CAPABILITY FOR THE VAST FINITE ELEMENT PROGRAM -
PHASE II

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ABSTRACT

This report contains a description of the work done in the second phase of a contract awarded by the Defence Research Establishment Atlantic (DREA) of the Canadian Department of National Defence for the development of an in-house random response analysis capability. A description of additional work to complete the modal random vibration analysis module (RANVB1) is given. The development of a twin module (RANVB2) based on the direct frequency response method is presented. A brief description of the graphics support to the random response analysis programs is also given. Example problems illustrating the operations of RANVB1 and RANVB2 are given. The report closes with some comments about the impressive features of the random vibration capabilities of the VAST finite element analysis system and highlights some recommendations that would further enhance the current capabilities.

RÉSUMÉ

Ce rapport contient une description des travaux réalisés dans le cadre de la deuxième phase d'un contrat passé par le Centre de recherches pour la défense/Atlantique (CRDA) du ministère de la Défense nationale du Canada en vue du développement des capacités internes en analyse de la réponse modale. Le texte décrit les travaux additionnels réalisés pour compléter le modèle d'analyse des vibrations aléatoires modales (RANVB1). Le rapport décrit aussi le développement d'un module très semblable (RANVB2) fondé sur la méthode de la réponse en fréquence directe. On trouvera aussi une brève description des fonctions de soutien graphique pour les divers programmes d'analyse de la réponse aléatoire. Le texte contient des exemples de problèmes montrant le fonctionnement de RANVB1 et de RANVB2. Le rapport se termine par quelques commentaires sur les remarquables capacités des fonctions en mode de vibrations aléatoires du système d'analyse par éléments finis VAST et formule certaines recommandations qui permettraient de poursuivre l'enrichissement des possibilités actuelles.

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1. INTRODUCTION

This is a report of the second phase of the work performed under contract to the Defence Research Establishment Atlantic (DREA) concerning the provision of an in-house capability for the probabilistic structural integrity assessment of naval ships. In the first phase of the work [1], computer programs for performing random vibration analysis were developed and integrated in the VAST finite element analysis (FEA) system.

In this second phase, the development of computer programs for random vibration analysis using the modal frequency response method was completed. First, the capability for the computation of secondary responses (i.e. stresses and strains) in RANVB1 (formerly referred to as RANVIB in the Phase I report) module, was provided. A graphics support capability for the efficient display of random response results was developed within the VASTG post-processing program. Also, as part of this phase, a new module called RANVB2 was developed for random response analysis via the direct frequency response method. This capability has the advantage that it does not require a prior eigenvalue analysis and is able to handle structures that have frequency dependent mass, damping, and stiffness properties. However, it is computationally more intensive than the modal frequency response method implemented in RANVB1.

The present document describes the work done during the second phase. In Chapter 2, a description of the theoretical basis and computer implementation of the procedure for computing stresses and strains under random excitations is given. Chapter 3 gives the graphics support capabilities that have been implemented in VASTG for the display of random response results. in Chapter 4, the development of RANVB2 and its theoretical basis is presented. Chapter 5 gives some typical results and discussions emanating from these efforts. Chapter 6 closes the report with a few remarks about the status of the random response analysis features of VAST and some recommendations for program enhancements.

2. COMPLETION OF THE DEVELOPMENT OF THE MODAL FREQUENCY RESPONSE RANDOM VIBRATION ANALYSIS MODULE (RANVB1)

The theoretical formulation in respect of the random response analysis of discretized structures subjected to stationary random excitations was given in Chapter 2 of the report of Phase I of this contract [1]. The formulation was presented within the framework of the displacement-based finite element method for which the solution of the governing equations of motion is primarily for displacements. In Reference [1], the procedure for computing the statistical properties for velocities and accelerations from those of displacements was given. The computation of random stresses (or strains) was also described in terms of a transformation matrix relating stresses (or strains) to displacements.

In [1], the transformation matrix relating the stress $\{\sigma\}$ at a given set of points to the modal displacements $\{q\}$ is defined as $[T]$. Similarly, the strain transformation matrix is defined as $[W]$ so that:

$$\{\sigma\} = [T]\{q\} \tag{2.1}$$

and

$$\{\epsilon\} = [W]\{q\} \tag{2.2}$$

A typical component T_{ij} of the matrix $[T]$ represents the stress at point i due to a normalized oscillation in the oscillation mode j. In other words, therefore, $[T]$ is the modal stress transformation matrix corresponding to the points and stress components of interest in the structure. The same goes for the definition of the components of $[W]$. Once $[T]$ and $[W]$ have been determined, the cross-spectral density matrices of stresses and strains are obtained from the modal responses:

$$[S_{\sigma\sigma}(\omega)] = [T][S_{qq}(\omega)][T]^T \tag{2.3}$$

$$[S_{\epsilon\epsilon}(\omega)] = [W][S_{qq}(\omega)]\ [W]^T \tag{2.4}$$

where $[Sqq(\omega)]$ is the cross-spectral density matrix of the modal displacement response. In a similar fashion, the covariance matrices of stresses and strains can be obtained from the modal transformation matrix using the relations:

$$[C_{\sigma\sigma}] = [T][C_{qq}][T]^T \tag{2.5}$$

$$[C_{\epsilon\epsilon}] = [W][C_{qq}][W]^T \tag{2.6}$$

Correlation functions for stresses and strains are directly obtainable from the spectral densities computed from Equations (2.3) and (2.4) as described in [1]. Apparent frequencies for stresses and strains are also easily obtained. It is easy to see that these transformation matrices are the secondary response counterpart of the modal transformation matrix [R] used in the computation of primary responses.

In order to determine matrix [T], a knowledge of the modal stress is required. Modal stresses $\{\sigma\}$ are stresses computed (at the element level) using the eigenvectors as the modal displacements $\{\sigma\}$ from the classical finite element relation:

$$\{\sigma\} = [D][B]\{\delta\} \tag{2.7}$$

where [D][B] is the so-called stress matrix in which [D] is the constitutive matrix and [B] is the strain matrix relating strains to nodal displacements.

The computation in (2.7) was effected in the stress module (stress) of VAST by looping over the modes in much the same manner as one would loop over successive displacement vectors in a dynamic analyses. Thus, for each mode, the eigenvector for that mode is used as the modal displacements for the computation of element stresses. These element stresses are stored as usual, on the binary output file PREFX.T53.

In order to avoid the computation of random response results at the element level, it was necessary to post-process the element stresses to obtain averaged modal nodal stresses and strains. The module that performs this post-processing averaging operation is POSTV2 which can be run in a batch mode by the module POSPR1 of VAST or in an interactive mode by VASTG.

The user has the option of selecting the geometric nodes for which the random stresses and/or strains are to be computed or requesting that these response quantities be computed for all the nodes of the structure. The selection of nodes for the computation of secondary responses need not be the same as for primary responses as can be seen in the revised input data described in Appendix A. The user must ensure that the VAST master control codes ISTRES and IPOSTP are set to 1 with the appropriate element stresses requested in the PREFX.USE file. The user must also request that stress post-processing by POSTV2 be performed following the procedure described in the VAST user manual [2]. Since this procedure involves the use of POSTV2, the user has the responsibility to check that the elements in the FEA model are acceptable to this post-processing module.

When the input data for the random response analysis is read, the user-supplied information is then used for the extraction of the stress and strain transformation matrices corresponding to the nodes of interest.

Five user options are available as to which random stress/strain components are to be computed. These options are defined by the parameter ISOPT as described in the input data requirements in Appendix A. The options include six stress/strain components, principal stresses/strains, von Mises stress/strain, maximum shear stress/strain, and a combination of all of these components.

The random stress and strain results that are printed out by RANVB1 are nodal values and not values at element integration points.

3. DEVELOPMENT OF A DIRECT FREQUENCY RESPONSE RANDOM VIBRATION ANALYSIS PROGRAM (RANVB2)

The governing equation of motion of a continuous structure discretized by the finite element method is of the form:

$$\underline{M}\,\ddot{\underset{\sim}{X}} + \underline{C}\,\dot{\underset{\sim}{X}} + \underline{K}\,\underset{\sim}{X} = \underset{\sim}{F}(t) \tag{3.1}$$

In Equation (3.1), $\underline{M}$ is the assembled mass matrix, $\underline{C}$ is the damping matrix, $\underline{K}$ is the assembled stiffness matrix, $\underset{\sim}{X}(t)$ is the vector displacements response to the vector excitation $\underset{\sim}{F}(t)$, $\dot{\underset{\sim}{X}}(t)$ is the random velocity vector, and $\ddot{\underset{\sim}{X}}(t)$ is the random acceleration vector. For the present, it is assumed that the system parameters $\underline{M}$, $\underline{C}$, and $\underline{K}$ are known deterministic quantities thereby leaving $\underline{F}(t)$ the only random input for which the random output $\underset{\sim}{X}(t)$ is sought. For a structure discretized in this manner with a total of NS global degrees of freedom, $\underline{M}$, $\underline{C}$, and $\underline{K}$ are (NSxNS) square matrices while both $\underset{\sim}{X}$ and $\underset{\sim}{F}$ are vectors with NS components.

It can be shown that the cross-spectral density of the vector random displacement response is related to that of the vector random force excitation via the expression:

$$[S_{XX}(\omega)] = [H(i\omega)][S_{FF}(\omega)][H(i\omega)]^{T*} \tag{3.2}$$

where $[S_{FF}(\omega)]$ and $[S_{XX}(\omega)]$ are matrices of excitation and response spectra including auto- and cross-spectral density functions, and $[H(i\omega)]$ is the complex frequency response function matrix corresponding to Equation (3.1). On taking the Fourier transform of both sides of Equation (3.1), it is easy to see that $[H(i\omega)]$ is given by:

$$[H(i\omega)] = [\underline{K} - \omega^2\underline{M} + i\omega\underline{C}]^{-1} \tag{3.3}$$

The procedure for computing $[S_{xx}(\omega)]$ by using Equations (3.2) and (3.3) involves an inversion of the matrix shown on the right hand side of Equation (3.3) at each discrete frequency and is known as the direct frequency response method of analysis. The inversion of this usually large and complex matrix is computationally intensive and so consumes far more CPU time than the modal frequency response method. The method is called "direct" because the solution procedure is based on the direct inversion of the matrix in Equation (3.3) to give the full complex frequency response matrix.

The primary advantage of the direct method over its modal counterpart is the capability to handle non-classical forms of damping. Classical forms of damping are those for which the equations of motion can be decoupled (are i.e., diagonalized) by applying the modal transformation matrix. Three forms of classical damping were described in Reference [1]. In the direct method, however, the damping matrix does not have to satisfy this restriction, and could be of any form. Furthermore, because the complex frequency response matrix is determined as shown in (3.3) for every frequency, the method is very suitable for structures with frequency dependent mass, stiffness, and damping properties. The methodology also accommodates materials with complex stiffness, for example, viscoelastic materials. This makes it possible to study the random response characteristics of composite structures designed using the constrained layer damping technique. The use of the direct frequency response method does not require a prior eigenvalue analysis of the structure for the determination of the mode shapes and natural frequencies.

The direct frequency response random vibration analysis module is called RANVB2, and like RANVB1, is called from the main program (MAIN) in VAST. The choice of solution method is described by the parameter IOPT which is set to 1 for the modal method (RANVB1) and to 2 for the direct method (RANVB2). The subroutines in RANVB2 are a little different from those in RANVB1 because of the difference in solution techniques. Because the computation of secondary responses is based on modal stresses, RANVB2 does not compute random stresses or strains. Also, there are two damping options (Rayleigh or proportional damping and structural damping) in RANVB2 as compared with three in RANVB1.

This is for the obvious reason that modal damping is not compatible with the direct method of solution. Apart from these two items, the computation options available in RANVB2 are very much the same as those of RANVB1. The binary output file formats are also identical so that graphical display of results is independent of the solution method employed by the user. The same subroutine PRNTRR is used to print out the random response results in the VAST output file (PREFX.LPT).

Similar to the IRESP1 parameter in RANVB1, a parameter IRESP2 is available in RANVB2 to allow the user to utilize a previously generated complex frequency response function matrix stored as file PREFX.CFR for response computations. There is also an option, of course, of running RANVB2 solely for the purpose of generating this file which can then be used in a future program run. This is a useful restart type of feature that avoids a repetition of the time-consuming process of generating the complex frequency response matrices at every frequency.

As would be expected, RANVB2 consumes far more CPU time than RANVB1 because the inversion of the matrix $[K-\omega^2M + i\omega C]$ at every frequency is a very computer intensive process. Also, the response computation involves the multiplication of larger matrices (NSxNS instead of NMxNM) in the case of RANVB2.

Program RANVB2 produces results that are in good agreement with those produced by RANVB1. Typical comparisons are shown in Chapter 5.

The input data format for the random response analysis is fully described in Appendix A, while the loading input format is described in Appendix C.

4. GRAPHICS SUPPORT

A new module (PLOTV18) has been developed within the VAST post-processing program VASTG for the display of the random response results generated by either RANVB1 or RANVB2.

Program PLOTV18 has the capability to plot power spectrum versus frequency using either a linear scale, a semi-logarithmic scale, or a log-log scale, at the user's choice. It also plots auto-correlation function versus time delay. These plots may be for displacements, velocities, accelerations, stresses or strains at user specified nodes and degrees of freedom.

PLOTV18 also has the capability to plot random stress and strain contours based on root-mean-square values of these quantities computed in RANVB1. The component specified by the user may be any of σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{yz}, σ_{xz}, σ_1, σ_2, σ_3, von Mises stress strain or maximum shear stress strain.

The operating instructions of PLOTV18 are included as Appendix B and are self-explanatory. Typical plots obtained by the program are included in Chapter 5.

5. TYPICAL RESULTS PRODUCED BY RANVB1/RANVB2

In this section, some typical results produced by the VAST random vibration analysis modules (RANVB1 and RANVB2) are presented.

Table 5.1 gives sample outputs (PREFX.LPT files) comparing the results obtained using the modal frequency response method (RANVB1) and the direct frequency response method (RANVB2). It can be seen that the results are in very good agreement. The results were earlier presented in reference [1] for RANVB1 and shown to agree very well with those of Olson [3] and ABAQUS [4]. Figure 5.1 shows the comparison of results generated using the lumped-load (LOAD9A) and consistent distributed load (LOAD9C) methods in VAST. The distributed load gives more accurate results and Figure 5.1 illustrates that the errors arising from the use of lumped loading increases as the frequency increases. This is a demonstration of the importance of consistent finite element discretization of distributed random loads. The plots in Figures 5.1 and 5.7 were obtained using the Harvard Graphics package before PLOTV18 was developed for VASTG. Typical plots that were later obtained using VASTG are shown in Figures 5.2, 5.3, and 5.4.

As a further verification problem, the response of a cantilever subjected to random base motion in the vertical direction as shown in Figure 5.5 was considered. The base acceleration power spectral density function is as shown in Figure 5.6. This problem is one of those in the ABAQUS example manual [4]. Table 5.2 shows the numerical values of the power spectral density of displacements at three nodes. Again, these results are in very good agreement with the results of ABAQUS. The agreement is well demonstrated by the comparison plot presented in Figure 5.7 showing the displacement response at the tip of the cantilever.

Overall, the results produced by the random vibration modules of VAST are very encouraging.

TABLE 5.1

SAMPLE OUTPUTS FROM RANVB1 AND RANVB2

```
R A N D O M   R E S P O N S E   A N A L Y S I S

   MODAL FREQUENCY RESPONSE METHOD

P O W E R   S P E C T R U M   O F   D I S P L A C E M E N T S

FREQUENCY -  0.000E+00
     1  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.579E-03
     2  0.000E+00 0.267E-04 0.000E+00 0.000E+00 0.000E+00 0.207E-03
     3  0.000E+00 0.415E-04 0.000E+00 0.000E+00 0.000E+00 0.188E-04
     4  0.000E+00 0.124E-04 0.000E+00 0.000E+00 0.000E+00 0.278E-03
     5  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.430E-04
     6  0.000E+00 0.191E-06 0.000E+00 0.000E+00 0.000E+00 0.353E-04
     7  0.000E+00 0.227E-05 0.000E+00 0.000E+00 0.000E+00 0.123E-05
     8  0.000E+00 0.719E-06 0.000E+00 0.000E+00 0.000E+00 0.293E-04
     9  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.483E-05
    10  0.000E+00 0.352E-05 0.000E+00 0.000E+00 0.000E+00 0.804E-04
    11  0.000E+00 0.993E-05 0.000E+00 0.000E+00 0.000E+00 0.757E-15
    12  0.000E+00 0.352E-05 0.000E+00 0.000E+00 0.000E+00 0.804E-04
    13  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.483E-05
    14  0.000E+00 0.719E-06 0.000E+00 0.000E+00 0.000E+00 0.293E-04
    15  0.000E+00 0.227E-05 0.000E+00 0.000E+00 0.000E+00 0.123E-05
    16  0.000E+00 0.191E-06 0.000E+00 0.000E+00 0.000E+00 0.353E-04
    17  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.430E-04
    18  0.000E+00 0.124E-04 0.000E+00 0.000E+00 0.000E+00 0.278E-03
    19  0.000E+00 0.415E-04 0.000E+00 0.000E+00 0.000E+00 0.188E-04
    20  0.000E+00 0.267E-04 0.000E+00 0.000E+00 0.000E+00 0.207E-03
    21  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.579E-03

FREQUENCY -  0.200E+01
     1  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.613E-03
     2  0.000E+00 0.284E-04 0.000E+00 0.000E+00 0.000E+00 0.221E-03
     3  0.000E+00 0.443E-04 0.000E+00 0.000E+00 0.000E+00 0.192E-04
     4  0.000E+00 0.135E-04 0.000E+00 0.000E+00 0.000E+00 0.294E-03
     5  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.578E-04
     6  0.000E+00 0.729E-06 0.000E+00 0.000E+00 0.000E+00 0.403E-04
     7  0.000E+00 0.310E-05 0.000E+00 0.000E+00 0.000E+00 0.310E-05
     8  0.000E+00 0.972E-06 0.000E+00 0.000E+00 0.000E+00 0.359E-04
     9  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.452E-05
    10  0.000E+00 0.338E-05 0.000E+00 0.000E+00 0.000E+00 0.792E-04
    11  0.000E+00 0.965E-05 0.000E+00 0.000E+00 0.000E+00 0.494E-07
    12  0.000E+00 0.338E-05 0.000E+00 0.000E+00 0.000E+00 0.792E-04
    13  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.457E-05
    14  0.000E+00 0.969E-06 0.000E+00 0.000E+00 0.000E+00 0.358E-04
    15  0.000E+00 0.309E-05 0.000E+00 0.000E+00 0.000E+00 0.310E-05
    16  0.000E+00 0.720E-06 0.000E+00 0.000E+00 0.000E+00 0.402E-04
    17  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.577E-04
    18  0.000E+00 0.135E-04 0.000E+00 0.000E+00 0.000E+00 0.294E-03
    19  0.000E+00 0.443E-04 0.000E+00 0.000E+00 0.000E+00 0.192E-04
    20  0.000E+00 0.284E-04 0.000E+00 0.000E+00 0.000E+00 0.222E-03
    21  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.613E-03
```

```
R A N D O M   R E S P O N S E   A N A L Y S I S

   DIRECT FREQUENCY RESPONSE METHOD

P O W E R   S P E C T R U M   O F   D I S P L A C E M E N T S

FREQUENCY -  0.000E+00
     1  0.000E+00 0.130E-36 0.000E+00 0.000E+00 0.000E+00 0.582E-03
     2  0.000E+00 0.267E-04 0.000E+00 0.000E+00 0.000E+00 0.207E-03
     3  0.000E+00 0.415E-04 0.000E+00 0.000E+00 0.000E+00 0.192E-04
     4  0.000E+00 0.124E-04 0.000E+00 0.000E+00 0.000E+00 0.275E-03
     5  0.000E+00 0.159E-37 0.000E+00 0.000E+00 0.000E+00 0.433E-04
     6  0.000E+00 0.191E-06 0.000E+00 0.000E+00 0.000E+00 0.347E-04
     7  0.000E+00 0.227E-05 0.000E+00 0.000E+00 0.000E+00 0.120E-05
     8  0.000E+00 0.719E-06 0.000E+00 0.000E+00 0.000E+00 0.286E-04
     9  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.481E-05
    10  0.000E+00 0.352E-05 0.000E+00 0.000E+00 0.000E+00 0.794E-04
    11  0.000E+00 0.994E-05 0.000E+00 0.000E+00 0.000E+00 0.101E-35
    12  0.000E+00 0.352E-05 0.000E+00 0.000E+00 0.000E+00 0.794E-04
    13  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.481E-05
    14  0.000E+00 0.719E-06 0.000E+00 0.000E+00 0.000E+00 0.286E-04
    15  0.000E+00 0.227E-05 0.000E+00 0.000E+00 0.000E+00 0.120E-05
    16  0.000E+00 0.191E-06 0.000E+00 0.000E+00 0.000E+00 0.347E-04
    17  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.433E-04
    18  0.000E+00 0.124E-04 0.000E+00 0.000E+00 0.000E+00 0.275E-03
    19  0.000E+00 0.415E-04 0.000E+00 0.000E+00 0.000E+00 0.192E-04
    20  0.000E+00 0.267E-04 0.000E+00 0.000E+00 0.000E+00 0.207E-03
    21  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.582E-03

FREQUENCY -  0.200E+01
     1  0.000E+00 0.149E-36 0.000E+00 0.000E+00 0.000E+00 0.617E-03
     2  0.000E+00 0.283E-04 0.000E+00 0.000E+00 0.000E+00 0.221E-03
     3  0.000E+00 0.444E-04 0.000E+00 0.000E+00 0.000E+00 0.196E-04
     4  0.000E+00 0.135E-04 0.000E+00 0.000E+00 0.000E+00 0.291E-03
     5  0.000E+00 0.108E-37 0.000E+00 0.000E+00 0.000E+00 0.579E-04
     6  0.000E+00 0.729E-06 0.000E+00 0.000E+00 0.000E+00 0.397E-04
     7  0.000E+00 0.311E-05 0.000E+00 0.000E+00 0.000E+00 0.320E-05
     8  0.000E+00 0.972E-06 0.000E+00 0.000E+00 0.000E+00 0.350E-04
     9  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.443E-05
    10  0.000E+00 0.338E-05 0.000E+00 0.000E+00 0.000E+00 0.782E-04
    11  0.000E+00 0.965E-05 0.000E+00 0.000E+00 0.000E+00 0.709E-07
    12  0.000E+00 0.338E-05 0.000E+00 0.000E+00 0.000E+00 0.782E-04
    13  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.448E-05
    14  0.000E+00 0.969E-06 0.000E+00 0.000E+00 0.000E+00 0.349E-04
    15  0.000E+00 0.309E-05 0.000E+00 0.000E+00 0.000E+00 0.320E-05
    16  0.000E+00 0.720E-06 0.000E+00 0.000E+00 0.000E+00 0.396E-04
    17  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.577E-04
    18  0.000E+00 0.135E-04 0.000E+00 0.000E+00 0.000E+00 0.291E-03
    19  0.000E+00 0.444E-04 0.000E+00 0.000E+00 0.000E+00 0.196E-04
    20  0.000E+00 0.283E-04 0.000E+00 0.000E+00 0.000E+00 0.221E-03
    21  0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.617E-03
```

TABLE 5.2

COMPARISON OF THE RESULTS OF ABAQUS AND VAST (LOAD9B)

Node No.	PSD of Displacements (in distance^2/Hz)			
	ω_1 = 82.6		ω_2 = 511.8	
	VAST (LOAD9B)	ABAQUS	VAST (LOAD9B)	ABAQUS
3	0.698E-10	0.699E-10	0.314E-12	0.311E-12
6	0.197E-8	0.197E-8	0.179E-11	0.175E-11
11	1.171E-7	0.171E-7	0.355E-11	0.351E-11

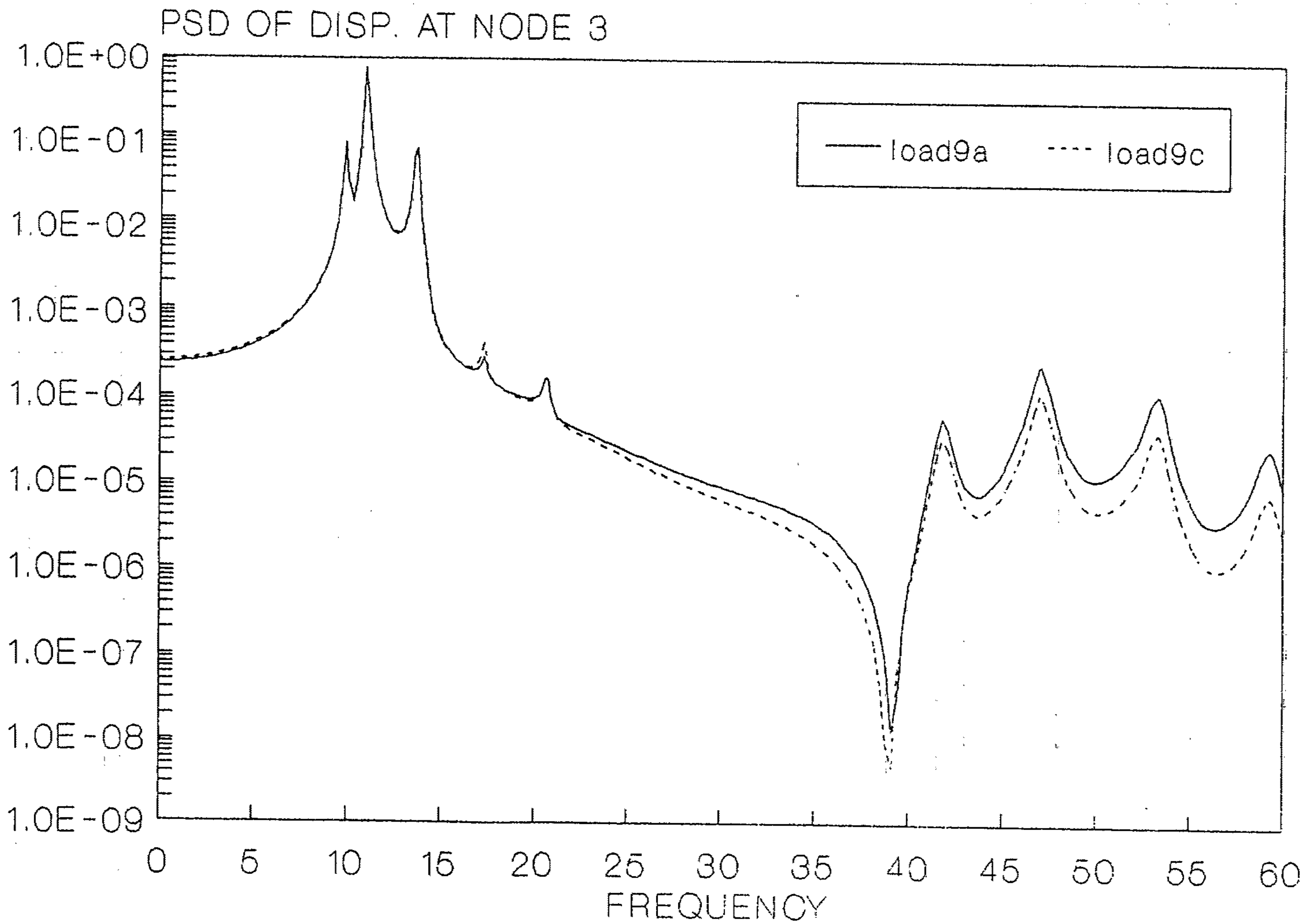

FIGURE 5.1. Comparison of the Performance of Lumped-Load and Consistent-Load Formulations for the Five Span Beam Problem

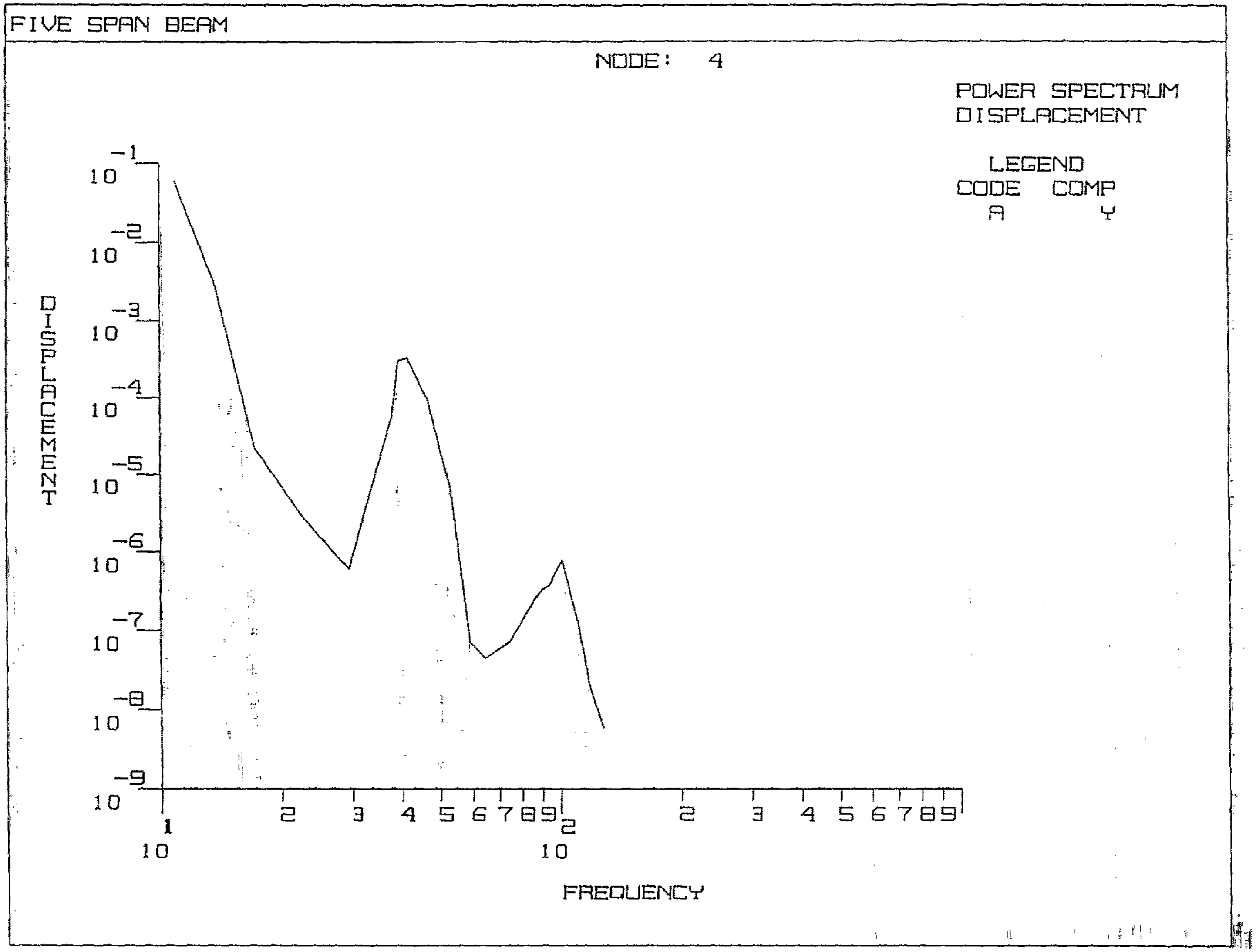

FIGURE 5.2. Random Displacement Response at Node 4

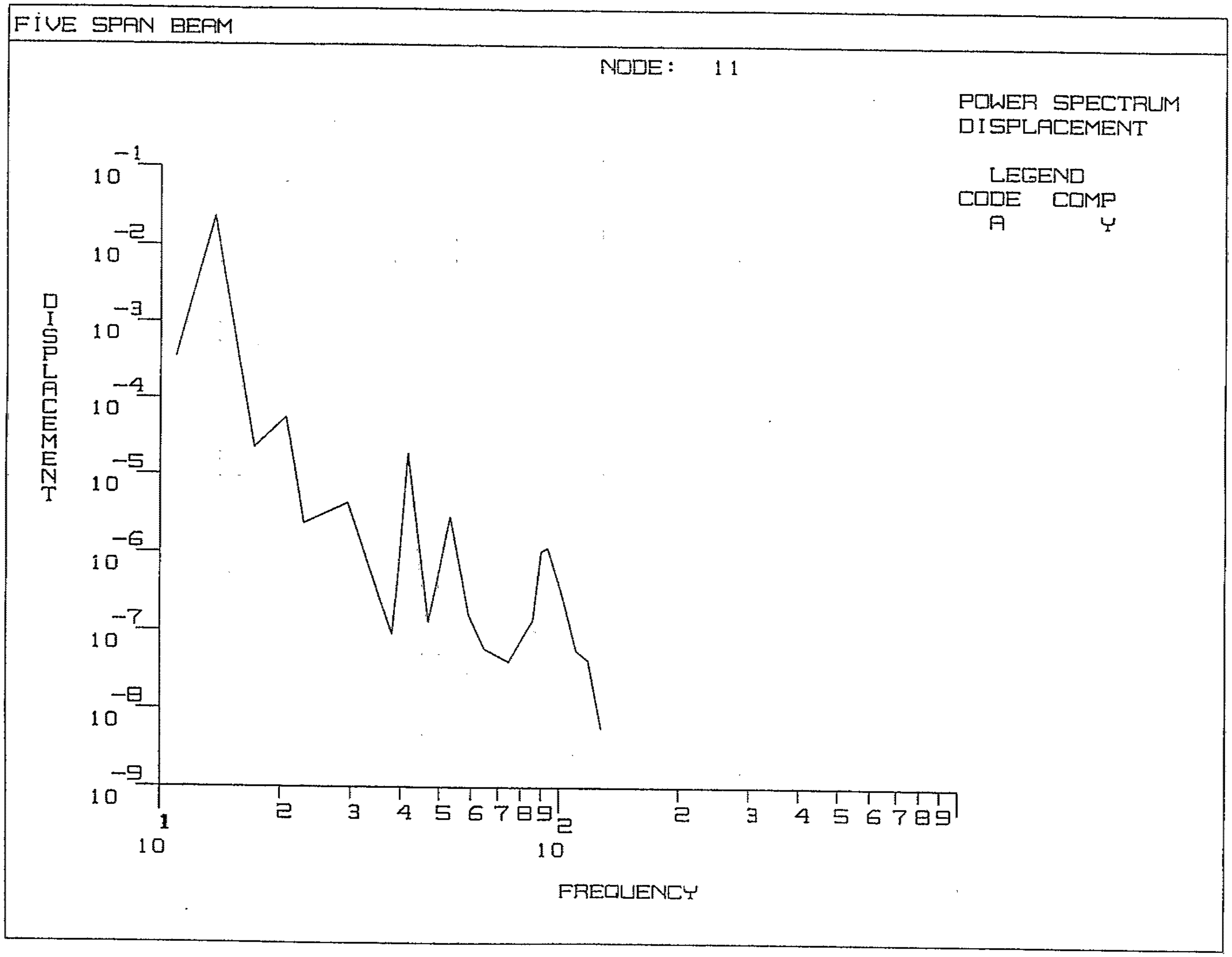

FIGURE 5.3. Random Displacement Response at Node 11

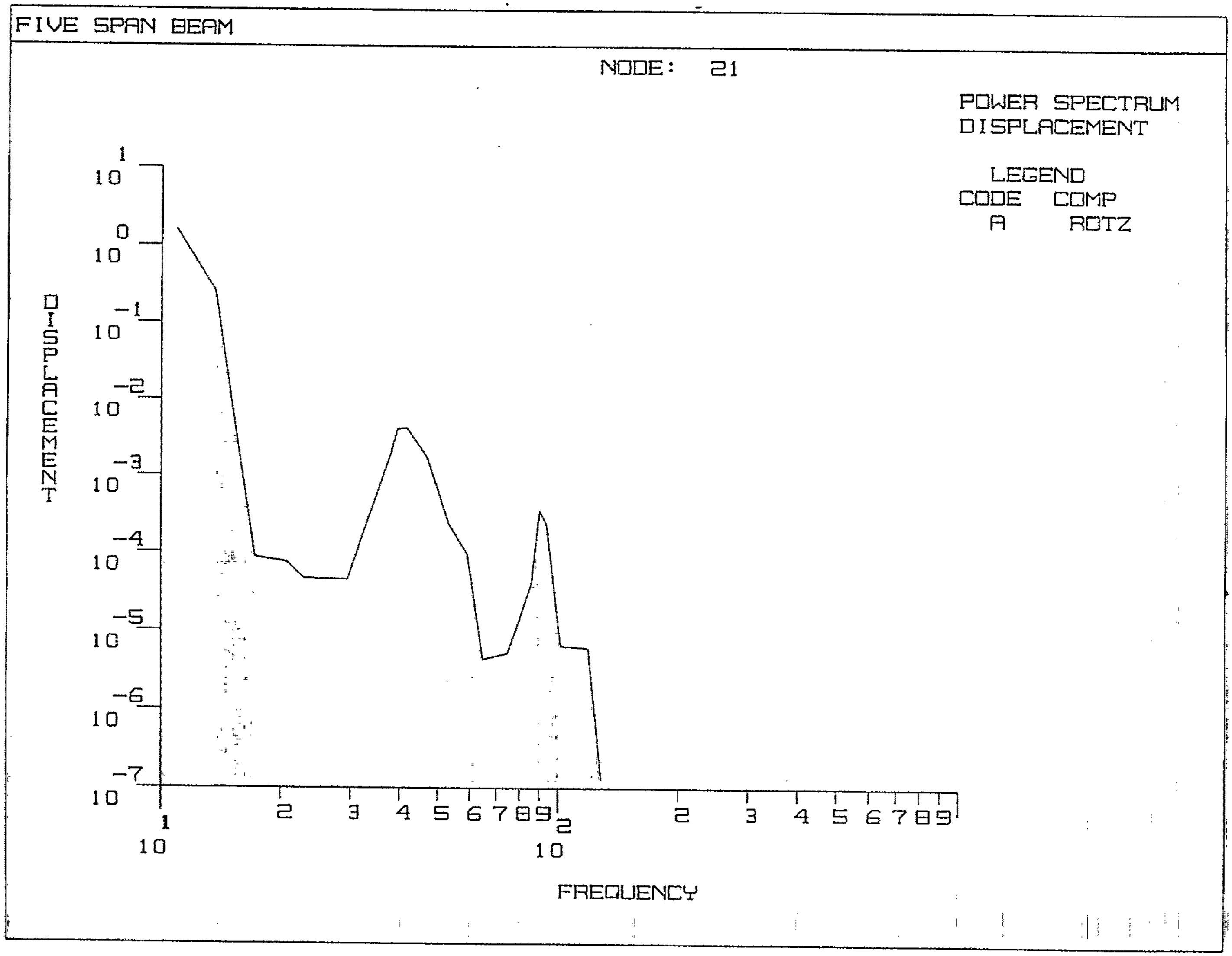

FIGURE 5.4. Random Displacement Response at Node 21

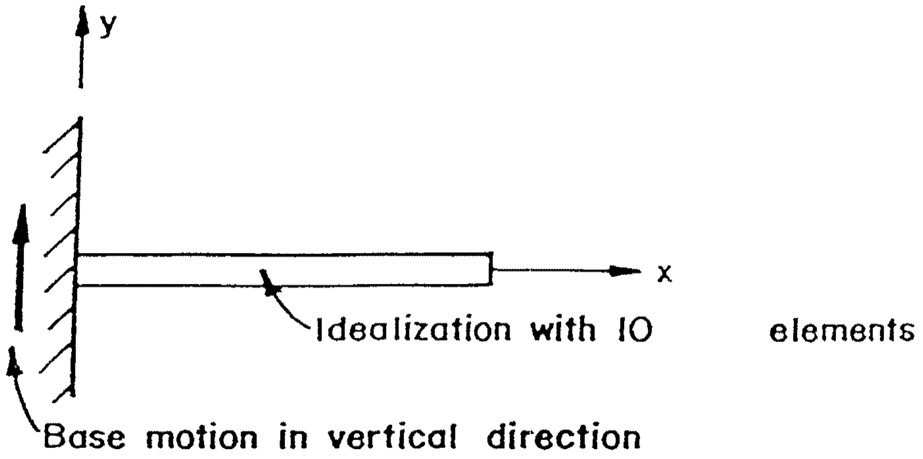

FIGURE 5.5. A Cantilever Subjected to Random Base Motion

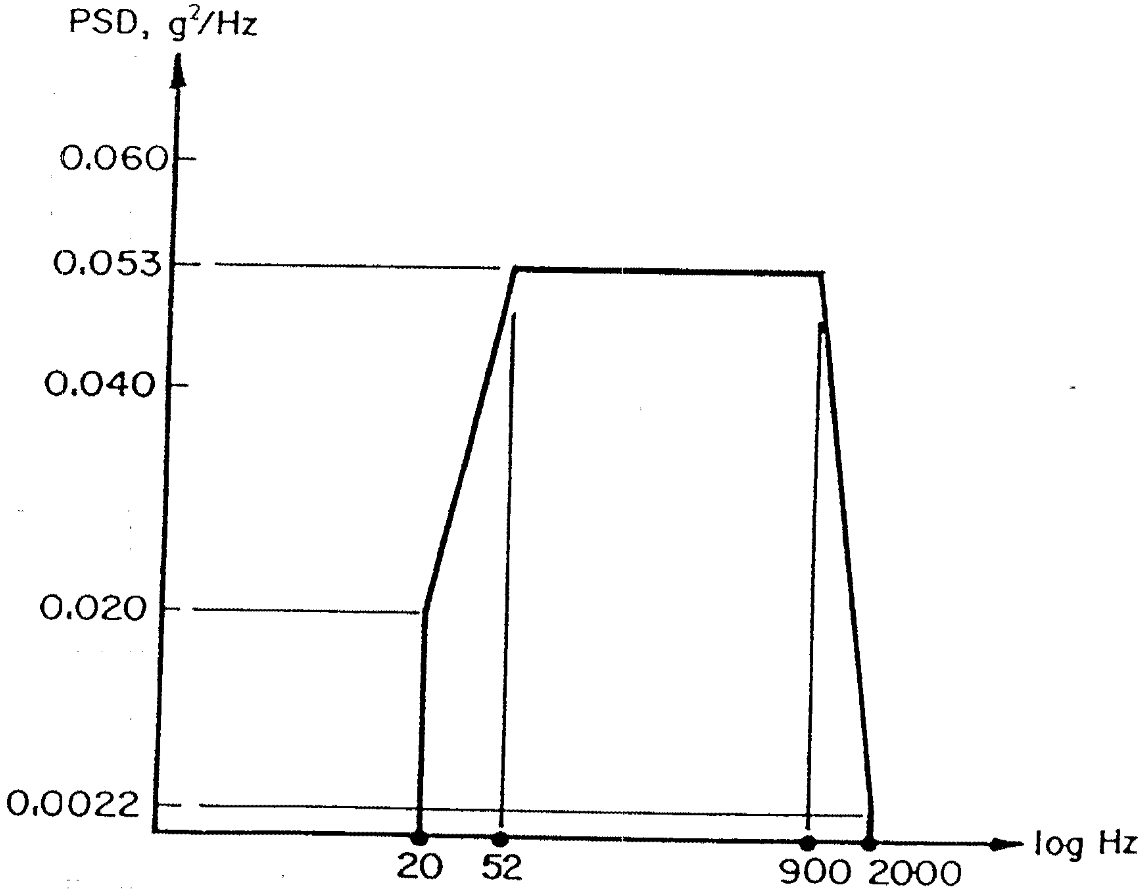

FIGURE 5.6. Base Acceleration PSD

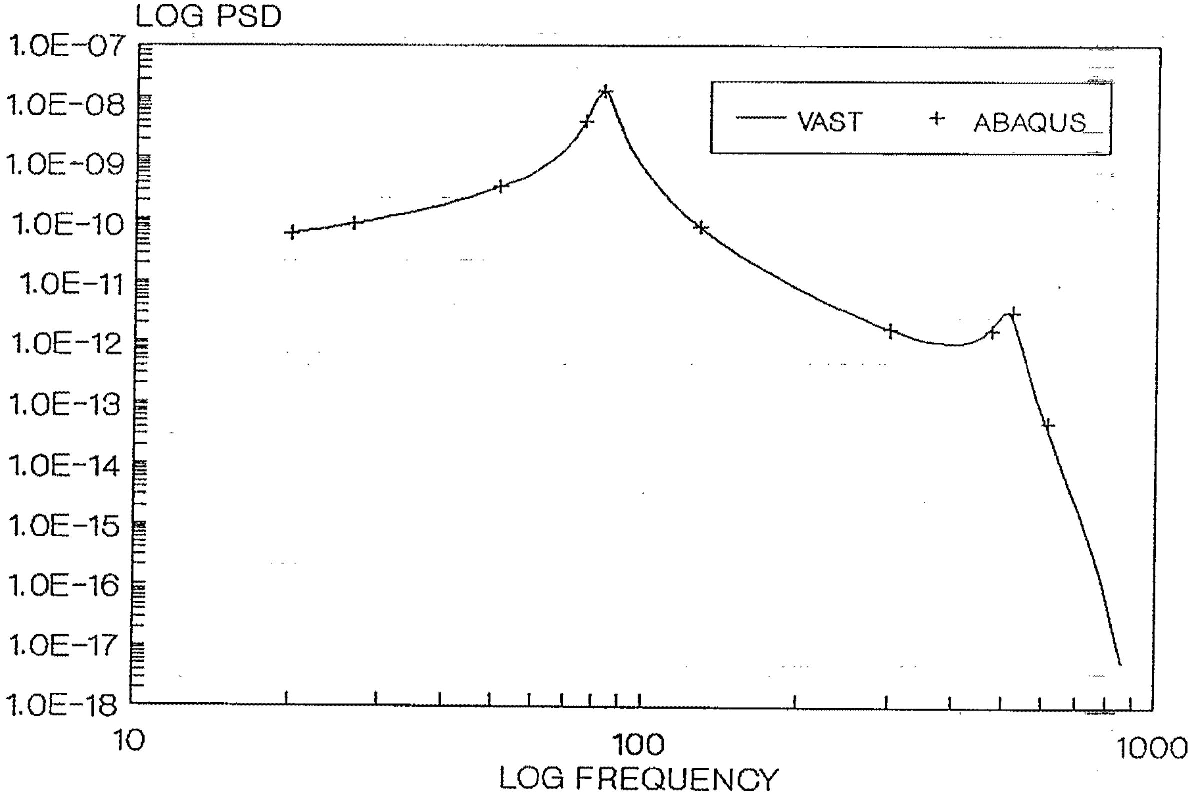

FIGURE 5.7. PSD of the Displacement Response at the Tip of the Cantilever Subjected to Random Base Motion

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Overall, the random vibration analysis capabilities implemented in the VAST FEA system are powerful and reliable. These capabilities, at present, surpass (or are at least equal to) those available in most commercial FEA packages in North America. The accuracy of the results produced has been illustrated in the report of the first phase of this contract. Since program verification is a continuing process, increasing confidence will develop in the program capabilities as further problems are solved by users.

The following is a list of some potential enhancements to RANVB1 and RANVB2 that would even further improve the random response analysis capabilities of the VAST FEA system.

The development of personal computer and workstation versions of RANVB1 (especially) is urgently needed. The codes were developed on a VAX/VMS system in standard Fortran 77 language and are generally machine independent. However, for PC operation, adjustments with respect to the file handling strategy might be required to permit the use of fewer files than on mainframes.

The numerical integration procedure for computing the covariances of the response from the power spectral densities in RANVB1 and RANVB2 is based on the trapezoidal rule just as is used in MSC/NASTRAN and ABAQUS. In general, accurate results are obtained when a sufficient number of frequency points are requested by the user. To improve the accuracies of the covariances it might be desirable to use Simpsons's rule (especially the composite rule) which, in general, is more accurate than the trapezoidal rule. It is also desirable to provide a scheme whereby responses are generated at intermediate points between the frequency points requested by the user. This would also produce better graphical display of results.

As for RANVB2, the first enhancement should be concerned with the capability for the utilization of the newly developed VAST modules called ASSEM4 and ASSEM5 for frequency dependent stiffness and damping matrices.

The current complex matrix inversion algorithm in RANVB2 is based on an in-core solution procedure. The development of an out-of-core complex matrix inversion algorithm will be very useful so that large problems can be solved without memory space limitations.

It is recommended that an FPS version of RANVB2 in particular, be developed for the VAX system. This will considerably reduce the computation time since most of the time consuming operations performed are matrix inversions and matrix multiplications. Even for RANVB1, an FPS version would also be significantly faster than the regular version. Notwithstanding this recommendation, algorithmic efficiency enhancements may still be possibly achieved for the current versions of the programs.

It is pertinent to point out that the authors, in an independently funded effort, are also enhancing the features and random vibration analysis capabilities of VAST in other ways. A capability for random base excitations has recently been developed. So also is a capability for finite element discretization of distributed random loads. A random loading module (LOAD9) is also being developed and integrated into the VAST system like other loading modules for deterministic analysis.

It is hoped that extensions of this work to the computation of fatigue damage and structural reliability would be initiated by the scientific authority in the near future. As was emphasized in [1], this is the only way that the scientific authority can meaningfully exploit the existing capabilities for the structural integrity assessments of naval ships.

In general, the horizon of probabilistic structural analysis for ship structures is very wide. Issues like the development of stochastic finite elements (SFEM's), material and/or geometric nonlinearities, non-stationary loads and responses, and non-Gaussian random process models of loads and responses are all of direct relevance. Any of these could be quite justifiably pursued in the search for more realistic and accurate computational prediction tools for the benefit of safer, more reliable, and cost effective operations and maintenance of naval ships. It is hoped that DREA will maintain its interest in probabilistic analysis strategies especially as there is a worldwide trend towards the application of these procedures to problems in virtually all branches of engineering and industry.

REFERENCES

1. I.R. Orisamolu, M.E. Norwood, and M.W. Chernuka, "Development of Random Response Analysis Capability for the VAST Finite Element Program, Phase I," Martec Technical Report 91-2, March, 1991.

2. Vibration and Strength Analysis Program (VAST): User's Manual, Version #6.0, Martec Limited, Halifax, Nova Scotia, September, 1990.

3. M.D. Olson, "A Consistent Finite Element Method for Random Response Problems, Computers and Structures," Vol. 2, pps. 163-180, (1972).

4. ABAQUS Example Manual, Version 4.8, Hibbitt, Karson & Sorensen, Inc., Providence, Rhode Island, 1989.

APPENDIX A

APPENDIX A

DESCRIPTION OF INPUT DATA FILE PREPARATION FOR RUNNING RANDOM VIBRATION ANALYSIS IN VAST

The following is a description of the method for creating the PREFX.RIN input data file (to be included in PREFX.USE) for running a random response analysis in VAST.

The user is advised to exercise caution in requesting the computations of the various statistical properties of the different possible random processes because a random response analysis is more expensive than a corresponding deterministic dynamic analysis. As such, it is recommended that only responses of interest should be selected by the user through the appropriate codes. Also, where possible, computations should be requested only at selected number of nodal locations.

FORMAT OF INPUT FILE: TO BE INCLUDED IN FILE PREFX.USE

NOTE: STATS = Statistical Properties
Primary Responses = displacements, velocities, and accelerations
Secondary Responses = stresses and strains

HEADER = 'RANRES' - six character literal constant

Card 1A (2I5)

IOPTR = 1 Modal frequency response method for analysis

= 2 Direct frequency response method for analysis

IDAMP = 1 Modal damping ratios used for describing damping (ξ_γ, $\gamma=1,2,\ldots,NM$)
(NOTE: Not applicable for IOPT=2)
= 2 Proportional or Rayleigh Damping ($C = \alpha_m M+\alpha_k K$)

= 3 Structural Damping ($C\dot{X} = igKX$)

Card 1B (I5)

ITER = 0 linear random analysis
≥ 1 nonlinear random analysis

Card 1C (4I5) (omit if ITER = 0)

ITERMAX maximum number of iteration allowed

ITERPR intervals in iteration for printing intermediate results

NLNDMP = 1 use the following equation to diagonalize modal damping matrix

$$[C_a]_{ij} = \begin{cases} 0 & i\neq j \\ C_{mij} & i=j \end{cases} .$$

= 2 use the following equation to diagonalize modal damping matrix

$$[C_a]_{ij} = \begin{cases} 0 & i \neq j \\ \dfrac{\sum_{K=1}^{NM} C_{mjk}\, E\,[\dot{q}_j \dot{q}_k]}{E\,[\dot{q}_j^2]} \, . & i = j \end{cases} ,$$

ITERTR = 1 use the following equation to determine convergence

$$\overline{e} = \sum_{j=1}^{n} (\sigma^2_{j\mathrm{new}} - \sigma^2_{j\mathrm{old}})^2$$

= 2 use the following equation to determine convergence

$$\overline{e} = \sum_{j=1}^{n} \left(\frac{(\sigma^2_{j\mathrm{new}} - \sigma^2_{j\mathrm{old}})}{\mathrm{Max}\ (\sigma^2_{j\mathrm{new}}\ ,\ \sigma^2_{j\mathrm{old}})} \right)^2$$

<u>Card 1D</u> (E10.3) (omit if ITER = 0)

TOLR iteration tolerance ϵ as shown in the following equation $\overline{e} < \mathrm{TOLR}$

<u>Card 1E</u> (I5) (Omit if IOPT≠1)

IRESP1 = 0 Only modal response to be computed during this run, i.e. for the sole purpose of creating PREFX.RMR

= 1 Random response to be computed using the modal response computed during the current program run

= 2 Random response to be computed using the modal response computed during a previous program run (PREFX.RMR must be available for this selection. This is like a restart and will usually reduce computation time significantly.)

<u>Card 1F</u> (2I5) (Omit if IOPT≠2)

IRESP2 = 0 Only complex frequency response function to be computed during this run, i.e. for the sole purpose of creating PREFX.CFR

= 1 Random response to be computed using the complex frequency response function computed during the current program run

= 2 Random response to be computed using the complex frequency response function computed during a previous program run

(PREFX.CFR must be available for this selection. This is like a restart and will usually reduce computation time significantly.)

NAF = Number of applied (or forcing) frequencies

Card 1G (8E10.3) (Omit if IOPT≠2) (Provide as many cards as required)

WAFR(I)

(I=1,...,NAF) Applied frequencies (in rad/s) at which responses are to be computed
(Note: The load file PREFX.PSD must be consistent with these frequencies.)

Card 1H (2E10.3) (Omit if IDAMP ≠ 2)

ALFAM = α_M (constant in Rayleigh damping model)
ALFAK = α_K (constant in Rayleigh damping model)

Card 1I (E10.3) (Omit if IDAMP ≠ 3)

STRDMP = g (structural damping factor)

Card 1J (4I5)

IFORCE = 0 Force STATS not required

= 1 Force STATS wanted at all nodes

= -1 Force STATS wanted only at selected nodes

IPRIMY = 0 STATS of primary responses not required

= 1 STATS of primary responses wanted at all nodes

= -1 STATS of primary responses wanted at selected nodes

ISECND = 0 STATS of secondary responses not required

= 1 STATS of secondary responses wanted at all nodes

= -1 STATS of primary responses wanted at selected nodes

NTAU = 0 No correlation functions are required

= NTAU Correlation functions will be required in the analysis (maximum of 100) where

NTAU = number of sequence of non-zero τ values for which the correlation functions are to be computed

Note: If ISECND≠0, the user must have requested the computation of modal stresses by setting the master control code ISTRES to 1 so that the PREFX.T53 file containing modal stresses would have been generated and used in POSTV2 for the generation of averaged nodal stresses/strains. Of course, the user must also have appropriately requested a POSTV2 batch run.

Card 2 Information for the calculation and printout of the statistical properties (i.e. STATS) of random nodal forces

(Omit if IFORCE=0)

Card 2A (I5)

IFX = 1 Only AUTO-STATS of forces are of interest

= 2 Both AUTO- and CROSS-STATS of forces are of interest

Card 2B (4I5)

IFST(1) = 0 Power spectral densities of forces not of interest

= 1 Power spectral densities of forces to be saved on random force file and printed in output file

= -1 Power spectral densities of forces saved but not printed

IFST(2) = 0 Covariance of forces not of interest

= 1 Covariance of forces to be computed and printed

= -1 Covariance of forces to be computed but not printed

IFST(3) = 0 Autocorrelation functions of forces not of interest

= 1 Autocorrelation functions of forces to be computed and printed

= -1 Autocorrelation functions of forces to be computed but not printed

IFST(4) = 0 Apparent frequencies of force not of interest

= 1 Apparent frequencies of force to be computed and printed

= -1 Apparent frequencies of force to be computed but not printed

<u>Card 2C</u> (omit if IFORCE≠-1)

<u>Card 2C(i)</u> (I5)

NFN = Number of nodes for which nodal force STATS are required

<u>Card 2C(ii)</u>

(JFN(I), I=1, NFN) Actual node numbers (arranged in ascending order) for which STATS of nodal forces are wanted.

Note: Error message is issued if IFORCE≠0 but IFST(1)=IFST(2)=IFST(3)=IFST(4)=0

<u>Card 3</u> Information for the calculation and printout of the STATS of primary responses

(omit if IPRIMY=0)

<u>Card 3A</u> (4I5)

IPX = 0 Only AUTO-STATS of primary responses are of interest

= 1 Both AUTO- and CROSS-STATS of primary responses wanted

IPD = 0 Displacement STATS not wanted

= 1 Displacement STATS wanted

IPV = 0 Velocity STATS not wanted

= 1 Velocity STATS wanted

IPA = 0 Acceleration STATS not wanted

= 1 Acceleration STATS wanted

(Note: Error message is issued if IPRIMY≠0 but IPD=IPV=IPA=0)

<u>Card 3B(i)</u> (4I5) (omit if IPD=0)

IDD(1) = 0 Power spectral densities of displacements not of interest

= 1 Power spectral densities of displacements to be computed and printed

= -1 Power spectral densities of displacements to be computed but not printed

IDD(2) = 0 Covariance of displacements not of interest

= 1 Covariance of displacements to be computed and printed

= -1 Covariance of displacements to be computed but not printed

IDD(3) = 0 Correlations of displacements not of interest

= 1 Correlations of displacements to be computed and printed

= -1 Correlations of displacements to be computed but not printed

IDD(4) = 0 Apparent frequencies of displacements not of interest

= 1 Apparent frequencies of displacements to be computed and printed

= -1 Apparent frequencies of displacements to be computed but not printed

Note: Error message is issued if IPD=1 but IDD(1)=IDD(2)=IDD(3)=IDD(4)=0

Card 3B(ii) (4I5) (omit if IPV=0)

IVV(1) = 0 Power spectral densities of velocities not of interest

= 1 Power spectral densities of velocities to be computed and printed

= -1 Power spectral densities of velocities to be computed but not printed

IVV(2) = 0 Covariance of velocities not of interest

= 1 Covariance of velocities to be computed and printed

= -1 Covariance of velocities to be computed but not printed

IVV(3) = 0 Correlations of velocities not of interest

= 1 Correlations of velocities to be computed and printed

= -1 Correlations of velocities to be computed but not printed

IVV(4) = 0 Apparent frequencies of velocities not of interest

= 1 Apparent frequencies of velocities to be computed and printed

= -1 Apparent frequencies of velocities to be computed but not printed

Note: Error message is issued if IPV=1 but IVV(1)=IVV(2)=IVV(3)=IVV(4)=0

<u>Card 3B(iii)</u> (4I5) (omit if IPA=0)

IAA(1) = 0 Power spectral densities of accelerations not of interest

= 1 Power spectral densities of accelerations to be computed and printed

= -1 Power spectral densities of accelerations to be computed but not printed

IAA(2) = 0 Covariance of accelerations not of interest

= 1 Covariance of accelerations to be computed and printed

= -1 Covariance of accelerations to be computed but not printed

IAA(3) = 0 Correlations of accelerations not of interest

= 1 Correlations of accelerations to be computed and printed

= -1 Correlations of accelerations to be computed but not printed

IAA(4) = 0 Apparent frequencies of accelerations not of interest

= 1 Apparent frequencies of accelerations to be computed and printed

= -1 Apparent frequencies of accelerations to be computed but not printed

Note: Error message is issued if IPA=1 but IAA(1)=IAA(2)=IAA(3)=IAA(4)=0

<u>Card 3C</u> (omit if IPRIMY≠1)

<u>Card 3C(i)</u> (I5)

NDNP = <u>N</u>umber of selected <u>D</u>isplacement <u>N</u>odes for which <u>P</u>rimary responses are to be computed

<u>Card 3C(ii)</u> (16I5)

JPN = Actual displacement node numbers (arranged in ascending order) for which primary responses are to be computed

(JPN(I),I=1,NDNP)

<u>Card 4</u> (omit if ISECND=0)

<u>Card 4A</u> (3I5)

ISX = 0 Only AUTO-STATS of secondary responses are of interest

= 1 Both AUTO- and CROSS-STATS of secondary responses are of interest

ISC = 1 Stress STATS only are wanted

= 2 Strain STATS only are wanted

= 3 Both stress and strain STATS are wanted

ISOPT = 1 Six stress/strain components wanted (σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{yz}, σ_{zx}) or ϵ_{xx}, ϵ_{yy}, ϵ_{zz}, ϵ_{xy}, ϵ_{yz}, ϵ_{zx})

= 2 Principal stresses/strains wanted (σ_1, σ_2, σ_3 or (ϵ_1, ϵ_2, ϵ_3)

= 3 von Mises stress/strain wanted

= 4 Maximum shear stress/strain wanted

= 5 All of the above wanted

<u>Card 4B(i)</u> (4I5) (omit if ISC=2)

ISS(1) = 0 Power spectral densities of stresses not of interest

= 1 Power spectral densities of stresses to be computed and printed

= -1 Power spectral densities of stresses to be computed but not printed

ISS(2) = 0 Covariance of stresses not of interest

= 1 Covariance of stresses to be computed and printed

= -1 Covariance of stresses to be computed but not printed

ISS(3) = 0 Correlations of stresses not of interest

= 1 Correlations of stresses to be computed and printed

= -1 Correlations of stresses to be computed but not printed

ISS(4) = 0 Apparent frequencies of stresses not of interest

= 1 Apparent frequencies of stresses to be computed and printed

= -1 Apparent frequencies of stresses to be computed but not printed

Card 4B(ii) (4I5) (omit if ISC=1)

ISN(1) = 0 Power spectral densities of strains not of interest

= 1 Power spectral densities of strains to be computed and printed

= -1 Power spectral densities of strains to be computed but not printed

ISN(2) = 0 Covariance of strains not of interest

= 1 Covariance of strains to be computed and printed

= -1 Covariance of strains to be computed but not printed

ISN(3) = 0 Correlations of strains not of interest

= 1 Correlations of strains to be computed and printed

= -1 Correlations of strains to be computed but not printed

ISN(4) = 0 Apparent frequencies of strains not of interest

= 1 Apparent frequencies of strains to be computed and printed

= -1 Apparent frequencies of strains to be computed but not printed

Card 4C (omit if ISECND≠-1)

NGNS = Number of selected geometric nodes for which secondary responses are to be computed

JSEN = Actual geometric node numbers (arranged in ascending order) for which secondary responses are to be computed

(JSEN(I),I=1,NGNS)

Note: The elements corresponding to these nodes must have been communicated to the stress module as described in the VAST manual.

Card 5 (omit if NTAU=0)

Card 5A (I5)

ICOREL = 1 1st value of τ (non-zero), RTAU1, and constant increment in values of τ, DELTAU, are provided

= 2 Non-zero NTAU values of τ are provided

Card 5B (2E10.3) (omit if ICOREL=2)

RTAU1 = 1st (non-zero) value of time delay for the computation of correlation functions

DELTAU = Constant increment in values of τ to be used for generating other values of time delay

Card 5C (8E10.3) (omit if ICOREL=1)

RTAU = The NTAU values of time delay for which correlation functions are to be computed
(RTAU(I), I=1, NTAU)

A.2 Format of User-Supplied Subroutine NLNDFN for Equivalent Nonlinerization

```
C
C**********************************************************************C
      SUBROUTINE NLNDFN(AD,AV,AA,NS)
C**********************************************************************C
C
C     THIS SUBROUTINE DEFINES THE EQUIVALENT STIFFNESS MATRIX, DAMPING
C     MATRIX, AND MASS MATRIX IN GLOBAL COORDINATE SYSTEM.
C
C     INPUT:
C     AD(NS,NS)  --- CURRENT COVARIANCE OF DISPLACEMENT
C     AV(NS,NS)  --- CURRENT COVARIANCE OF VELOCITY
C     AA(NS,NS)  --- CURRENT COVARIANCE OF ACCELERATION
C     NS         --- SIZE OF THE PROBLEM
C
C     OUTPUT:
C     AD(NS,NS)  --- EQUIVALENT STIFFNESS MATRIX
C     AV(NS,NS)  --- EQUIVALENT DAMPING   MATRIX
C     AA(NS,NS)  --- EQUIVALENT MASS      MATRIX
C
C     NOTE:
C     FULL OUTPUT MATRICES AD, AV & AA HAVE TO BE DEFINED.
C
C     FOR DOUBLE PRECISION ARITHMETIC, ACTIVATE THE FOLLOWING :
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION AD(NS,NS), AV(NS,NS), AA(NS,NS)
C
C     COMPUTE EQUIVALENT STIFFNESS, DAMPING AND MASS MATRICES.
C     STORE THESE MATRICES IN AD, AV AND AA.
C
      RETURN
      END
```

Example of User-Supplied Subroutine NLNDFN

```
C
C***********************************************************************C
      SUBROUTINE NLNDFN(AD,AV,AA,NS)
C***********************************************************************C
C
C     THIS SUBROUTINE DEFINES THE EQUIVALENT STIFFNESS MATRIX, DAMPING
C     MATRIX, AND MASS MATRIX IN GLOBAL COORDINATE SYSTEM.
C
C     INPUT:
C     AD(NS,NS)  --- CURRENT COVARIANCE OF DISPLACEMENT
C     AV(NS,NS)  --- CURRENT COVARIANCE OF VELOCITY
C     AA(NS,NS)  --- CURRENT COVARIANCE OF ACCELERATION
C     NS         --- SIZE OF THE PROBLEM
C
C     OUTPUT:
C     AD(NS,NS)  --- EQUIVALENT STIFFNESS MATRIX
C     AV(NS,NS)  --- EQUIVALENT DAMPING   MATRIX
C     AA(NS,NS)  --- EQUIVALENT MASS      MATRIX
C
C     NOTE:
C     FULL OUTPUT MATRICES AD, AV & AA HAVE TO BE DEFINED.
C
C     FOR DOUBLE PRECISION ARITHMETIC, ACTIVATE THE FOLLOWING :
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION AD(NS,NS), AV(NS,NS), AA(NS,NS)
      DIMENSION DTMP(10,10),VTMP(10,10)
C
C     FOR DOUBLE PRECISION ARITHMETIC, ACTIVATE THE FOLLOWING :
      SQRT(X) = DSQRT(X)
C
      DO 2 I  = 1,NS
      DO 1 J  = 1,NS
      DTMP(I,J) = AD(I,J)
      VTMP(I,J) = AV(I,J)
      AD(I,J) = 0.
      AV(I,J) = 0.
      AA(I,J) = 0.
    1 CONTINUE
    2 CONTINUE
C
      EK      = 0.05D0
      EC      = 0.05D0
      AD(6,6) = 3.D0*EK*2.D0*DTMP(6,6)
      AV(6,6) = 2.D0*0.05D0
      AV(9,9) = 2.D0*0.20D0+ 4.D0*EC*SQRT(VTMP(9,9)/3.141592654)
C
      RETURN
      END
```

APPENDIX B

APPENDIX B

PLOTV18

Operating Instructions for Plotting Program PLOTV18

Files Required:
PREFX.T41
PREFX.T48
PREFX.T54 (if superelement analysis)
PREFX.T52 (if not superelement analysis)
PREFX.T59 (if superelement analysis)
PREFX.RFC (Random Vibration - Force)
PREFX.RDP (Random Vibration - Displacement)
PREFX.RVL (Random Vibration - Velocity)
PREFX.RAC (Random Vibration - Acceleration)
PREFX.RSS (Random Vibration - Stress)
PREFX.RSN (Random Vibration - Strain)

Terminal Response:

(Note: all input is in free format unless otherwise specified.)

(1) PROGRAM PLOTV18 VAST GRAPHICS PROGRAM FOR PLOTTING POWER SPECTRAL DENSITY VERSUS FREQUENCY OF RANDOM VIBRATION ANALYSIS

(2b) PROGRAM PLOTV18 VAST GRAPHICS PROGRAM FOR PLOTTING AUTO CORRELATION FUNCTION VERSUS TIME DELAY AT SPECIFIED NODES OF RANDOM VIBRATION ANALYSIS

Prompt (1) or (2) appears depending upon user option.

(3) POWER SPECTRUM VERSUS FREQUENCY

(4) AUTO CORRELATION FUNCTION VERSUS TIME DELAY

Prompt (3) or (4) appears depending upon user plotting option.

(5a) SPECIFY TYPE OF PLOT
1 = FORCE
2 = DISPLACEMENT
3 = VELOCITY
4 = ACCELERATION
5 = STRESSES
6 = STRAINS

If the type of plot specified has not been selected for output results the following error message is displayed and control is transferred to (5a). If the response is valid then control is transferred to (6a).

(5b) ERROR: OUTPUT DATA NOT AVAILABLE.

(6a) SPECIFY NUMBER OF NODES TO BE PLOTTED:

The user specifies the number of node results to be plotted.

(6b) ENTER III NODE NUMBER(S)

The user specifies the node number(s) for which the plot is desired. If the node numbers specified were not selected to calculate random response data then the following error message is displayed and the user is re-prompted. Upon successful data entry control is transferred to (7).

(6c) DATA NOT AVAILABLE FOR
NODE XX. RE-ENTER NODE:

(7) ENTER THE NUMBER OF COMPONENTS TO BE PLOTTED

If more than one node is to be plotted, only one component may be plotted and this prompt is omitted.

(8a) SPECIFY COMPONENT(S) TO BE PLOTTED:

(8b) (X=1, Y=2, Z=3)

(8c)	SXX	SYY	SZZ	SXY	SYZ	SXZ	SP1	SP2	SP3	SVM	SSM
	1	2	3	4	5	6	7	8	9	10	11

(8d)	EXX	EYY	EZZ	EXY	EZY	EXZ	EP1	EP2	EP3	EVM	ESM
	1	2	3	4	5	6	7	8	9	10	11

Prompt (8b) appears if the user has specified force, displacement, velocity, or acceleration plot in response to (7).

Prompt (8c) or (8d) as appropriate appears if the user has specified stress or strain plots.

(9) ENTER COMPONENT SPECIFICATION #1:

The user must specify which component is to be plotted. If more than one component was requested in response to (8a), prompt (9) appears the required number of times to prompt for component specifications.

(10) * GRAPHING SPECIFICATIONS *

(11a)

```
ENTER LABEL IDENTIFIERS FOR CURVES
(LINE TYPES   LETTERS   NUMBERS
     0           1          2    ):
```

The user specifies the identifier for the curves.

(11b) ENTER LABEL STEP INCREMENT:

If the response to (11a) is 1 or 2 the user then enters the interval or step for labelling curve data.

(12a)

```
ENTER TYPE OF VERTICAL SCALE TO BE PLOTTED
(0 = LINEAR, 1 = LOGARITHMIC)
```

The user specifies the vertical scale type. If the user selects linear control is transferred to (13).

(12b)

```
ENTER TYPE OF TICK MARK FOR LOGARITHMIC SCALE
     0 - MINOR TICK MARK
     1 - FULLY EXTENDED TICK MARK
```

If the user selects to use logarithmic scale in response to (12a) then this prompt appears.

(12c)

```
WARNING: FOR LOGARITHMIC SCALE
         NEGATIVE OR ZERO DATA NOT ALLOWED
         SPECIFY SCALE RANGE
```

If the data contains '0' or negative values this warning is displayed and control is transferred to (14).

(13) ENTER 0 FOR DEFAULT SCALING OF VERTICAL AXIS:
1 FOR USER SPECIFIED

If default scaling of the ordinate axis is used, PLOTV18 scales the data in such a way as to fill up as much of the screen as possible, using only the data for the present plot. In some cases, however, the user may desire to have the axis of a series of plots all the same. This prompt allows the user to achieve such an effect. An entry of 0 causes the next prompt to be bypassed.

(14) PRESENT MIN. & MAX. ARE XXXX & XXXX
ENTER NEW MIN. & MAX.:

The user must input the new minimum and maximum values of the data to be used for scaling the ordinate axis. The present values are printed for reference. Generally, the range of the entries will be greater than the range of the corresponding present values. If it is not, the plot will be 'clipped', an effect which may also be achieved through windowing.

(15a) ENTER TYPE OF FREQUENCY SCALE TO BE PLOTTED
(0 = LINEAR, 1 = LOGARITHMIC)

(15b) ENTER TYPE OF TICK MARK FOR LOGARITHMIC SCALE:
0 - MINOR TICK MARK
1 - FULLY EXTENDED TICK MARK

If the user selects to use logarithmic scale then this prompt appears.

(15c) WARNING: FOR LOGARITHMIC SCALE NEGATIVE
OR ZERO DATA NOT ALLOWED. SPECIFY SCALE.

If the data contains '0' or negative values then this warning is displayed and control is transferred or (17).

(16) ENTER 0 FOR DEFAULT SCALING OF FREQUENCY AXIS
1 FOR USER SPECIFIED

If default scaling of the axis is used, PLOTV18 scales the data in such a way as to fill up as much of the screen as possible, using only the data for the present plot. In some cases, however, the user may desire to have the axis of a series of plots all the same. This prompt allows the user to achieve such an effect. An entry of 0 causes the next prompt to be bypassed.

(17) PRESENT MIN. & MAX. ARE XXXX & XXXX
ENTER NEW MIN. & MAX.:

The user must input the new minimum and maximum values of the data to be used for scaling the ordinate axis. The present values are printed for reference. Generally, the range of the entries will be greater than the range of the corresponding present values. If it is not, the plot will be 'clipped', an effect which may also be achieved through windowing.

(18) AFTER PLOTTING USE:

```
                W - TO WINDOW
                R - TO RECOVER ORIGINAL
                S - TO SAVE PLOT FILE
PRESS "RETURN" TO PLOT
```

The user presses the "RETURN" key and the plot appears on the screen. If a hard copy is desired, it should be made at this time. A single bell will sound to indicate that alphanumeric keyboard input is expected. If the terminal has no graphics cursor, any alphanumeric keyboard entry followed by "RETURN", or just "RETURN" causes the screen to clear and control to transfer to (19). Otherwise the user has the option to window, recover the original plot, or continue to (19).

In order to window, the user must enter either an upper or lower case "W", followed by "RETURN". Two bells will sound, indicating input is expected via the graphics cursor, and the cursor will appear on the screen. The user positions the cursor at the lower left hand corner of the area to be windowed, and enters any alphanumeric keyboard character, or "RETURN". Two bells again sound and the procedure is repeated for the upper right hand corner of the area to be windowed. A border is then drawn around the area to be windowed and a single bell will sound. When the user enters any alphanumeric keyboard character, followed by "RETURN", or simply "RETURN", the enlarged portion of the plot will appear, and control transfers back to the beginning of this section (14).

If the user desires to recover the original plot following the single bell prompt described in the first paragraph of this section, the user must enter either an upper or lower case "R", followed by "RETURN". The original plot is the first plot which appeared after the current input parameters were specified. If the user chooses this option, control transfers back to the beginning of this section.

To continue to (19), the user may enter any alphanumeric keyboard character except "W" or "R", followed by a "RETURN", or simply "RETURN", in response to the single bell prompt mentioned in the first paragraph.

```
(19)   ENTER 0 TO TERMINATE PLOTTING WITH PLOTV18
             1 TO CONTINUE:
```

An entry of 1 causes control to transfer back to (3).

APPENDIX C

APPENDIX C

RANDOM LOADING DESCRIPTION

A random loading module, LOAD9, has been developed and integrated into the VAST FEA system. This load module currently has four parts:

LOAD9A for random point loads,
LOAD9B for random base motion,
LOAD9C for random pressure loads, and
LOAD9F for nonlinear wave loading based on the Morison model.

The function of the LOAD9 module is the generation of the consistent finite element representation of the given random loads in the form of a full cross-spectral density matrix. Nonzero values of this matrix are stored rowwise in a permanent file called PREFX.PSD for every forcing frequency of interest, and is used by the random vibrations analysis modules (RANVB1 or RANVB2) for random response computations.

The execution of LOAD9 is triggered by setting the VAST master control code ILOADS in the PREFX.USE file to nine. A zero value of ILOADS in a random response analysis implies a previously generated PREFX.PSD file exists,i.e. a restart analysis. A LOAD9 execution like other VAST modules, requires a six-character header card 'ILOAD9' in the PREFX.USE file. The only other card required is the specification of the parameter LDTYPE which defines what kind of random loading is supplied.

The formats of the input data corresponding to various random loading types are given in what follows.

C.1 Changes to PREFX.USE File for Random Loading

1. Cards for load module LOAD9

Header Card (A6)

HEADR = 'ILOAD9' six character literal constant

Card 1 (I5)

LDTYPE =	1	random point load (LOAD9A)
	2	random base motion (LOAD9B)
	3	random pressure load (LOAD9C)
	6	Morison random wave load (LOAD9F)

C.2 INPUT FILES FOR RANDOM POINT LOAD

Note on module LOAD9A (random point load):

The purpose of the sub-program LOAD9A is to generate excitation cross PSD matrix for random point loads. The cross PSD matrix is stored row-wise in a binary file PREFX.PSD to be used by any of the random vibration analysis modules (RANVB1 or RANVB2) for random response computations. The loads can be either uncorrelated or correlated and may be applied at any node in any degree of freedom (DOF). In addition, multiple loads on the same global DOF are permitted.

Two input files are required, i.e. PREFX.LOD to define the loads; PREFX.SDF to define the excitation PSD. Users can either use spectrum library or define their own spectra. The user defined spectra are described by piecewise linear functions. The data input format and sample files are given next.

PREFX.LOD	**(load definition)**
Card 1 (2I5)	
NLDGRP	Number of load groups (i.e. random load sources)
NLD	Number of point loads
Card 2 (3I5,E10.3)	**(repeat NLD times in any sequence)**
LDNODE	Node number of load
LDDOF	DOF number of load
LDGRP	Group (source) number of load
FCTR	Scale factor of load
Card 3 (I5)	
NSPC	Number of non-zero upper-triangle components of group (source) cross PSD matrix
Card 4 (4I5)	**(repeat NSPC times)**
LDG1, LDG2	Row and column numbers of a non-zero component (LDG1 $\leq$ LDG2)
ISPC	Specify spectrum ID
IBS	Input 0

C.3 INPUT FILES FOR RANDOM BASE MOTION

Note on module LOAD9B (random base motion):

The purpose of the sub-program LOAD9B is to generate excitation cross PSD matrix for random translational base motion problems. The cross PSD matrix is stored row-wise in a binary file PREFX.PSD to be used by any of the random vibration analysis modules (RANVB1 or RANVB2) for random response computations. The base motion may be correlated.

Two input files are required, i.e. PREFX.LOD to define the loads; PREFX.SDF to define the excitation PSD. Users can either use spectrum library or define their own spectra. The user defined spectra are described by piecewise linear functions. The data input format and sample files are given next.

PREFX.LOD	**(load definition)**
Card 1 (I5)	
NLDGRP	Number of translational base excitations Input 3
Card 2 (I5)	
NSPC	Number of non-zero upper-triangle components of cross PSD matrix of base excitation
Card 3 (4I5)	**(repeat NSPC times)**
LDG1, LDG2	Row and column numbers of a non-zero component (LDG1 ≤ LDG2)
ISPC	Specify spectrum ID
IBS = 1	Displacement PSD is supplied
= 2	Velocity PSD is supplied
= 3	Acceleration PSD is supplied

C.4 USER-PROVIDED SUBROUTINE FOR RANDOM PRESSURE LOAD

Note on module LOAD9C (random pressure load):

Sub-program LOAD9C is developed based on the proposed approach. It has been implemented into VAST as part of the loading module LOAD9 for general beam element (IEC=3), triangular plate element (IEC=4), thick-thin shell element (IEC=1), and quadrilateral shell element (IEC=5). Gaussian quadrature is used in numerical computation.

The cross PSD matrix of excitation is stored row-wise in a binary file PREFX.PSD to be used by any of the random vibration analysis modules (RANVB1 or RANVB2) for random response computations.

At present, subroutine PSDNODES is required to describe the random pressure field, i.e. the cross PSD of any given two nodes in the random excitation field. The subroutine PSDNODES is defined as:

```
SUBROUTINE PSDNODES(FREQ,X1,Y1,Z1,X2,Y2,Z2,SND,L)
```

Input: FREQ - the frequency at which cross PSD of two give nodes is evaluated

X1,Y1,Z1 - global coordinates of the first node

X2,Y2,Z2 - global coordinates of the second node

L - dimension of matrix SND

Output: SND - A LxL matrix in which the obtained cross PSD is stored.

C.5: Format of VAST Input File PREFX.LOD For Morison Wave Loading

PREFX.LOD	(load definition for LOAD9F)
Card 1 (2I5)	
NLDGRP	input 1
Card 2 (I5)	
NSPC	input 1
Card 3 (4I5)	
LDG1, LDG2	input 1, 1
ISPC	specify spectrum ID
Card 4 (5E10.3)	
ρ	fluid density
g	gravity
km,kd	parameters in Morison equation
h	water depth
Card 5 (I5, E10.3)	(repeat NE times)
i	element number
D	diameter of element number i

C.6: Format of VAST Input File PREFX.SDF

PREFX.SDF	(spectrum definition)

Card 1 (I5)

NDFN	Number of spectral definitions to be provided

(Cards 2-3 repeat NDFN times and omit if NDFN=0)

Card 2 (3I5)

IDFN	Spectrum number
IOPT = 1	Use spectrum library
= 2	Use user defined spectrum
IND	Spectrum ID in library if IOPT=1 or number of frequencies to define the spectrum IDFN if IOPT=2

(Choose one of the following cards if IOPT=1 and omit if IOPT$\neq$1)

Card 3a.1 (E10.3)	(ILIB=1, white noise)
S_0	Spectral intensity
Card 3a.2 (3E10.3)	(ILIB=2, band limited white noise)
S_0, B_1, B_2	Spectral intensity and band boundaries
Card 3a.3 (2E10.3)	(ILIB=3, filtered white noise)
S_0, α	$S = S_0 \frac{1}{\omega^2+\alpha^2}$
Card 3a.4 (3E10.3)	(ILIB=4, filtered white noise)
S_0, α_1, α_2	$S = S_0 \frac{1}{(\alpha_1-\omega^2)^2+(\alpha_2\omega)^2}$
Card 3a.5 (2E10.3)	(ILIB=5)
S_0, A	$S = S_0 \exp(-i\omega A)$
Card 3a.6 (4E10.3)	(ILIB=6, piecewise linear spectrum)
S_0, ω_1, ω_2, ω_3	

Card 3a.7 (3E10.3) (ILIB=7, K-T spectrum)

S_0, ξ_g, ω_g

$$S = S_0 \frac{1+4\xi_g^2(\omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2 + 4\xi_g^2(\omega/\omega_g)^2}$$

Card 3a.8 (5E10.3) (ILIB=8, modified K-T spectrum)

S_0, ξ_g, ω_g, ξ_c, ω_c

$$S = S_0 \frac{1 + 4\xi_g^2(\omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2 + 4\xi_g^2(\omega/\omega_g)^2} \frac{(\omega/\omega_c)^4}{[1-(\omega/\omega_c)^2]^2 + 4\xi_c^2(\omega/\omega_c)^2}$$

Card 3a.9 (3E10.3) (ILIB=9, Pierson-Moskowitz spectrum 1)

α,g,U

$$S=\alpha g^2\omega^{-5} \exp \left[-0.74 \left(\frac{\omega U}{g}\right)^{-4}\right]$$

Card 3a.10 (3E10.3) (ILIB=10, Pierson-Moskowitz spectrum 2)

α,g,ω_0

$$S=\alpha g^2\omega^{-5} \exp \left[-1.25 \left(\frac{\omega}{\omega_o}\right)^{-4}\right]$$

Card 3a.11 (2E10.3) (ILIB=11, ISSC spectrum)

α,H_s, ω_0

$$S=\alpha H_S^2 \frac{\overline{\omega}^4}{\omega^5} \exp \left[-0.4427 \left(\frac{\overline{\omega}}{\omega}\right)^{-4}\right]$$

where $\overline{\omega} = 1.29^6\omega_0$

Card 3a.12 (6E10.3) (ILIB=12, Jonswap spectrum)

α,g,ω_0,γ,τ_1,τ_2

$$S=\alpha g^2 \omega^{-5} \exp \left[-1.25\left(\frac{\omega}{\omega_o}\right)^{-4}\right] \gamma^{\exp\left[-0.5(\omega-\omega_o)^2/\tau^2\omega_o^2\right]}$$

where $\tau = \begin{cases} \tau_1 & , \quad \omega \le \omega_o \\ \tau_2 & \quad \omega > \omega_o \end{cases}$

Card 3b (3E10.3) (repeat IND times if IOPT=2 and omit if IOPT≠2)

FRQ	Frequency at which spectrum IDFN is defined
PSDR	Real part of power spectral density at FRQ
PSDI	Imaginary part of power spectral density at FRQ

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This report contains a description of the work done in the second phase of a contract awarded by the Defence Research Establishment Atlantic (DREA) of the Canadian Department of National Defence for the development of an in-house random response analysis capability. A description of additional work to complete the modal random vibration analysis module (RANVBI) is given. The development of a twin module (RANVB2) based on the direct frequency response method is presented. A brief description of the graphics support to the random response analysis programs is also given. Example problems illustrating the operations of RANVBI and RANVB2 are given. The report closes with some comments about the impressive features of the random vibration capabilities of the VAST finite element analysis system and highlights some recommendations that would further enhance the current capabilities.

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