CONTRACTOR REPORT

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A Model for the Response of Vertical Axis Wind Turbines to Turbulent Flow Parts 1 and 2

David R. Malcolm
Indal Technologies, Incorporated
Mississauga, Ontario, Canada L5C2V8

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A MODEL FOR THE RESPONSE OF VERTICAL AXIS WIND TURBINES TO TURBULENT FLOW

PARTS 1 AND 2

David R. Malcolm
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Mississauga, Ontario, Canada, L5C2V8

Sandia Contract 32-3044

ABSTRACT

This report describes a project intended to incorporate the effects of atmospheric turbulence into the structural response of Darrieus rotor, vertical axis wind turbines. The basis of the technique is the generation of a suitable time series of wind velocities, which are passed through a double multiple streamtube aerodynamic representation of the rotor. The aerodynamic loads are decomposed into components of the real eigenvectors of the rotor and subsequently into full-power and cross-spectral densities. These modal spectra are submitted as input to a modified NASTRAN random load analysis and the power spectra of selected responses are obtained. This procedure appears to be successful. Results at zero turbulence agree with alternative solutions, and when turbulence is included, the predicted stress spectra for the Indal 6400 rotor are in good agreement with field data. The model predicts that the effect of turbulence on harmonic frequency peaks and on all lead-lag bending will not be great. However, it appears that only 11% turbulence intensity can almost double the rms of cyclic flatwise blade bending.

ACKNOWLEDGEMENTS

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A MODEL FOR THE RESPONSE OF VERTICAL AXIS WIND TURBINES TO TURBULENT FLOW

PART 1

1. INTRODUCTION

1.1 Background

The harnessing of wind energy has challenged man's ingenuity for thousands of years, whether it was for sailing ships, irrigation, or the grinding of wheat. The industrial revolution saw a decline in wind power use but now, with the recognition of the limitations and environmental effects of conventional power, wind power is regarded as one of the sources of energy with the greatest untapped potential.

Some of this potential has been realized in recent years, principally in California because of advantageous wind regimes, power pricing, and investment climate. However, as well as demonstrating the potential of wind turbines, the developments in California have also demonstrated some of the structural inadequacies of many designs. Most of the structural failures, on both horizontal axis (propeller) wind turbines (HAWTs) and on vertical axis wind turbines (VAWTs), have been due to high cycle fatigue. This has prompted a reassessment of the structural and aerodynamic behavior of both types of machines.

The deterministic cyclic loads in HAWTs originate from the effects of gravity, tower shadow, and from vertical wind shear. The stochastic loads are due to atmospheric turbulence and these effects have recently been shown to be dominant in the generation of fatigue damaging stress cycles (1,2).

Vertical axis rotors, such as the Darrieus rotor, differ from HAWTs in that their response is fundamentally

cyclic due to the aerodynamic principles on which they operate. However, these machines also operate in turbulent environments, and these stochastic effects must be considered before a full understanding of their behavior is reached.

1.2 Previous Work

The earliest investigation of the structural dynamics of Darrieus rotors (3) concentrated on the prediction of the natural frequencies and modes of the operating rotor. It became apparent that it was necessary to include not only the effects of stress stiffening due to centrifugal forces but also the other effects of the rotating frame, namely the softening and the Coriolis coupling. The latter influence is strongly felt due to the flexibility of the VAWT blades and results in the natural mode shapes being complex (in-plane and out-of-plane motion is coupled with a 90° phase difference). The NASTRAN-based procedure developed at Sandia National Laboratories (4) has been verified by experimental data from several rotors.

Other approaches to the calculation of the natural frequencies have been developed. The proprietary program GAROS, developed in West Germany, accommodates full rotating frame effects and has been used by Shawinigan Engineering. At Hydro Quebec's research institute the use of NASTRAN has been extended to internally generate the necessary additional matrices and to generate entire "fan plots" with an internal iteration (5).

The aerodynamic modelling of VAWT rotors has matured from a single stream tube model (6) to double multiple

stream tube models (DMST) with corrections for "secondary" effects (7) and vortex theory models (8). The principal objective of these models has been to predict, with increasing accuracy, the performance and energy output of the rotor. All of the models have assumed a steady flow.

The response of a Darrieus rotor to a steady flow must be cyclic at frequencies that are multiples of the rotational frequency. This response has been investigated by combining one of several aerodynamic models (usually a DMST model) with a NASTRAN-based direct frequency response with modifications similar to those used in the eigenvalue extraction technique (9,10,11). The results obtained using this method have been variable but encouraging. Agreement between measured and predicted standard deviations of stresses at key locations has been good, although the trend has been to under-predict stresses at low wind speeds and to over-predict at high winds. Examination of the response at multiples of the rotational speed has suggested that the one/revolution loading has been underpredicted while the three/revolution loading and response has been over-predicted (especially in high wind conditions)(12). The reasons for this may be either errors in the structural modelling whereby the dynamic amplification has been misrepresented or the aerodynamic loading is in error.

It has also been noticed (12) that at some locations (noticeably the inner and outer faces of the blades) there is considerable response at frequencies that are

not harmonics of the rotational speed. This response is probably due to random excitations resulting from the turbulence inherent in any real airflow.

Several studies have examined the turbulent flow typically seen by a wind turbine (13,14,15,16) and there are available mathematical models for the power spectral density at any point and for the coherence between any two points (13). This information was used recently at Sandia National Laboratories to model the turbulent loads seen by a Darrieus rotor (17). This work reviewed the turbulent nature of the airstream in three dimensions and the ways in which the power spectral densities may be converted to time series. A simplified two dimensional flow with complete coherence in the transverse direction was combined with a double multiple stream tube model to generate spectra of blade loading at the mid-rotor. The results of this investigation are significant, for they demonstrate that the load spectrum contains more high frequency content than is implied by the spectral density of the airstream. It also shows that, especially in high winds, the loadings at harmonics of the rotational speed are reduced (noticeably at 3/rev. and higher frequencies), whereas the total variance of the loading spectrum may not be changed. This behavior agrees closely with the trends in the responses observed experimentally (11).

The same modelling of turbulent flow has recently been used to predict the structural response of horizontal axis wind turbines (HAWTs) (18). This model was able to successfully predict a 4/rev. response that had plagued the MOD-2 wind turbine.

It appears, therefore, to be important to include a stochastic component of the streamflow if the blade loads under high winds and the total fatigue damage accumulation are to be estimated with accuracy. This importance is likely to increase with the size of the rotor [the results of Veers (17) referred to a 17-m diameter VAWT] since the rotational speed becomes lower and the low frequency components of the turbulent spectrum can contribute more significantly to the response spectrum. In addition, the transverse coherence within the wider stream tube is likely to deteriorate and may demand a more sophisticated stochastic model.

1.3 Objectives

The main objective of this project was to develop and test a procedure for the incorporation of turbulent flow into the structural analysis of VAWT rotors that can be easily and economically implemented. The primary methods of achieving this goal are

1. To model the turbulent flow in multiple parallel stream tubes by using linear interpolation between the vectors associated with a smaller number of points in a spatial array.

2. To decompose the aerodynamic loads into components of a limited number of generalized vectors corresponding to the natural modes of vibration of the stationary rotor.

3. To develop this model using FORTRAN 77 on a microcomputer so that the program can be fully transportable.

4. To modify an appropriate NASTRAN solution to accept spectral loadings as modal components.

5. To compare predicted results with field data obtained from the Indal 6400 VAWT at SCE's Devers Test Site.

The first objective aims at solving the problem of generating correlated time series for a large number of stream tubes. Application of the DMST model to a typical Darrieus rotor would result in approximately 16 x 30 = 480 stream tubes and a matrix of corresponding spectra of size 480 x 480; this would be computationally very expensive and beyond the capacity of most micro- or mini-computers.

The purpose of the second item is also to minimize a computational problem. As explained in Section 2.1, it is necessary to input the loading as power and cross spectral densities at all frequencies in the range of interest. Each of the physical loads, of which there may be 200 or more, is statistically partially independent of the other and requires a separate loading case. The total number of spectra that would have to be generated as input would be 200 x 200; there must be an easier method.

1.4 Statement of Work

The statement of work included in the contract document is reproduced below.

A. General:

Establish a procedure for the structural analysis of Vertical Axis Wind Turbines that:

1. Includes the effects of wind turbulence.

2. Minimizes the user input required for the structural dynamic analysis program.

3. Can readily incorporate different stochastic wind and aerodynamic load models.

4. Is suitable for use both for structural dynamics research and design engineering.

B. Specific:

1. Develop a computer code to generate NASTRAN-compatible frequency-domain aerodynamic loads in the stationary-rotor natural-mode coordinate system. This code will utilize a double-multiple stream tube aerodynamic model including the effects of the three-dimensional stochastic wind, wind shear, Reynolds number, dynamic stall, and central column loading. It will be specific to one rotor geometry with a single blade cross-section profile and will consider only the first 20 natural mode shapes. However, the code should be written in a modular manner to facilitate later incorporation of other aerodynamic and stochastic wind models. Paul Veers of SNL will furnish information and listings of the Fortran programs that he has developed to generate stochastic wind loads.

2. Generate the auto- and cross-spectral density distributions of the aerodynamic loads on the various modes. Investigate the effect of neglecting the cross spectra and the higher frequency contributions in turbine response calculations.

3. Develop the DMAP (Direct Matrix Abstraction Procedure) coding for NASTRAN solution 71 to accept the input of load spectra in the natural-mode coordinate system.

4. Use NASTRAN to determine the turbine frequency responses with and without the load cross-spectral contributions. Include the differential stiffening matrix (NASTRAN 64 solution) and the rotating frame effects (program FEVD results) in these calculations.

5. Compare the frequency response from this modal formulation against the response that results from a physical degree-of-freedom formulation.

6. Compare the code-predicted mean and vibratory stress levels and frequency content with data acquired from a 500-kW (or larger) turbine.

7. Modify, as necessary, the code developed in B-1, above, to enable the user to readily replace the stochastic wind and aerodynamic load model with others of his choice. Enhance the code to allow the user to specify the stochastic wind parameters, rotor geometries, and machine-dependent options in the format similar to that currently used in the FEVD and FFEVD programs.

8. Document the program and furnish the program listing, the program coding on magnetic tape, and a full report of the work performed.

2. THEORETICAL DEVELOPMENT

2.1 Structural Response to Stochastic Loads

The properties of a random process, or one that contains random elements, can only be described in statistical terms. These properties may be described in either the time or the frequency domains. The details of these descriptions may be found in many texts on the subject; for structures under the influence of stochastic loads details may be found in Clough and Penzen (19) and in Newlands (20). A short summary relevant to the present work is given below.

If the cross spectral density (csd) of loads at locations, or degrees of freedom, a and b is S_{pab} then the power spectral density (psd) of the response S_{vi} at location i is given by

$$S_{vi}(f) = \sum_{a=1}^{n} \sum_{b=1}^{n} H_{ia} H_{ib}^{*} S_{pab}(f), \qquad (2.1)$$

where H_{ia} is the frequency response function between degrees of freedom i and a, H_{ib}^{*} is the complex conjugate of H_{ib}, and n is the total number of degrees of freedom involved.

If the loads are statistically independent then $S_{pab}=0$ for $a \neq b$ and Eq. (2.1) becomes

$$S_{vi}(f) = \sum_{a=1}^{n} |H_{ia}|^{2} S_{paa}(f). \qquad (2.2)$$

Equation (2.2) shows that statistical independence does not reduce the number of response functions required.

For a Darrieus rotor, the aerodynamic loads differ continuously along the blades (and column, if also included) and the roughly 200 physical degrees of freedom cannot easily be grouped together to form a smaller number of statistically independent vectors. The large number of calculations involved in the procedure outlined above may be significantly reduced if, instead of physical degrees of freedom, natural modes are used as coordinates.

The equations of motion of a linearly elastic structure defined by physical coordinates, X, under a vector of forces, F(t), and in the absence of any damping, can be written

$$M\ddot{x} + Kx = F(t), \tag{2.3}$$

where M is the mass matrix, and K is the stiffness matrix. The solution to the homogeneous equation [F(t)=0] has the form

$$X = \phi_j \exp(iw_j t), \tag{2.4}$$

where w_j is the jth eigenvalue and ϕ_j is the corresponding eigenvector or natural mode shape. These natural modes may be shown to be orthogonal with respect to the matrices M and K so that when the equations are recast into modal coordinates, Y, by the transformation

$$X = \phi Y, \tag{2.5}$$

the equations become uncoupled. The motions described by the modal coordinates are, therefore, mechanically independent.

A vector of loads, F, may also be transformed into modal components, P, in a manner similar to Eq (2.5) above;

$$P = \Phi^T F \ . \tag{2.6}$$

The vector, P, is commonly dominated by a few terms associated with the lower natural frequencies so that, as well as transforming the problem into uncoupled equations, a relatively few such equations need be considered.

The same transformation may be used to convert the spectral density of stochastic loads, S_{pab}, into its modal equivalent, S_{pmn}. The spectral density S_{vr}, of the modal response may then be written in a manner similar to Eq. (2.1).

$$S_{vr}(f) = \sum_{m=1}^{N} \sum_{n=1}^{N} H_{rm} H_{rn}^* S_{pmn}(f), \tag{2.7}$$

which, due to the lack of coupling between natural modes, reduces to

$$S_{vr}(f) = |H_{rr}|^2 S_{prr}(f), \tag{2.8}$$

which is a considerable reduction in complexity and scale from Eqs. (2.1) or (2.2).

The modal formulation of the stochastic response of the Darrieus rotor cannot, however, make full use of this simplicity. The reason for this is that when the equations of motion of the operating rotor are written in the rotating frame they become (4)

$$M\ddot{x} + B\dot{x} + (K - \Omega^2 R)x = F(t), \tag{2.9}$$

where Ω is the rotational velocity, R is a symmetric softening matrix, and B is a skew symmetric Coriolis matrix. The eigenvalues of the homogeneous equation are again purely imaginary (indicating a conservative system) but the eigenvectors are complex. Such natural modes are no longer orthogonal and the equations of motion expressed in these coordinates are not uncoupled.

Some of the advantages of a modal formulation are, therefore, lost but the number of equations that must be solved simultaneously may still be drastically reduced. When the power spectral density of the response is expressed in terms of these coordinates, it is given by Eq. (2.7) but cannot be reduced to the form of Eq. (2.8) due to the presence of off-diagonal terms in the matrix H. For many structures and loads, however, the matrix S_{pmn} is almost diagonal; that is, the modal components of the loading are statistically independent, so that Eq. (1.7) becomes

$$S_{vr}(f) = \sum_{m=1}^{N} |H_{rm}|^2 \, S_{prm}(f), \tag{2.10}$$

which implies a reduction in the number of terms in the response calculation but still demands that all diagonal terms of the frequency response matrix, H, be determined.

2.2 The Aerodynamic Model

The unsteady or turbulent content in a flow of air may be described by its (power) spectral density (psd) which indicates the contribution to the total variance made at each frequency interval (20). Empirical expressions for the psd are available, such as those in Frost et al (13);

$$S(f) = \frac{C_1 V\, h\, [\ell n\ (10/Z_0 + 1)\ \ell n\ (h/Z_0 + 1)]^{-1}}{1 + C_2 [hf\ \ell n\ (10/Z_0 + 1)/V\ \ell n\ (h/Z_0 + 1)]^{5/3}} \qquad (2.11)$$

where f = frequency, h = height above ground, V = mean windspeed at H = 10 m, Z_0 = surface roughness coefficient, and C1 and C2 are constants for the longitudinal, lateral or vertical directions.

In order to be applied to a double multiple stream tube model the psd must be converted to a time series description, which may be carried out by using the inverse Fourier transform, F^{-1}, (17);

$$V(t) = \bar{V} + F^{-1} \sum_{j=1}^{n} (A_j + iB_j), \qquad (2.12)$$

where $A_j^2 = \frac{1}{2} S_j\ \Delta f\ \sin\phi_j$,

$B_j^2 = \frac{1}{2} S_j\ \Delta f\ \cos\phi_j$,

and where ϕ_j is a uniformly distributed random variable between 0 and 2π.

Each point and direction within the total stream tube affecting a wind turbine rotor may be described by similar equations. However, unless the motions are completely independent, they are related by a complex cross spectral density (csd) and the properly correlated time series may be represented by

$$\{V(t)\} = F^{-1} \{[H][X]\} \{1\} \tag{2.13}$$

where H*H = S, S = the matrix of spectral densities, and X = a diagonal matrix of "white noise" (17).

The mathematics of this solution may be simplified (17) assuming the csd to be real numbers given by

$$|S_{ij}|^2 = \gamma_{ij}^2 \, S_{ii} \, S_{jj},$$

where γ_{ij} is a coherence coefficient which, for locations separated by a distance Δr, may be written as in Frost et al (13).

$$\gamma_{ij}^2 = \exp\,(-af\Delta r/\bar{V}), \tag{2.14}$$

where a = a decay coefficient (7.5 is common for both lateral and vertical distributions), f = frequency, and $\bar{V}$ = mean velocity. For a rotor such as that of the 17-m DOE VAWT, γ may be greater than 0.5 for frequencies of 0.2 Hz or less. The one-dimensional flow with perfect transverse coherence may, in this case, be justifiable. However, as the rotor size grows, γ will decrease. For the DAF Indal 6400 with maximum Δr = 30 m, the corresponding γ value is only 0.22.

3.0 SOLUTION PROCEDURE

3.1 Organization

The entire solution is done in five parts.

(1) Generation of NASTRAN Bulk Data.

(2) NASTRAN Solution 64.

(3) NASTRAN Solution 03.

(4) FORTRAN program TRESM.

(5) NASTRAN Solution 30.

The relationship of these parts is illustrated in Figure 3.1 and each step is described in the following sections.

All NASTRAN analysis was carried out on Version 63A using a Cyber 176 machine. The DMAP Alters and other details may be version and machine dependent.

3.2 NASTRAN Bulk Data

The NASTRAN Bulk Data describes the finite element model appropriate for the rotor structure. It follows the many rules and requirements set out in the NASTRAN Users Manual. It may be generated by hand or automatically using Indal Technologies' (proprietary) program ROTGEN or Sandia National Laboratories program DMG
The FORTRAN Program ROTGEN was used to generate the

SOLUTION PROCEDURE

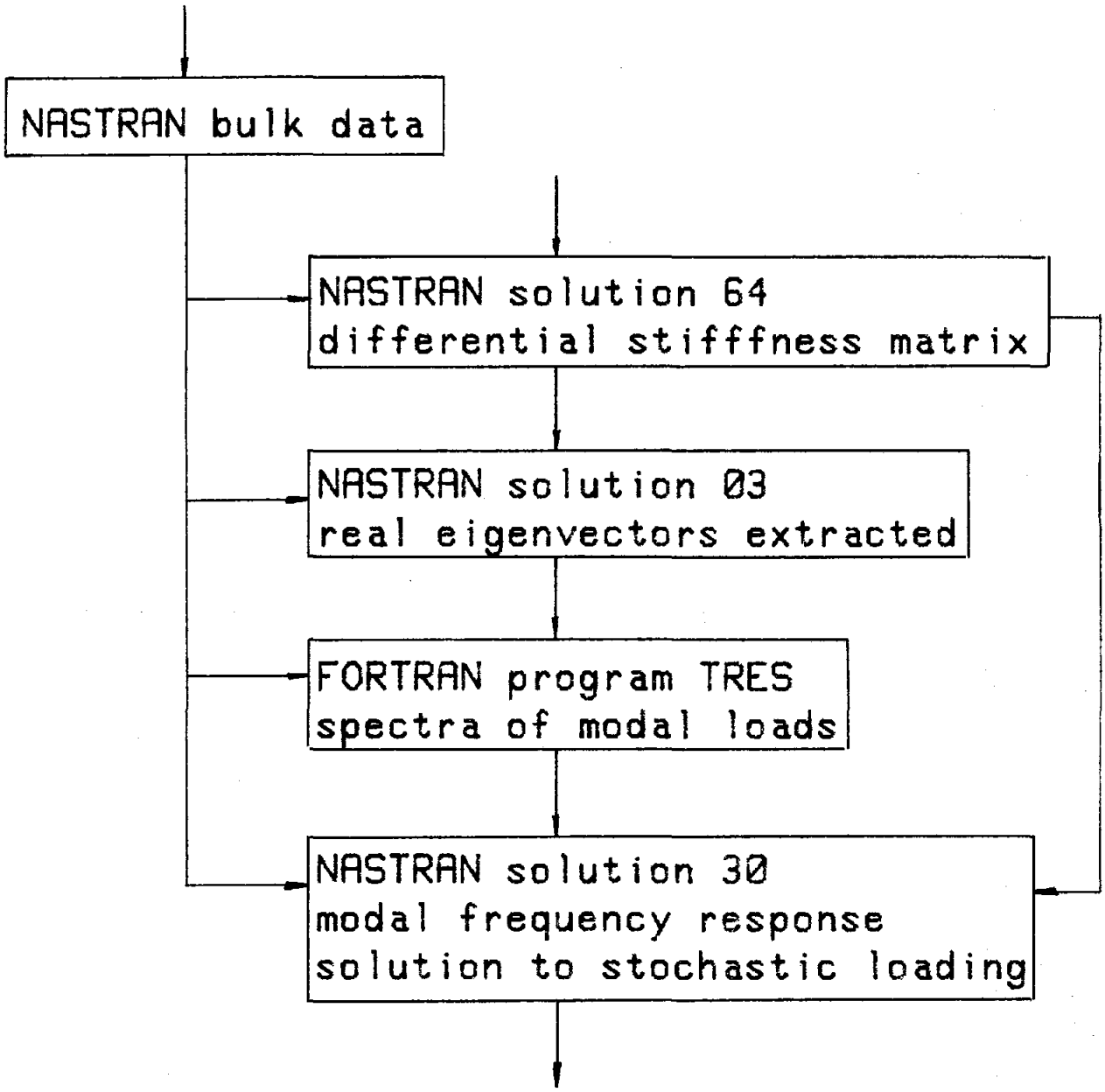

Figure 3.1 General Organization of Solution Procedure

sample bulk data included as Appendix B.4, (see Volume 2 of this report) which includes some of the special features for inclusion of the rotating frame effects.

3.3 Rotating Frame Effects

The analysis is done with reference to the rotating frame of the rotor. This requires the following modifications to the appropriate matrices (10):

(1) Differential stiffening due to centrifugal action,
(2) Softening of the stiffness matrix due to whirling,
(3) Addition of Coriolis terms to the damping matrix.

The differential stiffening is determined by carrying out two iterations in a solution 64. The DMAP used (see D.1) subtracts the initial stiffness matrix from the final stiffness matrix and stores the result in file INP1.

Both the softening and Coriolis terms may be input through DMIG cards, which can be prepared by a FORTRAN program in a manner developed at Sandia National Laboratories (10). Alternatively, if a lumped mass formulation is used, then both softening and Coriolis terms may be generated using DMAP alters. This has been adopted in the present procedure.

The differential stiffening and stiffness softening are included as K2GG terms, which means that they are incorporated before the real eigenvalues are extracted. This implies that the eigenvectors used are not those of the stationary rotor but rather of the operating rotor without Coriolis coupling terms.

The DMAP Alters require input of two 6 x 6 matrices, SYM and SKEW, through DMIG cards used in the bulk data. Some dummy K2GG and B2PP terms are also input through DMIG cards.

3.4 Solution 64 (Nonlinear Statics)

The job control cards (for NOS1 CDC Cybernet), executive control and case control cards for a NASTRAN Solution 64 are included as Appendix D1 in Volume 2 of this report. This generates the differential stiffening matrix as file INP1.

3.5 Solution 03 (Real Eigenvalue Extraction)

The job control, executive control, and case control cards for a Solution 03 are included as Appendix D.2 in Volume 2. This solution generates the real eigenvectors for the first 22 modes of the rotor, including the differential stiffening and the stiffness softening effects.

The vectors are directed through "punched" output onto a file named TRVECT. This file may be transferred to a micro-computer or other machine on which the program TRESM is run.

3.6 Solution 30 (Modal Frequency Response)

All of the cards needed to run this modal frequency response solution are included as Appendix D.3 of Volume 2 of this report. That listing includes the DMAP Alters for inclusion of the rotating frame effects and also the modifications required to allow the input of spectral terms as modal rather than physical loads.

Additional features of this DMAP Alter are lines to allow selected modes to be excluded from the solution, the output displacements in terms of the modal coordinates, and the writing of the frequency response output to a special file named OTP49. If the frequency response information is not required, then its (expensive) output may be completely avoided.

More details of these DMAP features are to be found in the report by Control Data Canada included as Appendix E in Volume 2 of this report.

4.0 NUMERICAL RESULTS

This section is divided into two parts: the testing and validation of the program and procedure that was carried out on a rough model of the SNL 17-m "low cost" rotor, and results obtained from the modelling of the Indal 6400 VAWT, which was located at Southern California Edison's Devers test site and for which experimental data were available.

4.1 Validation of Program & Procedure

Attempts to validate the program TRES and the NASTRAN procedure were made in two ways.

(1) The 17-m rotor was loaded at its mid-rotor nodes only. Physical coordinate loads were applied using both a "normal" double multiple stream tube model (uniform flow) and using the program TRES with a spectral density formulation (with turbulence equal to zero).

(2) The full 17-m rotor was loaded first by the normal DMST model and then with the program TRESM using the spectral formulation of the modal loads (with zero turbulence).

The results of these comparisons are given in the following sections.

4.1.1 Physical Loads at Mid-Rotor

The bulk data for the 17-m model are included as

Appendix B.1. The details of the input used in the DMST model are

Mean windspeed (mid-rotor)	= 40 mph
Air density	= 0.0766 lb/ft^3
Intervals per revolution	= 16
T+Ror speed	= 52 rpm

Some of the results of applying the aerodynamic load at the mid-rotor node only are given in Table 4.1. This table compares some of the bending moments obtained by using uniform flow DMST model "FBLADE2" with those obtained using TRES with zero turbulence. The FBLADE2 loads were used in two NASTRAN solutions: solution 26 uses a direct frequency response method whereas solution 30 carries out the frequency response using a selected number of real eigenvectors.

The two FBLADE2 solutions compare well except at the 5P frequency. The reason for this is that the model is very close to a resonant condition at 5P, and very slight alterations in the solution procedure can result in large response changes. This would not occur in practice.

For these runs the program TRES was modified to output loads in physical coordinates, of which there were only four in this case (two at each mid-rotor node). The input was in terms of the continuous one-sided power spectrum, which is related to the corresponding frequency amplitudes by

$$\text{amplitude} = \sqrt{2*(\text{power spectrum})*\Delta f}\ ,$$

TABLE 4.1 Application of Mid-Rotor Loads Only to 17-m Rotor

		Dynamic Input via FBLADE2 Amplitudes		Physical Load Spectral Input via TRES	
				Solution 30 (20 Modes)	
Output Quantity	Freq.	Solution 26	Solution 30 20 Modes	Continuous Power Spectral Density	Equivalent Amplitude
	0P	0	0	4.79E5	322
Element #3	1P	20,900	19,800	8.769E8	19,495
(mid column)	2P	16	13	0	0
M2 at end A	3P	32,300	38,300	3.325E9	37,961
	4P	2	1	3.290E3	37
	5P	6,180	2,748	2.096E7	3,013
Element #101	0P	235	209	2.378E5	227
(blade root)	1P	4,751	4,212	4.147E7	4,238
M1 at end A	2P	2,427	2,202	1.096E7	2,179
	3P	2,669	2,306	1.262E7	2,336
	4P	2,024	1,946	7.639E6	1,816
	5P	12,900	7,037	8.485E7	6,062
Element #101	0P	13,100	13,100	8.298E8	13,450
(blade root)	1P	5,819	5.911	7.738E7	5,788
M2 at end A	2P	14,900	14,400	5.090E8	14,850
	3P	33,500	34,500	2.717E9	34,320
	4P	699	740	1.172E6	712
	5P	17,500	13,661	3.333E8	12,020

Units: inches, lbsf

where Δf = the frequency interval. Note that the factor of 2.0 is absent at OP frequency.

Comparison of the second and fourth columns of Table 4.1 indicates acceptably close agreement between the two aerodynamic models.

4.1.2 Zero Turbulence Response

The modal formulation within TRES and the DMAP modifications made to the NASTRAN solution were tested by comparison with the "normal" solution, using FBLADE2 for uniform windspeed. The results of this comparison are shown in Table 4.2 and were obtained under the following conditions:

Rotor speed	= 52 rpm
Mean mid-rotor windspeed	= 40 mph
Air density	= 0.0766 lb/ft^3
Vertical wind shear exponent	= 0.16
Intervals per revolution	= 16

The remarks of Section 4.1.1 apply again to the solutions 26 and 30 based on FBLADE2. Comparison between the two 20-mode solutions confirm that the modal formulation with TRES and the DMAP Alters are valid.

Comparison of the last two columns confirms that the additional DMAP modification to allow suppression of a selected number of modes is also valid.

TABLE 4.2 Application of Full Blade Loads to 17-m Rotor

Output Quantity	Freq.	Dynamic Input via FBLADE2 Amplitudes: Solution 26	Dynamic Input via FBLADE2 Amplitudes: Solution 30 20 Modes	Modal Spectra Input via TRESM, Solution 30, Equivalent Amplitudes: 20 of 20 Modes	Modal Spectra Input via TRESM, Solution 30, Equivalent Amplitudes: 15 of 20 Modes
Element #3	0P	0	0	0	0
(mid column)	1P	155,900	151,800	150,300	149,000
M2 at end A	2P	197	174	2,498	2,523
	3P	159,800	168,000	164,300	165,900
	4P	14	10	1,281	1,318
	5P	44,700	27,200	27,443	30,509
Element #101	0P	565	549	449	402
(blade root)	1P	4,025	4,176	4,522	4,804
M1 at end A	2P	4,139	4,357	4,769	4,599
	3P	6,273	6,833	7,544	7,500
	4P	11,001	10,900	10,757	9,897
	5P	37,169	20,500	18,800	19,500
Element #101	0P	98,800	98,700	100,400	100,400
(blade root)	1P	52,300	53,200	52,400	50,000
M2 at end A	2P	118,600	115,800	119,000	118,900
	3P	93,300	96,500	93,300	96,200
	4P	4,693	3,949	3,502	3,952
	5P	68,700	50,500	46,700	38,000

Units: inches, lbsf

4.1.3 Simulation of Turbulent Windspeeds

In order to confirm the simulation of the turbulent windspeed time series, a number of tests were carried out.

(1) Regeneration of the frequency power spectrum from the time series.

(2) Calculation of the rms by integration of the frequency spectrum.

(3) Calculation of the rms of several of the time series.

These calculations were carried out on a 2 x 2 spatial array of points used for the 17-m rotor.

4.2 Indal 6400

The program TRES was applied to a mathematical model of the Indal 6400 Darrieus rotor prototype that was operated at Southern California Edison's test site near Palm Springs and for which the structural and experimental data were readily available. The outline of the finite element model is shown in Figure 4.1 and the NASTRAN bulk data file is included as Appendix B.4.

Both the model and field data refer to the initial configuration of this machine; that is, the out-of-plane motion of the struts relative to the central column was restrained by springs (of stiffness 3,000 lb/in.) and the central length of each blade contained additional ballast equivalent to 10 lb/ft.

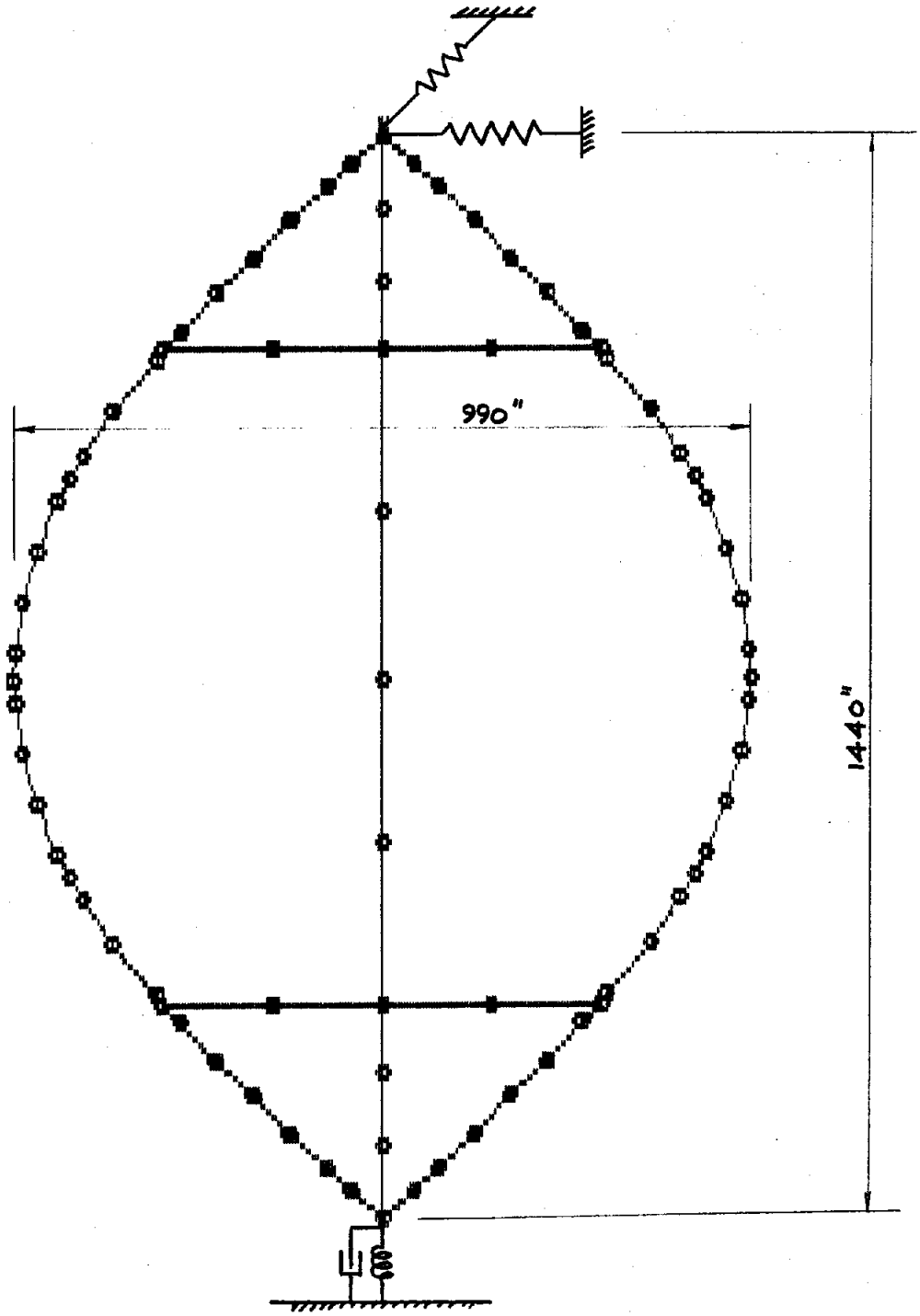

Figure 4.1 Finite Element Model of Rotor

The length of the time series vectors, the number of spatial array points and the resolution within the frequency spectra were limited by the micro-computer used (an IBM PC AT with 512 K bytes of memory). This limitation may have introduced some errors into the results but is unlikely to have affected the major conclusions.

The following variable values were used throughout the analysis of the Indal 6400:

Rotor height	= 1,440 in.	= 36.6 m
Rotor diameter	= 991 in.	= 25.2 m
Mid-rotor height	= 900 in.	= 22.9 m
Mid-rotor windspeed	= 45 mph	= 20.1 m/s
Rotor speed	= 45 rpm	
Air density	= 0.0728 lb/ft^3	= 1.17 kg/m^3
Wind shear exponent	= 0.16	
Time series, delta T		= 0.120 s
# of vertical divisions in spatial array		= 3
# of lateral divisions in spatial array		= 3
# of rotor revolutions		= 16
# of divisions per revolution		= 16
Decay coefficient for csd		= 7.5
# of eigenvectors used		= 22
# of eigenvectors in solution		= 20
# of ensemble values		= 18
Dynamic stall included		YES
Column loading included		YES
Length of windspeed time series		= 256
Length of loading time series		= 256

A NASTRAN solution 64 was carried out to generate the differential stiffness matrix. This was included in

the subsequent solution 03 together with the softening due to whirling. The resulting natural modes are those of the operating rotor except for the addition of Coriolis terms. These real modes and natural frequencies are illustrated in Appendix F.1.

The complex eigenvectors and natural frequencies of the operating rotor were extracted using NASTRAN solution 26 and these are shown in Appendix F.2.

4.2.1 Modal Loading

The program TRES decomposes the physical aerodynamic loads into components of the real modes illustrated in Appendix F.1. The following notation is used hereafter to describe the modal shapes:

P	propeller
B	butterfly
T	tower
FS	symmetric flatwise
FA	asymmetric flatwise

The load levels associated with the first 22 real modes are summarized in Table 4.4, which lists the modes in the order of the total variance of the power spectral density. The table also indicates the percentage of the total variance that is due to contributions at frequencies other than the harmonics of the rotor speed (i.e. the stochastic component) when the ambient flow contained 20% turbulence.

TABLE 4.4 ORDER OF TOTAL VARIANCE OF MODAL LOADS

ORDER	MODE #	NAT. FREQ.	TYPE	TOTAL VARIANCE	% STOCHASTIC
1	3	1.87	1T	26.E6	1.8
2	8	4.04	T	19.E6	2.1
3	1	.39	1P	5.7E6	4.5
4	22	10.38	3FA	1.9E6	5.7
5	19	8.43	3FA	1.6E6	7.5
6	15	6.44	FA	1.2E6	6.8
7	4	2.55	1B	.99E6	14
8	2	1.32	1B	.91E6	21
9	6	2.87	1FS	.81E6	80
10	5	2.82	1FA	.73E6	90
11	18	7.61	3FA	.46E6	12
12	13	5.51	2FA	.39E6	14
13	10	5.06	3P	.32E6	13
14	17	7.41	3FS	.21E6	24
15	20	9.61	3FS	.19E6	81
16	9	5.04	2P	.16E6	30
17	14	6.25	3B	.14E6	23
18	7	3.38	2B	.13E6	39
19	12	5.43	2FS	.11E6	39
20	16	7.28	3FS	.10E6	27
21	11	5.42	2B	.06E6	
22	21	9.96	4B	.04E6	
			TOTAL	61.1E6	

Indal 6400 (SCE1), V = 45 mph, turb. = 20%

Table 4.4 shows that there are significant loads associated with some of the higher frequency modal shapes. For example, modes 22 and 19 are respectively 4th and 5th in the order of total variance. It also appears that over 80% of the total load variance is associated with the first three modes; however it is likely that these modes are not responsible for the lead-lag and flatwise blade response, which are critical in determining fatigue life.

4.2.2 Effect of Turbulence Intensity

Three sets of analyses were carried out to investigate the effects of differing degrees of turbulence intensity. This intensity was measured by the coefficient of variation (standard deviation divided by mean velocity) of the ambient longitudinal flow. Full details of the various parameters are listed below.

		#1 Low	#2 Medium	#3 High
Turbulence spectrum coefficients				
Longitudinal	C1	2.0	12.3	40
Longitudinal	C2	80	192	300
Lateral	C1	1.0	4.0	12.3
Lateral	C2	70	70	70
Surface roughness, m at mid-rotor		0.1	0.1	0.1
Rms longitudinal turbulence, mph		4.8	9.2	14.3
Rms lateral turbulence, mph		3.6	7.1	12.5
Intensity, longitudinal turbulence		0.11	0.20	0.32
Intensity, lateral turbulence		0.08	0.16	0.28

The effect of these varying degrees of turbulence was determined by examination of the lead-lag and flatwise bending at the blade just above the lower strut. This location was selected because field data for that location were available and because it was the location of the highest blade stresses.

For these three analyses, the level of structural damping was 2% of critical and each mode was associated with an additional 1% of critical damping.

The predicted power spectral density (psd) of the lead-lag and flatwise bending moments are shown in Figures 4.2 and 4.3 respectively. Although continuous lines are used (for clarity) on these graphs, the spectra are discrete at intervals of 0.0938 Hz (1/8th of the rotor frequency of 0.75 Hz), rather than continuous.

Figures 4.4 and 4.5 show the predicted longitudinal stress levels at the leading edge and inner face (on the principal axes) respectively.

The following observations may be drawn from these four figures.

- The 1P, 2P and 3P peaks are affected very little by turbulence.

- Excitation of the two fundamental natural frequencies, most noticeable in lead-lag behaviour, is closely dependent on turbulence.

- There is pronounced flatwise response between 3P and 4P due, no doubt, to the presence in that range of the two fundamental flatwise natural frequencies.

- The increase in rms of cyclic stresses at the leading edge due to 32% turbulence is 26%.

- The rms of cyclic inner face stress is very sensitive to turbulence, the maximum increase being 320%. Even 11% turbulence causes an 89% increase.

4.2.3 Effect of Modal Damping

The degree of aerodynamic damping associated with each of the real modes is very important. A recent report from Sandia National Laboratories (21) on the aeroelastic effects on VAWT dynamics indicated that in still air there could be up to 20% damping associated with the first pair of flatwise natural modes and about 10% on the second pair of flatwise modes.

It should be noted that the modes referred to in Lobitz and Ashwill (21) are complex modes (due to Coriolis coupling) and their designation refers to their (real) shape at 0 rpm. In Figures 4.2 and 4.3, however, the natural modes are described by both of the coupled components. The first of the two descriptions indicates the dominant component.

In order to simulate the findings of Lobitz and Ashwill (21) the following levels of modal damping were imposed on the set of (real) modes:

Natural Frequency	Real Mode Shape	Modal Damping
2.82 Hz	FA	15%
2.88	FS	15%
5.43	2FS	10%
5.51	2FA	10%

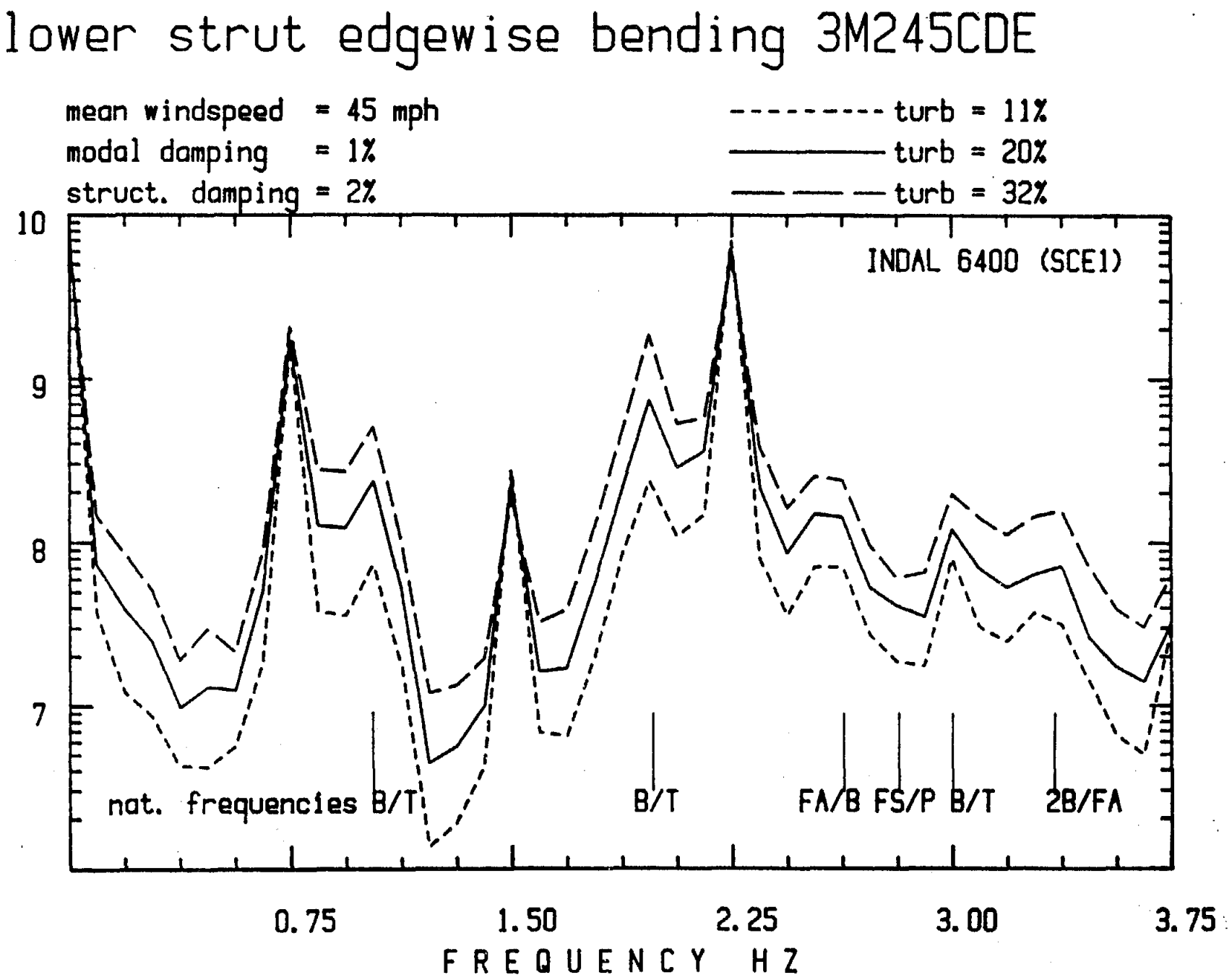

Figure 4.2 Lead-Lag Blade Bending at Lower Strut

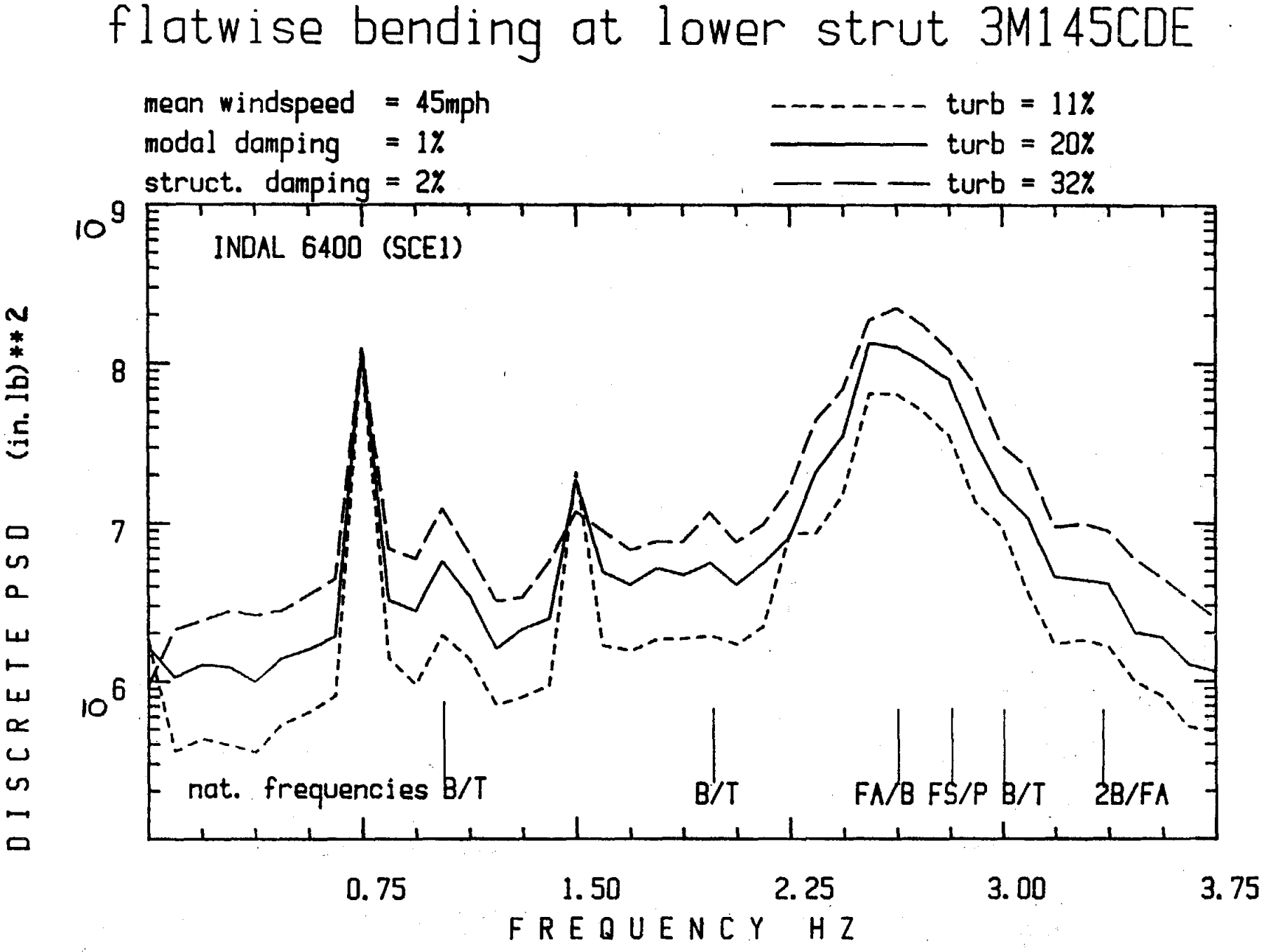

Figure 4.3 Flatwise Blade Bending at Lower Strut

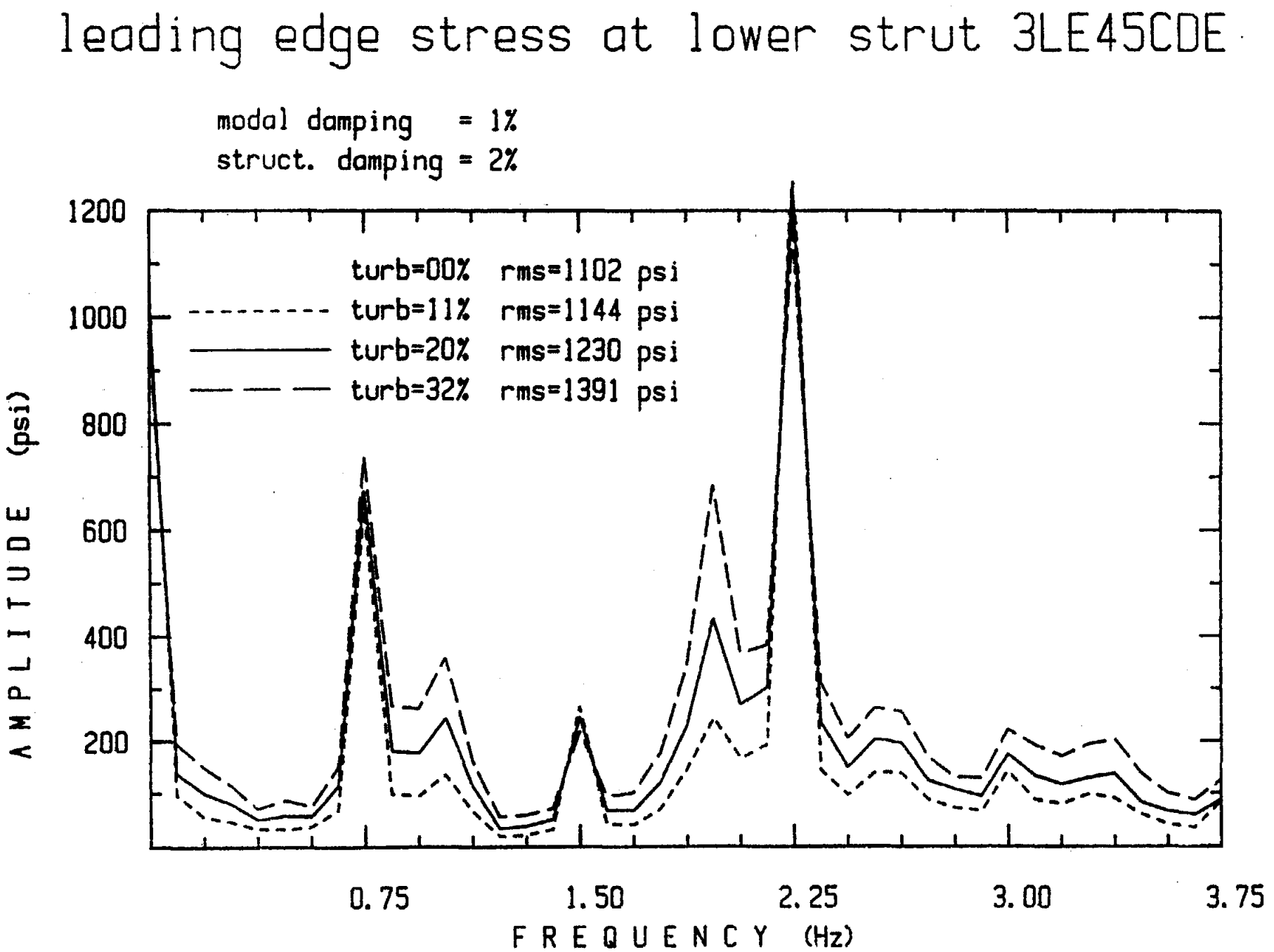

Figure 4.4 Leading Edge Stress at Lower Strut

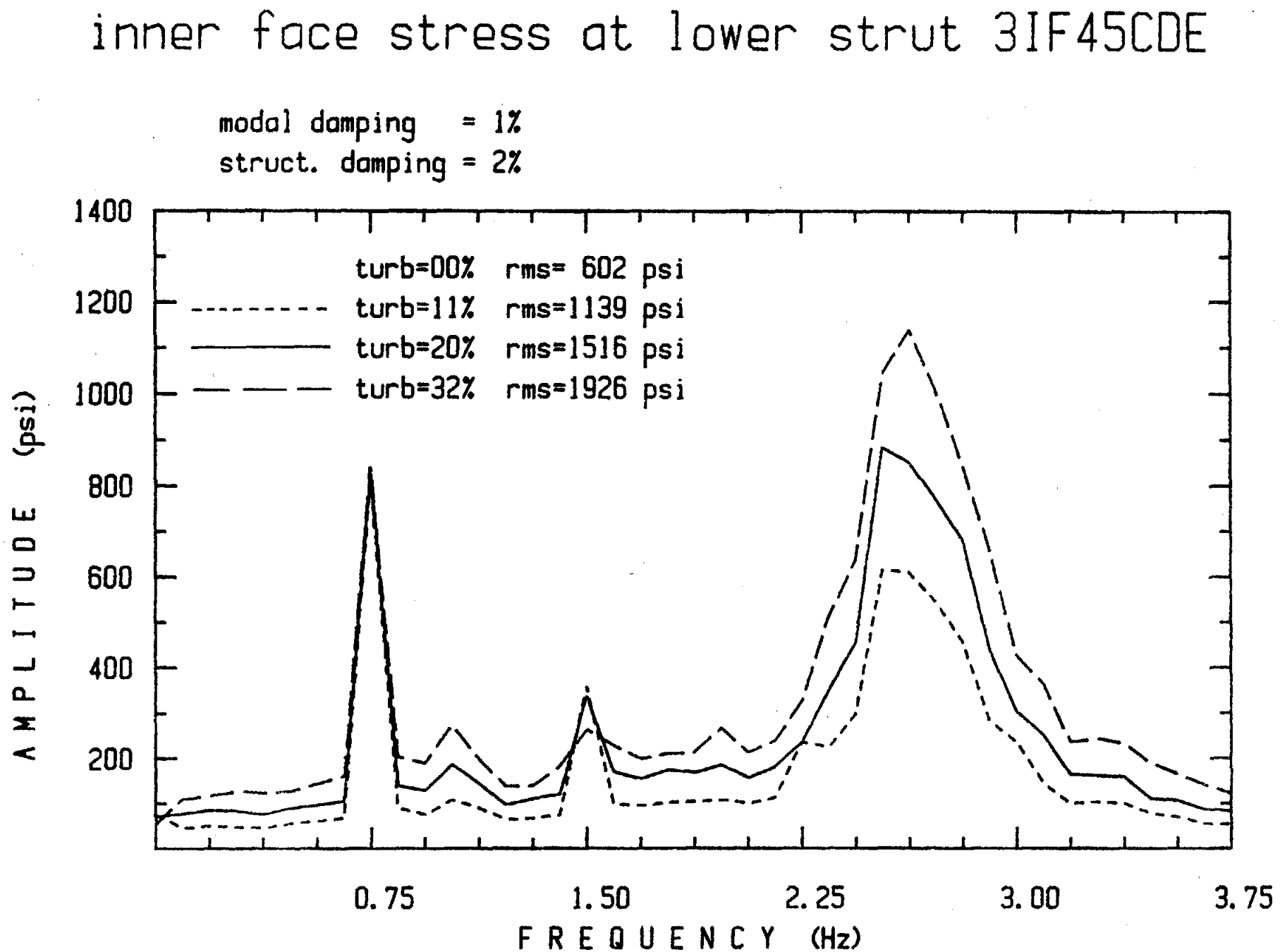

Figure 4.5 Inner Face Stress at Lower Strut

The results of imposing this degree of modal damping at the "medium" level of turbulence are shown in Figure 4.6, which gives the amplitude spectrum of inner face stress. This figure confirms that the flatwise response between 3P and 4P is largely due to response to these flatwise modes and indicates that the response is almost entirely removed by the level of damping selected.

4.2.4 Comparison with Field Data

From the field data available, typical records were selected, which showed the stress amplitude spectra at the leading edge and inner face of the blade above the lower strut under 45 mph winds. These records are shown in Figures 4.7 and 4.8 alongside the corresponding predictions redrawn to a similar scale.

The agreement of the values of the harmonic peaks is not exact, and this has been discussed elsewhere (12); what is of importance is the comparison of the response between the harmonic frequencies. The major stochastic response is the flatwise response between 3P and 4P where the model shows good agreement with the field data. In addition the response at the first two fundamental natural frequencies recorded in the field is similar to the modal predictions with 11% turbulence intensity.

The overall rms values at the leading edge are predicted accurately but are somewhat over-predicted at the inner face. However, the latter is very sensitive to the level of turbulence (see Figure 4.5).

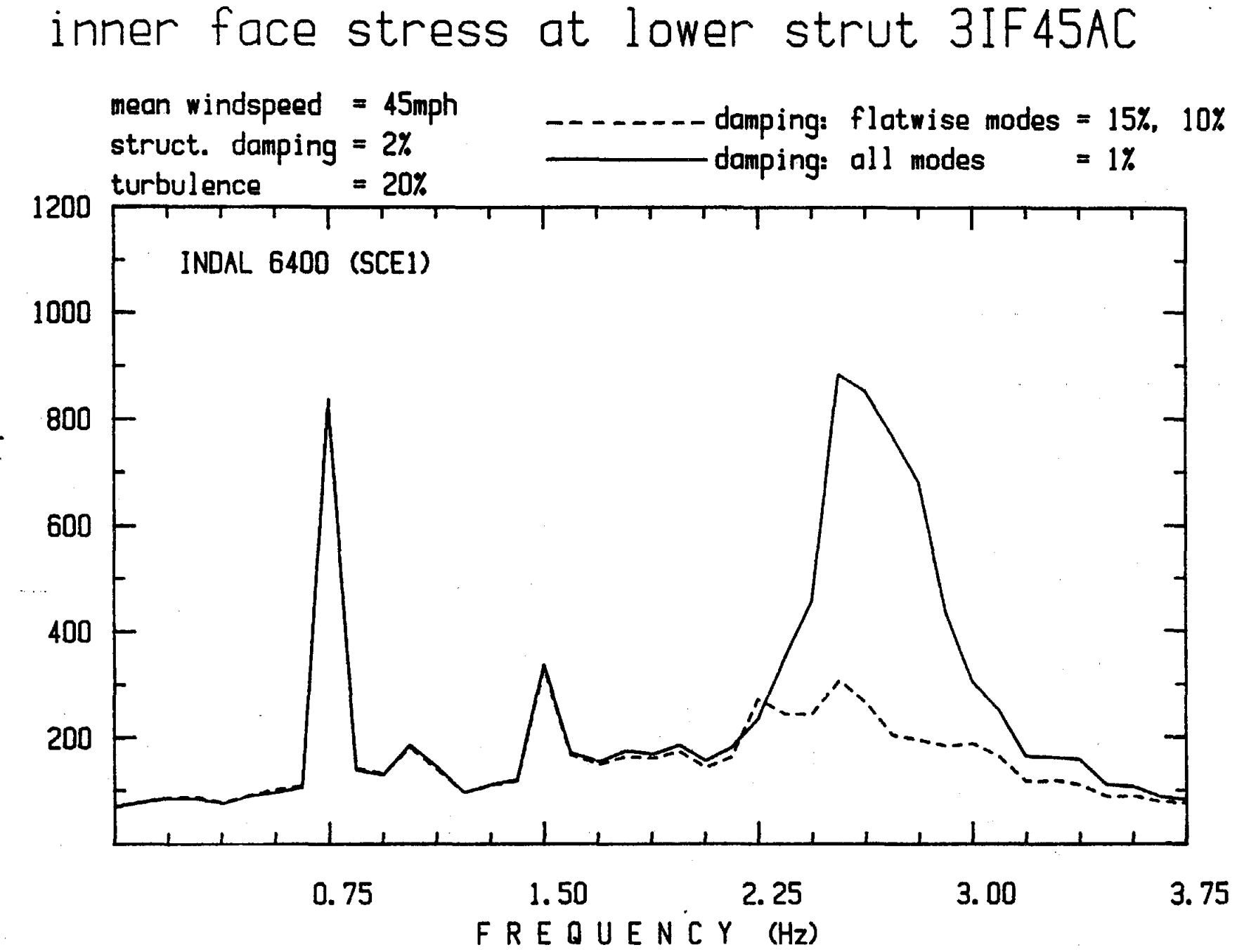

Figure 4.6 Inner Face Stress at Lower Strut. Effect of Flatwise Modal Damping

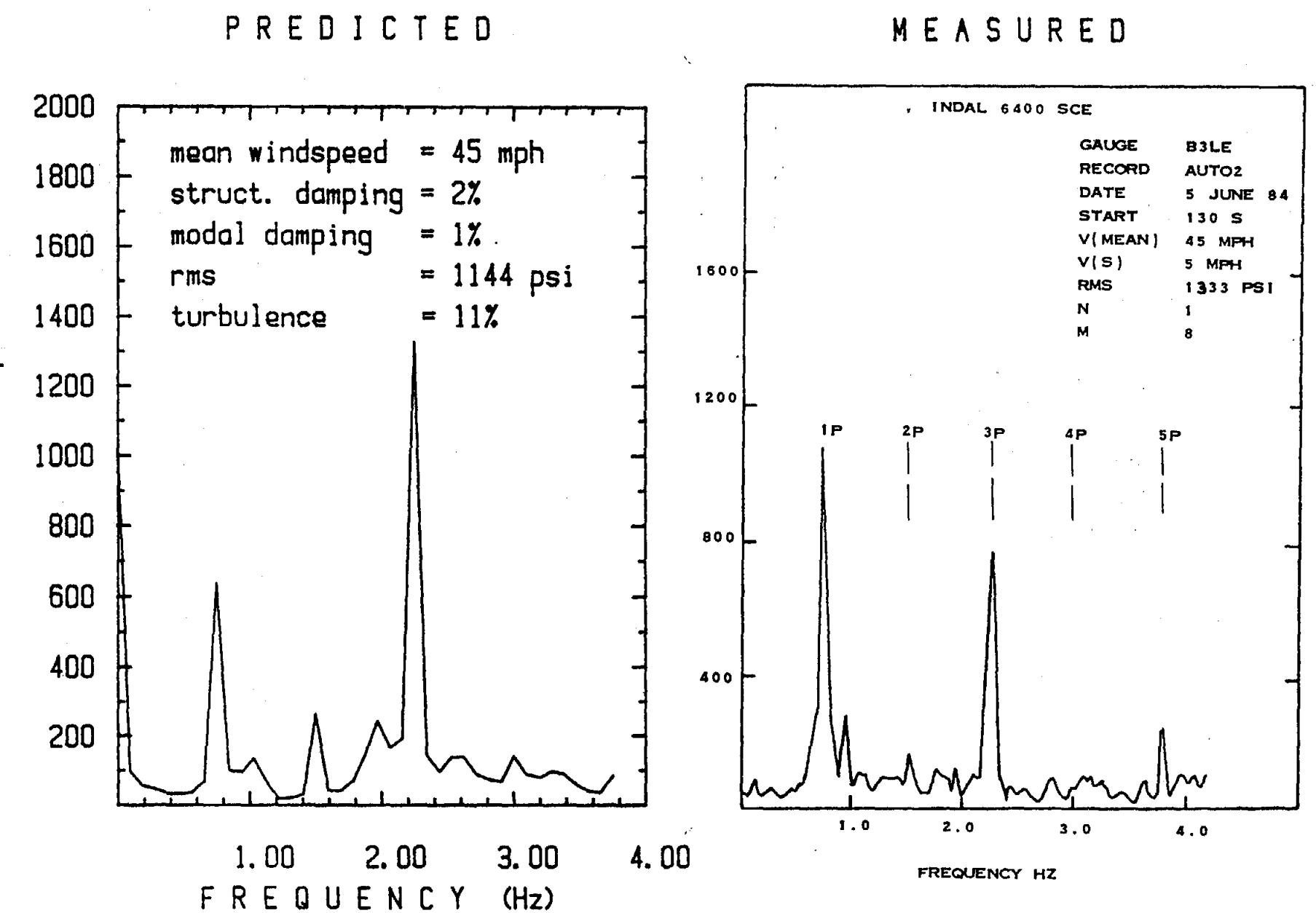

Figure 4.7 Leading Edge Stress at Lower Strut. Sample of Field Data

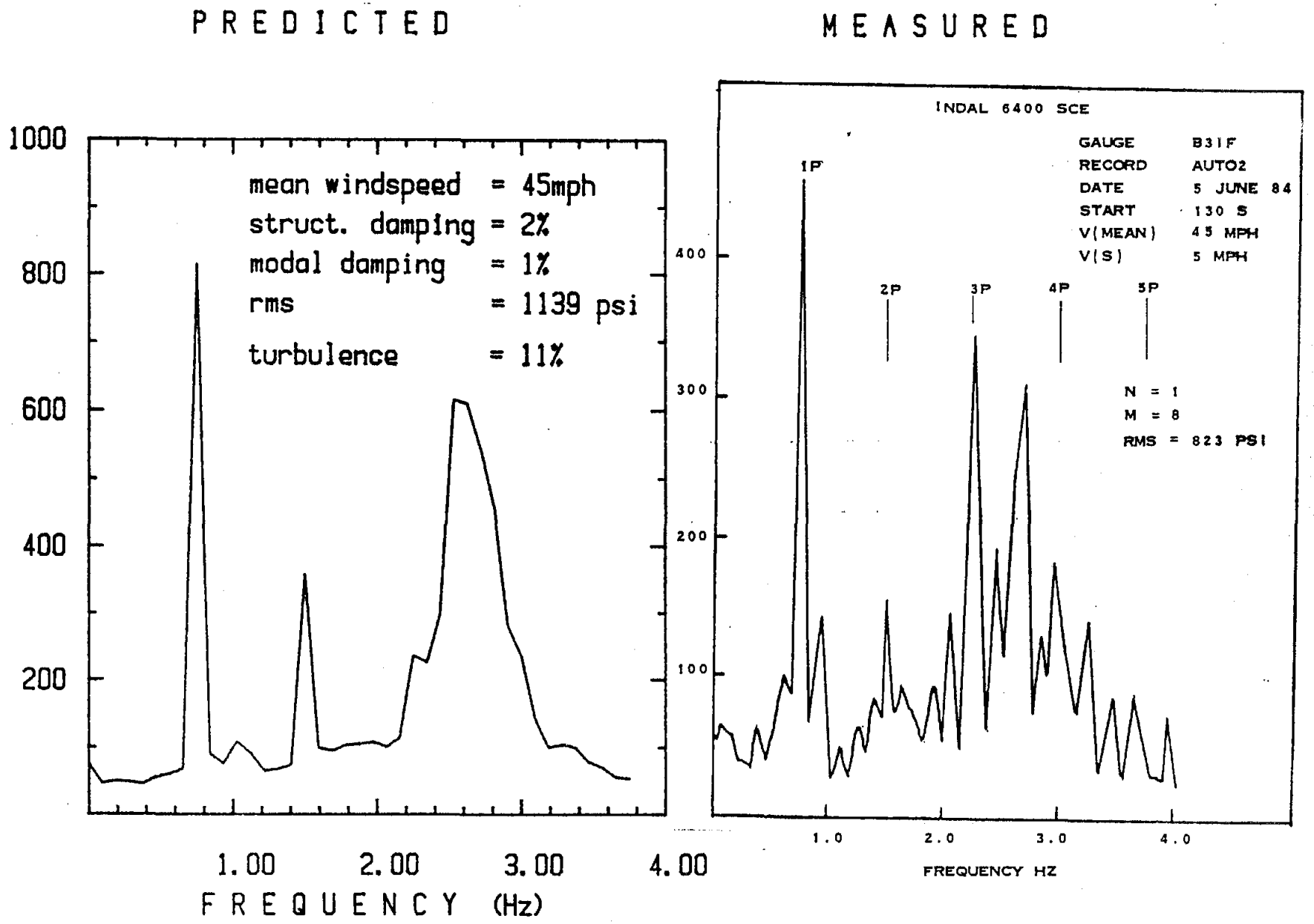

Figure 4.8 Inner Face Stress at Lower Strut. Sample of Field Data

4.2.5 Computing Resources

One objective of this project was to generate a model and a procedure that would be economical to use. This implies limiting the computing resources required.

The FORTRAN program TRES was run on an IBM PC AT with 512 K bytes of RAM memory. The capacity of this machine limited the size of arrays and vectors, and a mini computer or more powerful micro-computer should be used in the future. In addition, the speed of the machine should enable it to compute at least 50 ensemble values during an overnight run.

While the running of a FORTRAN program on a mini computer is not usually expensive nowadays, the access to and cost of NASTRAN can be more of a deterrent. The cost of a NASTRAN solution 30 using 22 modes and 40 frequency values in the spectrum for the Indal 6400 was approximately 1000 "standard billing units" on the Cybernet system of CDC. At overnight rates, this translated into approximately $250 CDN ($190 US). Although this cost is three times that of a deterministic frequency response at five or six frequencies only, it is still not an undue burden.

Additional costs are involved in the transmission and storage of files and in interactive processing. The processing of output data into graphical form can be costly but it is now more possible to carry this out on a small resident machine. In this project the NASTRAN output files were transmitted through a 1200 baud modem to a desk top computer where they were edited and processed by an inexpensive plotting software package.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Numerical Results

The computer model, which is based on the preparation of auto- and cross-spectral densities of a set of real modal loads, has been shown to give results that are in good agreement with field data from the Indal 6400. These results are

- 1P, 2P and 3P peaks are affected only slightly by turbulence;

- Lead-lag (out-of-plane) action is not highly sensitive to turbulence;

- Flatwise (in-plane) action is very sensitive to turbulence; addition of 11% turbulence will almost double the rms of cyclic response;

- The considerable flatwise response observed between 3P and 4P frequencies is correctly predicted by the model using 1% critical damping on all modes;

- The flatwise response between 3P and 4P is entirely eliminated by applying 15% damping to the fundamental pair of flatwise modes and 10% to the second fundamental pair.

5.2 Load Formulation

The preparation of the aerodynamic loads into (real) modal form revealed the following:

- It was necessary to consider the first 22 real modes in the loading formulation;

- In the NASTRAN solution it was found necessary to include all but two of these modes to obtain good agreement with other benchmarks.

- Over 80% of the total variance of the loading is associated with the first three modes (one propeller and two tower modes);

- Modal loads corresponding to third order flatwise bending modes are in the top five contributors to the total variance;

- It is not clear which modal loads can be omitted and which modes in the solution can be omitted without unacceptable error;

- The inclusion of aerodynamic drag on the central column has been included with very little additional effort; these terms do have an appreciable effect on the magnitude and ordering of some of the model loads;

- In order to avoid very lengthy NASTRAN input files, it is necessary to omit all cross-spectral density tables that do not contribute appreciably to the loading;

- The use of only 18 values in the ensemble averaging may have resulted in some error, especially in high turbulence; however, the extension to 50 ensemble values was observed to reduce the total variance due to turbulence by 10% only;

- The omission of cross-spectral loading terms at frequencies between the harmonics was considered; however this omission was found to affect the response at those frequencies substantially.

- The generation of wind time series by linear interpolation between neighboring spatial array points was abandoned. It was found that for turbulence in which correlation was low, linear interpolation tended to lower the rms of the resulting time series below that of the neighboring points. The technique was replaced by the procedure of selecting the time series associated with the closest spatial array point.

5.3 Recommendations

This project has been largely successful in reaching its goals. However, during its execution a number of aspects have come to light.

- The extent of damping associated with flatwise blade bending is critical. The approximately 15% inferred in Lobitz and Ashwill (21) appears too high. The aeroelastic behavior in operating conditions should be studied further.

- The minimum number of modes used in the load formulation and in the solution is not certain. It would be of use to decompose the aerodynamic loads into the complex modes of the operating rotor and also to study the modal response operators and the extent of intermodal coupling.

- The length of time and frequency vectors used were kept to a minimum. Greater accuracy would be obtained by increasing these lengths.

- The effect of different turbulence spectra has not been studied. The spectrum by Frost et al. (13) may not be the most suitable for many sites.

- The double multiple stream tube model used in the aerodynamic routines assumes that the airflow, with its accompanying turbulence, passes through the rotor in an essentially unchanged manner. This assumption may be adequate to predict overall performance, but is unlikely to predict accurate stochastic loads. An alternative aerodynamic model should be considered.

- It has been assumed that dynamic stall is present in both uniform and turbulent conditions and on the downwind as well as the upwind blade. These assumptions should be questioned and their effect on the output spectra examined.

- The use of linear interpolation between time series from neighboring spatial points appears unacceptable in a coarse mesh of points. It should be replaced by another procedure that does not reduce the rms of the resulting time series.

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A MODEL FOR THE RESPONSE OF VERTICAL AXIS WIND TURBINES TO TURBULENT FLOW

PART 2

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7. PROGRAM DESCRIPTION & DOCUMENTATION

7.1 Configuration of Program

The program is made up of one main routine and twenty-six subroutines, all of which fall into one of three groups: reading of input data, computation, and generation of output. This grouping and the calling relationship between routines is illustrated in Figure 7.1.

The following section (7.2) lists the variable names associated with the several common blocks used and gives the meaning(s) of each variable.

Section 7.3 gives details of each subroutine: a description of its purpose, a flow chart of its logic, and a list of the important variables.

7.2 Listing and Explanation of Common Block Variables

7.2.1 Common Block: GEOM

General Purpose: basic dimensions and integer variables for program

Name	Dimensions	Meaning
HT	in	height of rotor (between blade intersections).
DIA	in	max. diameter of rotor (assumed at mid-rotor).
HMR	in	height at mid-rotor.

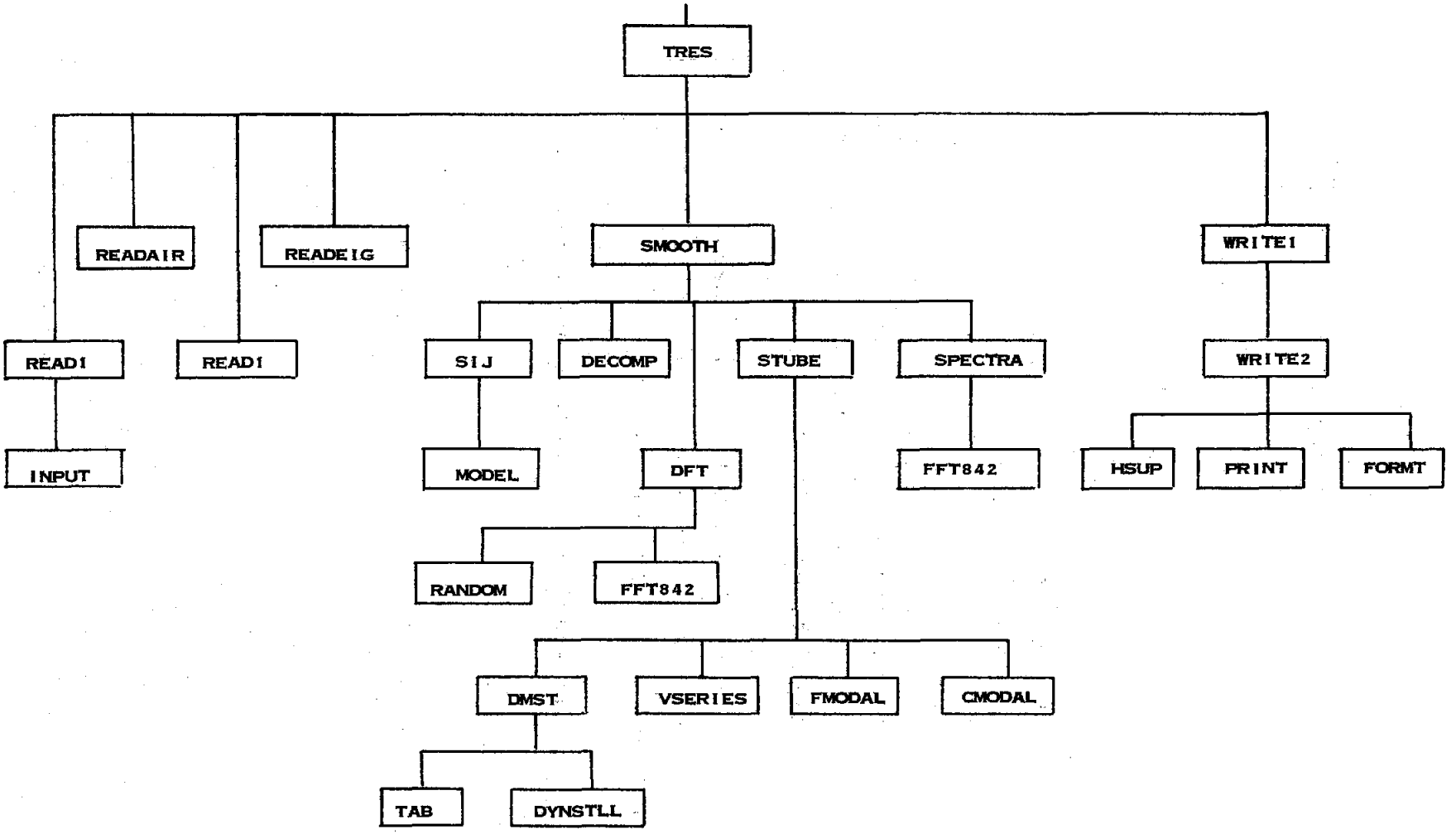


Figure 7.1 Program Configuration

Name	Dimensions	Meaning
NHT	-	no. of vertical divisions in spatial wind array.
NDIA	-	no. of lateral divisions in spatial wind array.
NZH	-	no. of elements in each blade.
NT	-	no. of intervals per rotor revolution.
NREV	-	no. of revolutions of rotor.
NEIG	-	no. of eigenvectors used in load formulation.
NLOOP	-	no. of loops used to generate ensemble of load spectra.
NPMAX	-	maximum per-rev frequency in output spectra.
NDIV	-	no. of divisions between per-rev frequencies in output spectra. Must be a power of 2.
NVECT	-	no. of eigenvectors to be used in NASTRAN modal solution.
NCOL	-	no. of elements in model of column.

7.2.2 Common Block: ROTOR

General Purpose: blade and column coordinates, location and densities of blade types

Name	Dimensions	Meaning
R(i)	in	radial coordinate of blade node #i.
Z(i)	in	vertical coordinate of blade node #i.
RPM	rpm	rotor speed.
CH(i)	in	chord dimension of airfoil #i.

Name	Dimensions	Meaning
FHT(i)	in	height from mid-rotor for start of airfoil #i.
NFOIL	-	no. of different airfoils used.
INDEX(i)	-	vector of NASTRAN node numbers of blade nodes.
DAMP(i)	-	modal critical damping coefficients associated with eigenvector #i.
INDEXC(i)	-	vector of NASTRAN node numbers of column nodes.
ZCOL(i)	in	height of column nodes.
DCOL(i)	in	diameter of column at node #i.

7.2.3 Common Block: WND

General Purpose: parameters of wind flow and turbulence

Name	Dimensions	Meaning
VBAR	mph	mean windspeed at mid-rotor height
WSE	-	exponent describing vertical wind shear.
C1X C2X C1Y C2Y		coefficients C1 and C2 for use in formula of turbulence spectrum used by Frost & Turner. X refers to longitudinal; Y refers to lateral directions. F & T formula uses S.I. units.
Zo	m	roughness height. Used in F & T formula.
DECAY	-	coefficient used in formula describing cross-spectra between points in spatial wind array.

Name	Dimensions	Meaning
DELT	sec	time interval used to describe wind-speed time histories.
NTRAN	-	no. of time intervals in vectors of turbulent wind.
VBARZ	mph	mean windspeed at current height.
ARHO	lb/ft^3	air density.

7.2.4 Common Block: EIGEN

General Purpose: variables related to eigenvectors and generalized loads

Name	Dimensions	Meaning
EIGV (i,j,k)	in	displacement at node i in direction j of eigenvector k.
GLOAD(i,j)		component i of generalized load j. Initially time domain; following FFT, frequency domain.
EVALUE(i)	Hz	eigenvalue associated with eigen-vector i.
IGLOAD(i)	-	re-ordered sequence of GLOAD vectors according to total variance.

7.2.5 Common Block: AIRFOIL

General Purpose: variables related to required airfoil data

Name	Dimensions	Meaning
DSET(i,j,k)		k = airfoil type #, j = pairs of Cl & Cd coefficients, i = angle of attack (alpha), j = 1 column gives alpha values.
DSET1(i,j)		Temporary storage of Cl & Cd values.
RE(i,j)		Value of Reynolds number #i for airfoil #j.
AS(i,j)		Value of alpha at stall for Reynolds number #i and foil #j.
CDMIN(i,j)		Cdmin value for Reynolds number #i and airfoil #j.
NRE(i)		no. of Reynold numbers for airfoil #i.
TC(i)		thickness to chord ratio for airfoil #i.
ANG(i)		temporary storage of alpha values.

7.2.6 Common Block: SPECT

General Purpose: spectra of turbulent wind and dynamic loading

Name	Dimensions	Meaning
S(i,j)	$(m/s)^2/Hz$	ith component of turbulent spectrum for spatial array location j; longitudinal or lateral velocity.

Name	Dimensions	Meaning
TRH(i,j,k)		An array used for general storage of (1) transfer matrix, H, for matrix S. (2) time series of turbulent wind-speeds for longitudinal (k=1) and lateral (k=2) motion. (3) power and cross spectral densities of modal loads; i = length, j = column no., k = real/imaginary parts.
VTUBE(i,j)	m/s	Turbulent time series at current rotor streamtube; longitudinal (j=1) and lateral (j=2).

7.2.7 Common Block: AERO

General Purpose: variables related to DMST model

Name	Dimensions	Meaning
VDEF	-	Fractional velocity deficit downstream of current upwind actuator disc.
THETA	rad	Azimuth position of current streamtube.
DTHETA	rad	Incremental azimuth angle for rotor streamtubes.
DEL	rad	Angle between normal to blade and mean flow.
COSD	-	cosine (DEL)
OMEGA	rad/s	Rotor angular velocity.
RR	-	Radius/max. radius for current streamtube.

Name	Dimensions	Meaning
DZ	in.	Vertical span of stream tube.
ARHOG	lbm/in /g	Air density in absolute units.
VRW	-	Tip speed ratio of current stream tube.
VIRW	-	Tip speed ratio downstream of actuator disc.
PI	-	3.14159
POWER	kW	Power generated by rotor.
FNODE(i)	lbf	Blade loading at current stream tube, direction i.
VR	in/s	Relative wind velocity.
RE1	-	Current Reynolds number.
AS1	degrees	Current stall angle.
PHI	rad	Angle between wind flow and mean longitudinal direction.

7.3 Subroutine Descriptions

7.3.1 Routine TRESM

This is the main routine and its purpose is to allow interactive input of the various input file names and to call the relevant input, computation, and output routines.

The format of the OPEN statements is consistent with MS-FORTRAN for use on an IBM PC.

7.3.2 Subroutine READ1

This subroutine reads data from the basic data file (unit #1), echoes these data and calculates the

length of the wind speed and rotor loading time series. The format of the data is explained in Section 7.4.1 and the meaning of the COMMON block variables is given in Section 7.2.

Subroutine INPUT ( ) is used to pass over comment cards within the data file. These cards are associated with a "$" sign in column one.

Explanation of subroutine arguments:

IDS has value of 0 or 1 indicating that dynamic stall is not or is included.

ICL has value of 0 or 1 indicating that (central) column load is not or is included.

IPRINT has names of 1 (output full cross spectral densities), 2 (zero cross spectra except at harmonic frequencies), or 3 (output cross spectra at harmonics only).

7.3.3 Subroutine READ2

This subroutine reads all relevant geometric data describing the rotor from unit #5, the NASTRAN bulk data deck. There is no echo of this data.

The required data are the X-and Z-coordinates of the blade and column nodes together with the column diameter(s). The following format/limitations must be observed.

i) The nodes of blade #1 must have numbers lying on or between 100 and 199.

ii) The nodes of blade #1 need not be in consecutive order.

iii) The height of the rotor is considered synonymous with the distance between upper and lower blade intersection points.

iv) Column nodes must have numbers lying on or between 2 and 99.

v) The diameter of the column at each node level is located in field no. 10 of the NASTRAN GRID card and is given in F8 format.

vi) The column diameter may be tapered. It is not necessary to supply all diameter values since subroutine READ2 will replace zero values by linear interpolation. Initial and final values must, however, be given.

7.3.4 Subroutine READAIR

Subroutine READAIR selects the required airfoil data from unit #2 and stores it in a format suitable for later use in the aerodynamic model. The data on unit #2 must be stored in the format that is specified in Section 7.4.2. The following features should be noted:

i) Up to five different airfoil types may be used. Their names are read (using A8 format) in subroutine READ1 and stored in TYPE( ).

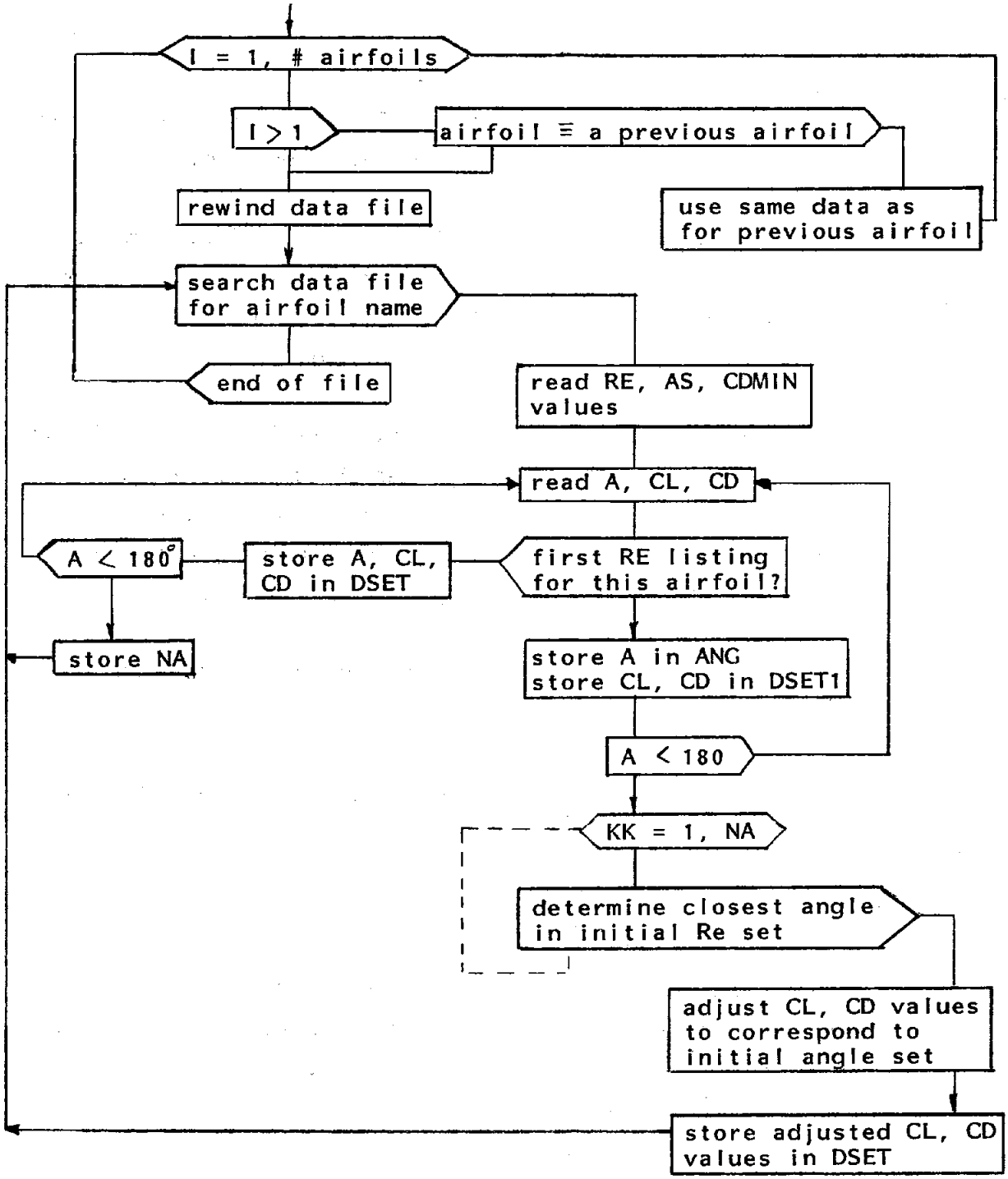


Figure 7-2 . Schematic Flowchart of Subroutine READAIR

ii) Each airfoil type may have Cl and Cd coefficients listed at five different Reynolds numbers.

iii) At each Reynolds number for each airfoil, there is an associated value of the static stall angle, AS, and a zero angle of attack drag coefficient, CDMIN, which will be added to all Cd values.

iv) The angles of attack associated with one airfoil at different Reynolds numbers need not be identical. The routine READAIR uses the angle of attack associated with the lowest Reynolds number and adjusts subsequent coefficients by linear interpolation.

v) The last angle of attack in any series must be 180° (exactly).

A schematic flow chart of the subroutine is shown in Figure 7.2.

7.3.5 Subroutine READEIG

This routine reads, from unit #3, the punched output from a NASTRAN real eigenvector analysis and extracts from it the eigenvalues and eigenvectors required. The following restrictions apply:

i) The format of unit #3 must be as described in Section 7.4.3 and correspond to that used as punched output of the solution-set displacements generated by NASTRAN solution 3 or 63.

ii) The subroutine reads only those components associated with nodes of the (two) blades or the central column.

iii) The numbering of the blade nodes must begin adjacent to the lower root and proceed in ascending order up to the upper node on blade #2.

iv) The numbering of the column nodes must begin at the lower end and proceed in ascending order. These node numbers must all be less than 100.

v) All other nodes should have numbers that are greater than 299.

vi) A maximum of 30 modes can be accommodated.

vii) The maximum number of nodes in the blades and column is 80.

All of the eigenvector components are stored in the three-dimensional array EIGV. The eigenvectors (in cycles per second) are stored in the vector EVALUE.

7.3.6 Subroutine SMOOTH

This routine controls the computational phase of the program. It calls subroutines that generate the time series of longitudinal and lateral turbulence, the double multiple stream tube aerodynamic routines and finally the modal decomposition routines.

The meaning of some variable names used in SMOOTH is given below.

IDS	1 or 0:	dynamic stall yes/no
ICL	1 or 0:	column loading yes/no

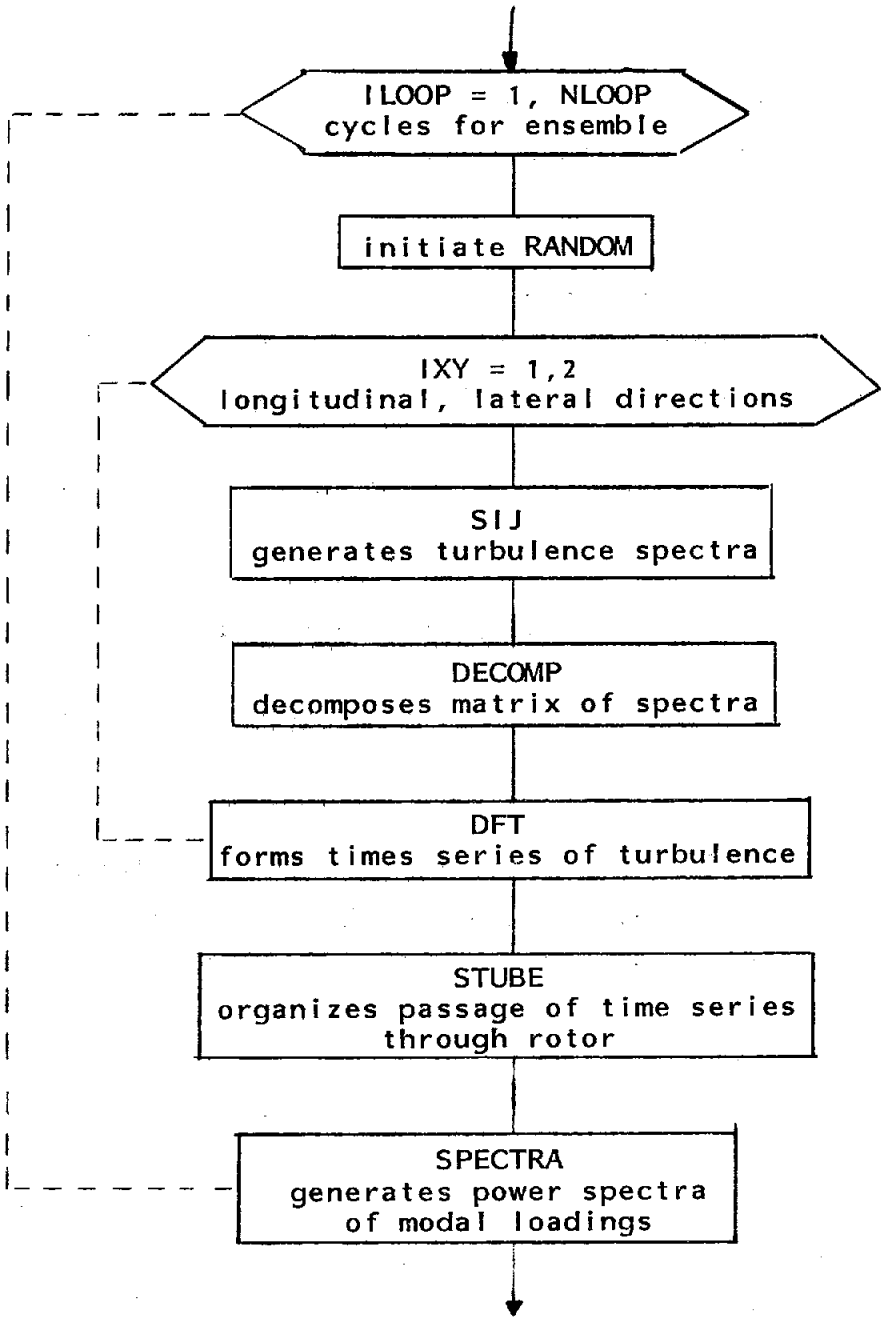


Figure 7.3. Schematic Flowchart of Subroutine SMOOTH

XSEED	seed for random generator
ILOOP	current loop # for ensemble
IOUT	current loop for intermediate printout
IXY	1 or 2: longitudinal/lateral directions

A schematic flow chart of the subroutine is shown in Figure 7.3.

7.3.7 Subroutine SIJ

This routine generates the spectral densities for all of the spatial array points using the subroutine MODEL. It also generates the cross spectra between all points using a real coherence coefficient and formula suggested by Frost et al. and used by P. Veers (17).

A schematic flow chart of the subroutine is given in Figure 7.4 and some internal variables are listed below:

NN	total number of points in spatial array
NSP	total number of auto- and cross-spectra
DELHT	vertical interval in spatial array (in)
DELF	frequency interval in spectral (Hz)
H	current height (in)
V	current mean wind speed (mph)
RMS	variance or rms of spectrum
DIST	distance between two current points (in.)
DX	lateral distance between two current points (in)
DZ	vertical distance between two current points (in)
WORK	working vector of current spectrum, (m/s) /Hz

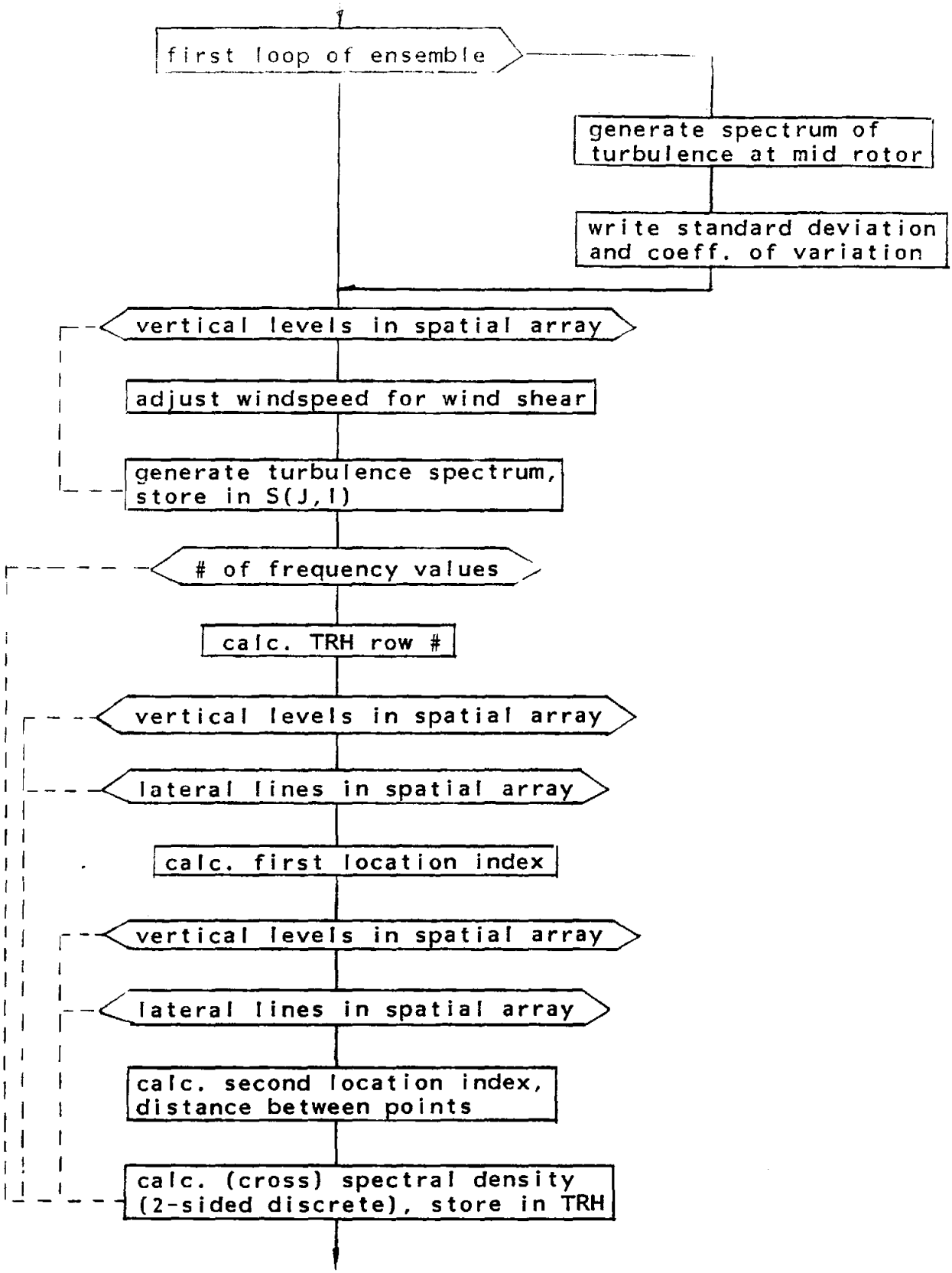


Figure 7.4. Schematic Flowchart of Subroutine SIJ

The spectra that comprise the symmetrix matrix describing the turbulence at the spatial locations and their correlations are stored in the columns of the array TRH. The numbering of these spectra for allocation to the columns of TRH is shown in Figure 7.5.

The elements of the spectra stored in TRH are assumed to be real. They are stored in every second row of the columns so that an imaginary part, generated in DFT, can be added later.

7.3.8 Subroutine MODEL

Subroutine MODEL supplies the formula for the turbulence spectrum. The present formula is that given by Frost (13) and defines the spectrum in S.I. units as a function of frequency, f, (Hz) as

$$S(f) = \frac{C_1 \bar{V} h [\ln (10/Z_0 + 1) \ln (h/Z_0 + 1)]^{-1}}{1 + C_2[hf \ln (10/Z_0 + 1)/\bar{V} \ln (h/Z_0 + 1)]^{5/3}},$$

where $\bar{V}$ = mean windspeed (at 10 m), ZO = roughness length, H = current height, and C1 and C2 are parameters with the following recommended values:

longitudinal turbulence	C1 = 12.3	C2 = 192
lateral turbulence	C1 = 4.0	C2 = 70
vertical turbulence	C1 = 0.5	C2 = 8.0

Arguments

H	current height (in)
V	current windspeed (in/s)
WORK	current spectrum ($(m/s)^2$ /Hz)
IXY	1 or 2: longitudinal/lateral direction

Internal Variables

HM	current height (m)
VM	current windspeed (m/s)
DELF	frequency interval (Hz)

Note that the value corresponding to zero frequency has been omitted and that WORK (1) corresponds to f = DELF*1.

7.3.9 Subroutine DECOMP

This routine decomposes the matrix, S, of (cross) spectra into a lower triangular transfer matrix, H, according to the relationship

$$[S] = [H^T]\,[H].$$

The elements of H are determined by the following recursive formulas:

$$H_{11} = (S_{11})^{1/2}$$

$$H_{21} = S_{21}/H_{11}$$

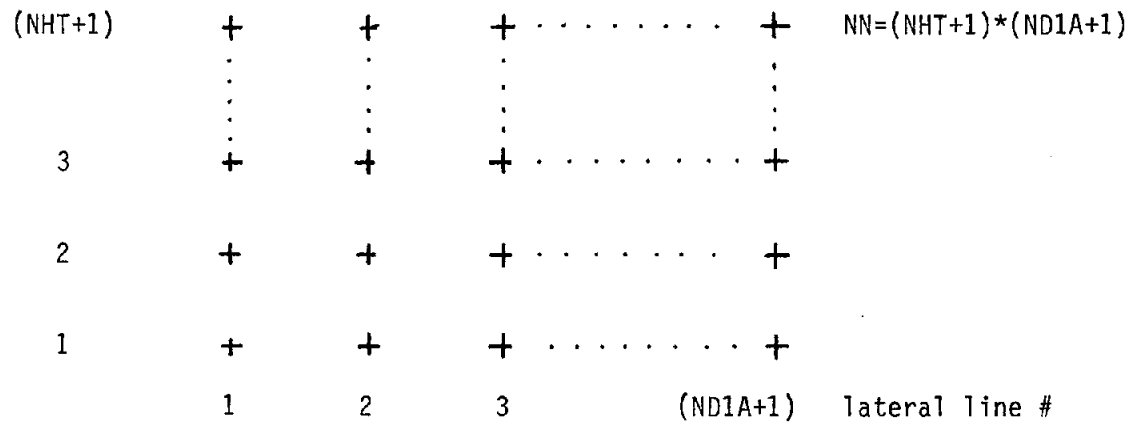
$$H_{22} = [S_{22} - (H_{21})^2]^{1/2}$$

$$H_{31} = S_{31}/H_{11}$$

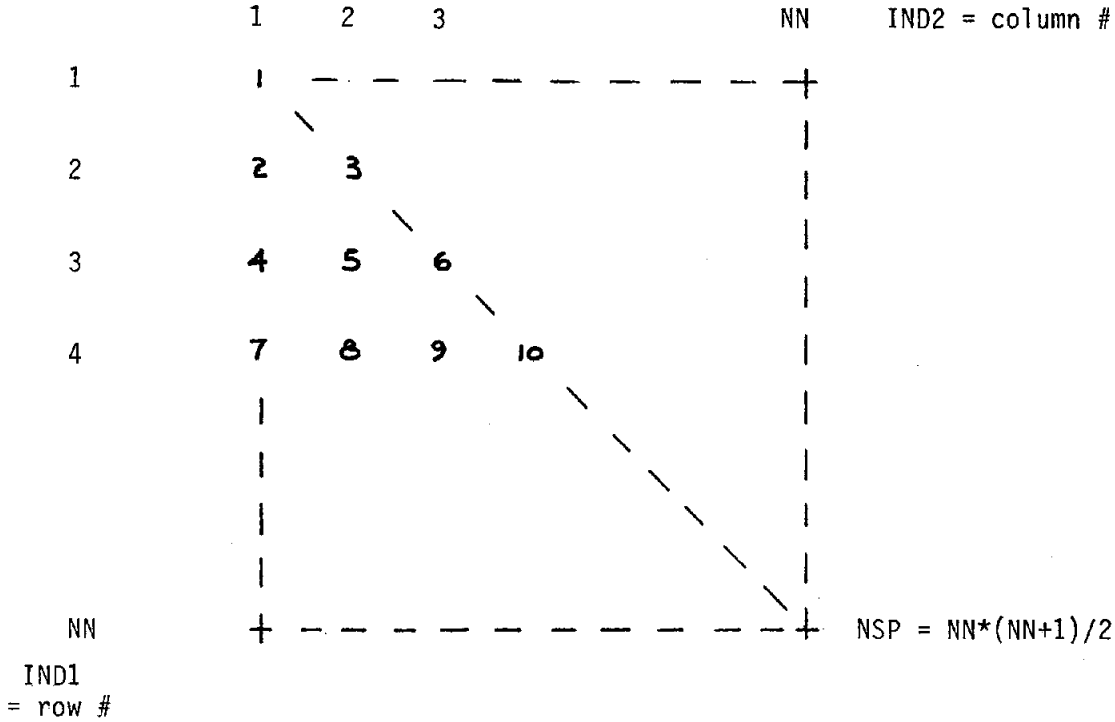
$$H_{32} = (S_{32} - H_{31}H_{21})/H_{22}$$

$$H_{ii} = [S_{ii} - \sum_{j=1}^{i-1} (H_{ij})^2]^{1/2}$$

$$H_{ij} = (S_{ij} - \sum_{k=1}^{j-1} (H_{ik}H_{jk})/H_{jj}$$



Numbering of Locations in Spatial Array



Numbering of Spectra in Matrix TRH

Figure 7.5 Numbering Systems for Spatial Array Locations and Storage of Spectra

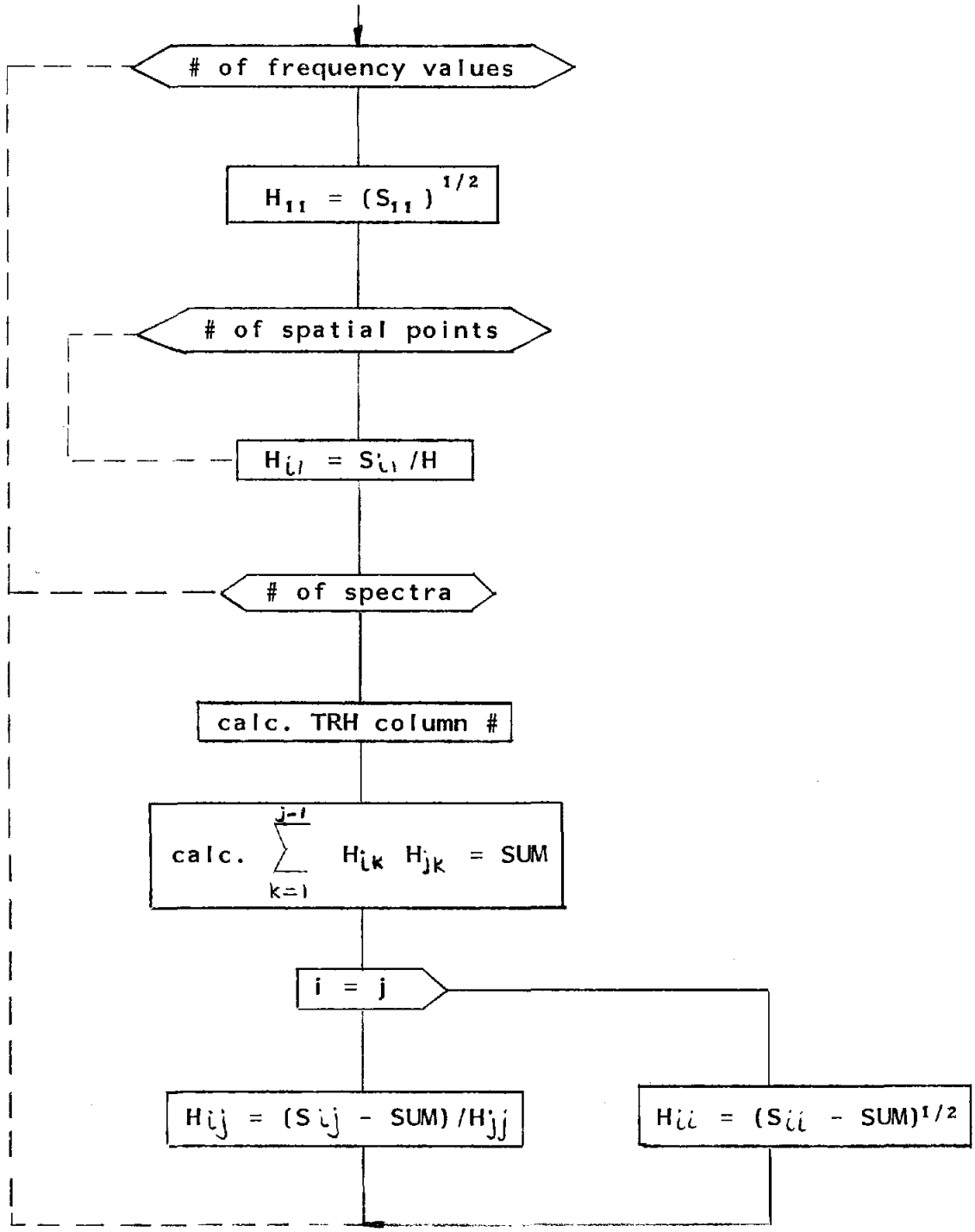


Figure 7.6. Schematic Flowchart of Subroutine DECOMP

The elements of H are also stored in the array TRH and are stored in a manner similar to that illustrated in Figure 7.5.

A schematic flow chart of the subroutine is shown in Figure 7.6.

7.3.10 Subroutine DFT

This routine adds a random phase to each of the spectra of the matrix H (stored in TRH), performs an inverse Fourier transform of each spectrum and obtains the final time series by summing the rows of the transformed matrix. This procedure is used in Veers (17).

A physical interpretation of the matrix, H, is that it acts as a transfer matrix between uncorrelated white noise and the matrix of partially correlated spectra, S, so that the time series is given by

$$V(t) = F^{-1} [(H)(X)] \ (1)$$

where X is a diagonal matrix of white noise of unit variance, and (1) is a column of ones. It is therefore necessary to give a different random phase to each column of the H matrix and, following the Fourier transform, to sum the rows of the resulting matrix.

The schematic flow chart of the subroutine is shown in Figure 7.7.

The routine uses the fast Fourier transform subroutine FFT842, which is described in Section 7.3.12.

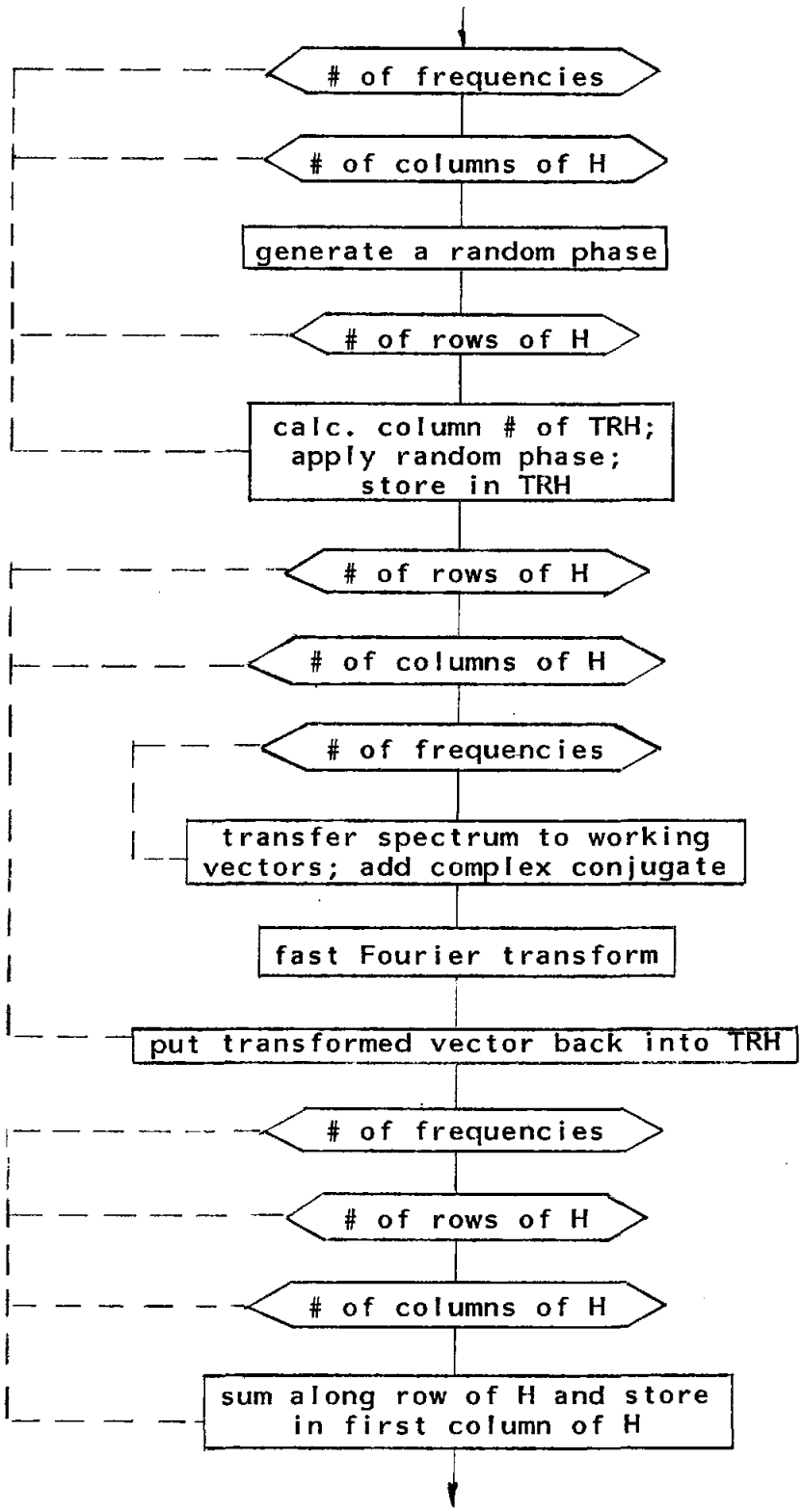


Figure 7.7. Schematic Flowchart of Subroutine DFT

The vectors initially stored in TRH correspond to discrete two-sided spectra and it is therefore necessary to add a complex conjugate to make up the second half of the vector to obtain the correct real-time series.

It should be noted that other Fourier transform routines may differ from FFT842 by a multiple of 2 or of N (the vector length) and should be checked before being substituted.

Some variables used in DFT are listed below:

WORK1, WORK2	real and imaginary parts of a working vector
IND1	row number in matrix H
IND2	column number in matrix H
INDX	column number in array TRH
NN	number of locations in spatial array

7.3.12 Subroutine FFT842

This fast Fourier transform routine was obtained from reference (22). It is a sophisticated algorithm that carries out radix 8 operations before any radix 4 or 2 operations.

A listing of the subroutine is included and the arguments are explained below:

IN = 0 for Fourier transform
= 1 for inverse transform
X real part of input and output vector
Y imaginary part of input and output vector
N size of vector

7.3.13 Subroutine STUBE

This routine is responsible for accessing the aerodynamic model at suitable intervals as the rotor passes through the prescribed number of revolutions and as the pre-stored time series of windspeed passes through the rotor. It also allows calculations of the turbulent wind loading on the central column.

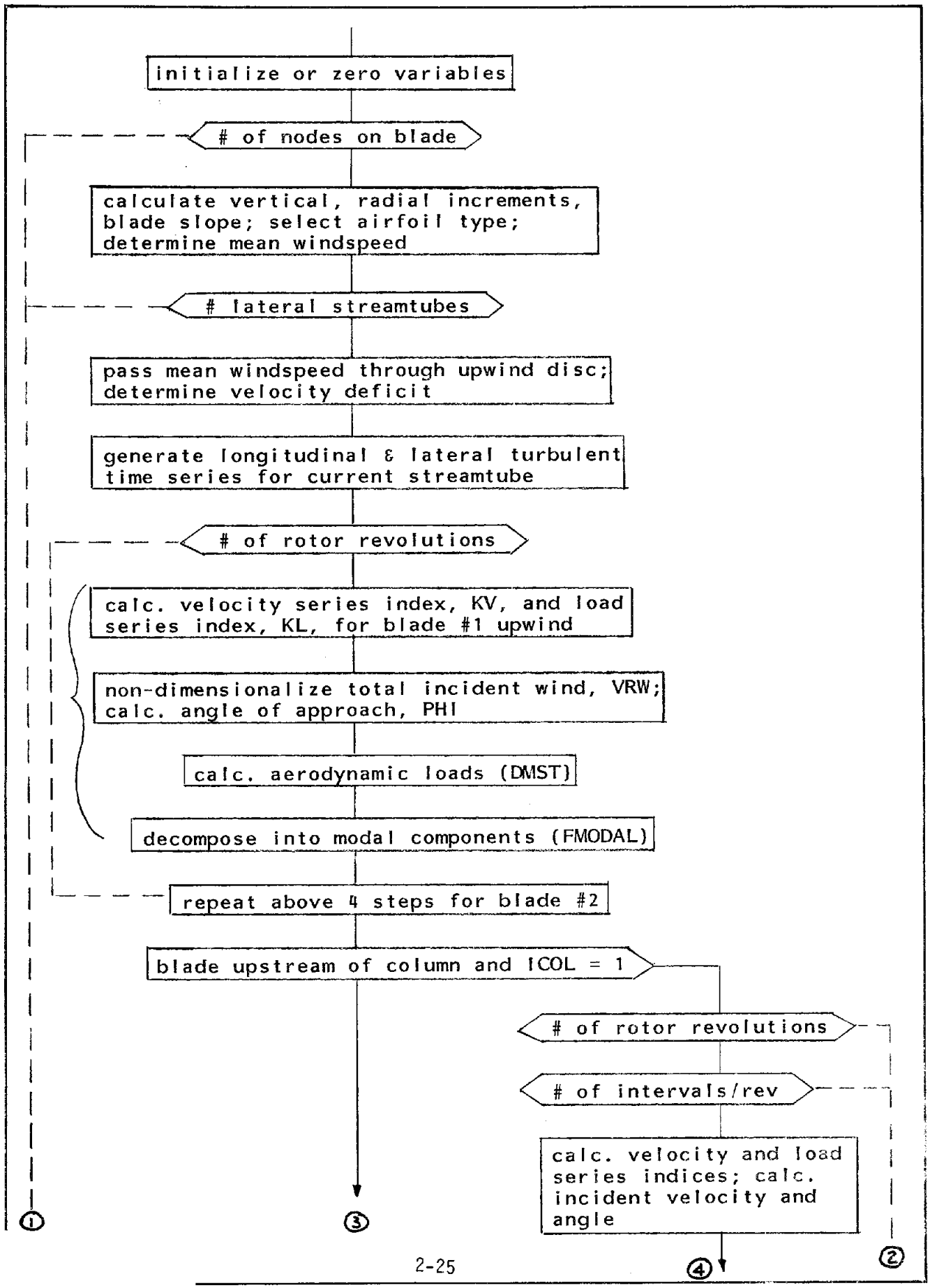
Figure 7.8 shows a schematic flow chart of this routine, and Figure 7.9 indicates the organization of stream tubes and the passage of the velocity time series.

The primary DO LOOP examines the vertical location of the stream tubes corresponding to the finite element nodes of the NASTRAN model. It also allows selection of the airfoil type and the mean wind speed (if vertical wind shear exists).

The second DO LOOP defines the lateral position of the stream tube, which depends on the number of intervals in one rotor revolution and the azimuthal position. It is then necessary to consider how the mean wind speed is affected as it passes through the upwind actuator disk; the accompanying turbulence is assumed to move with the mean wind speed.

The next step is to generate a suitable time series for both longitudinal and lateral turbulence. This is accomplished by a call to subroutine VSERIES which is explained more fully in Section 7.3.17.

The next DO LOOP considers the passage through the specified stream tube of blade #1 and then blade #2 for


initialize or zero variables
# of nodes on blade
calculate vertical, radial increments, blade slope; select airfoil type; determine mean windspeed
lateral streamtubes
pass mean windspeed through upwind disc; determine velocity deficit
generate longitudinal & lateral turbulent time series for current streamtube
# of rotor revolutions
calc. velocity series index, KV, and load series index, KL, for blade #1 upwind
non-dimensionalize total incident wind, VRW; calc. angle of approach, PHI
calc. aerodynamic loads (DMST)
decompose into modal components (FMODAL)
repeat above 4 steps for blade #2
blade upstream of column and ICOL = 1
# of rotor revolutions
# of intervals/rev
calc. velocity and load series indices; calc. incident velocity and angle
1
3
4
2

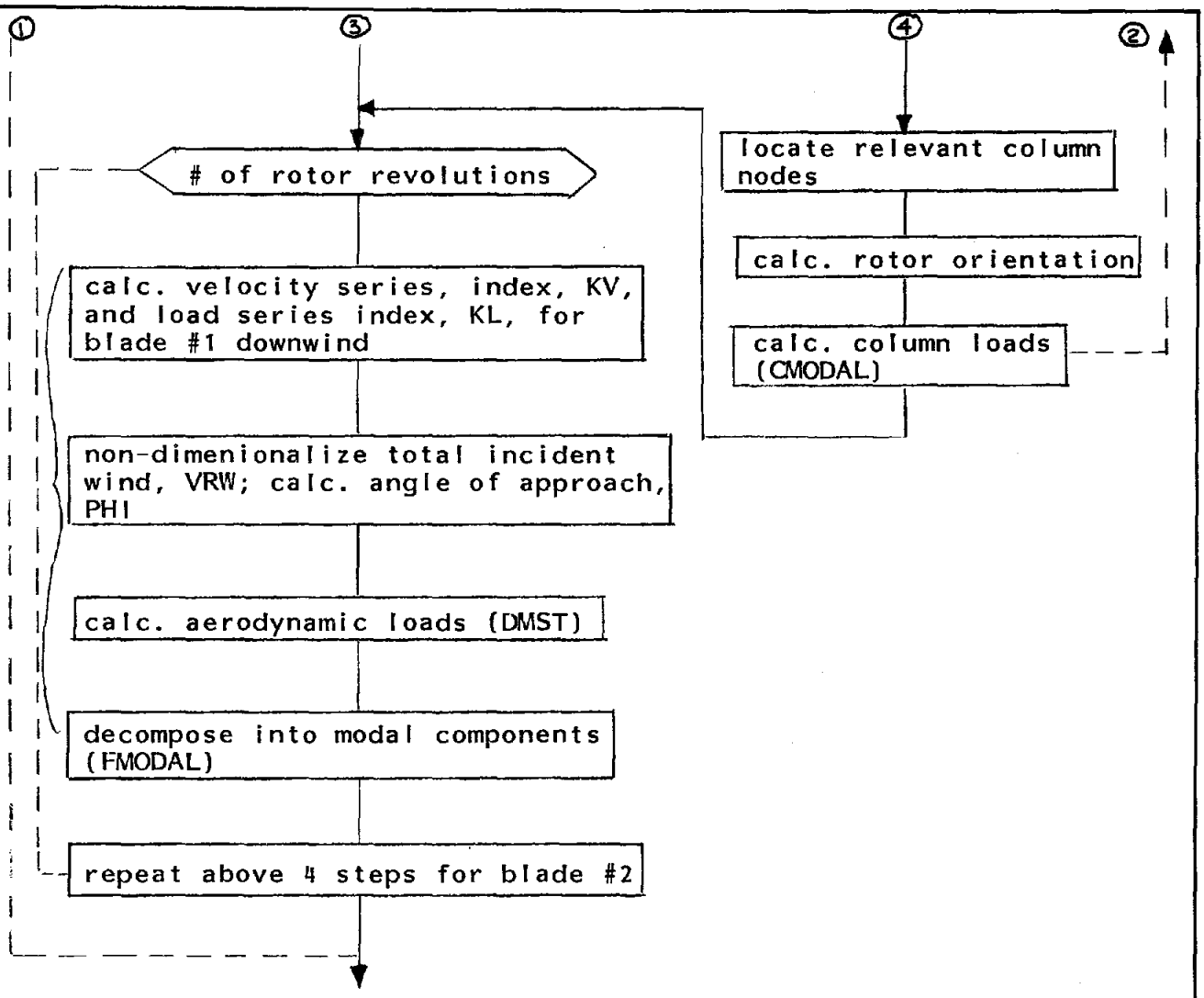


Figure 7.8. Schematic Flowchart of Subroutine STUBE

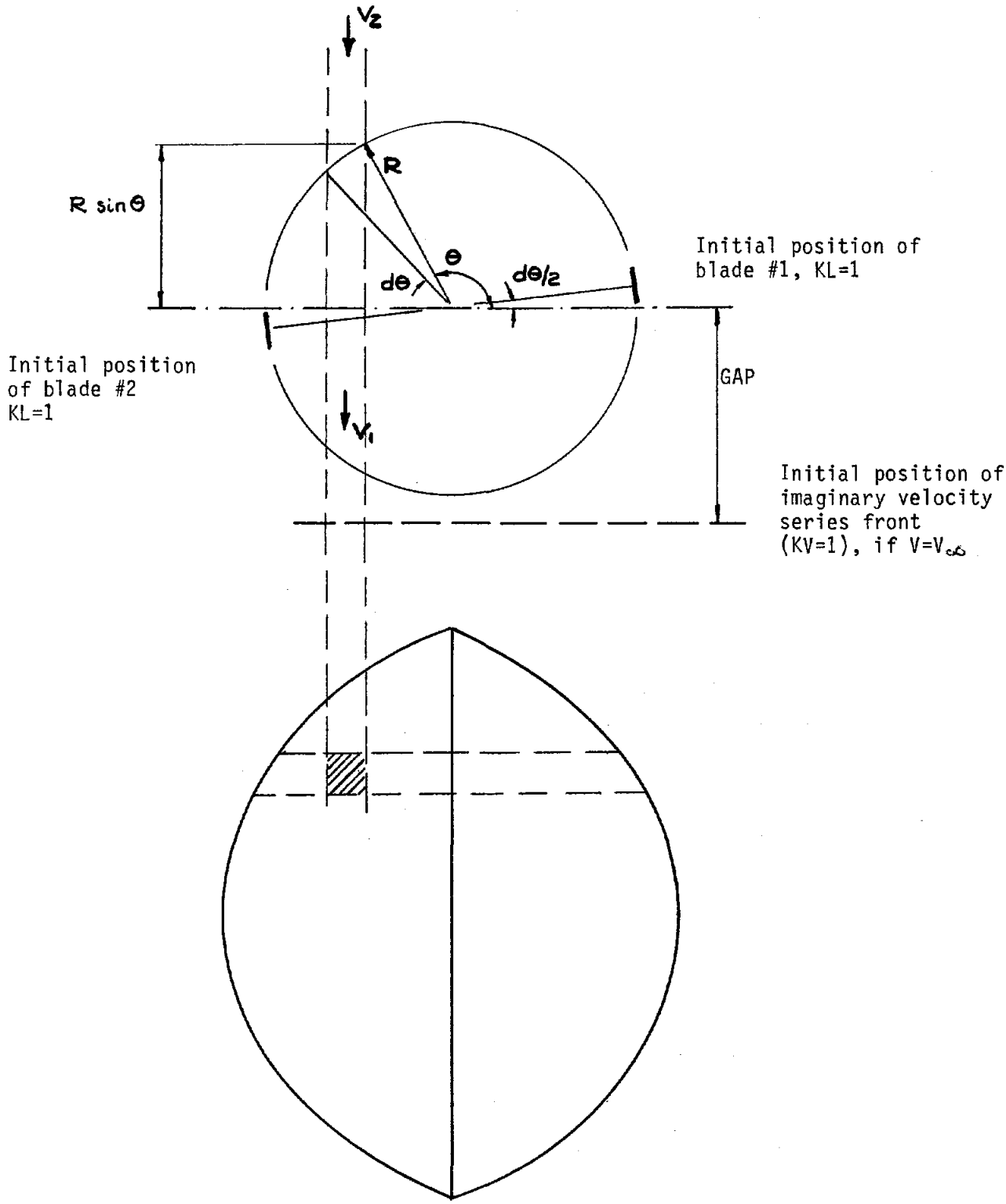


Figure 7.9 Arrangement of Streamtubes and Passage of Wind through Rotor

each of the required number of revolutions. For blade #1 at the upwind actuator disk, the load series index that defines the position in the loading time series is given by

$$KL = (IREV - 1)\frac{2\pi}{d\theta} + \frac{\theta}{d\theta},$$

where IREV = the current rotor revolution number.

The identification of the wind speed time-series index is based on the concept of a wavefront which, in the absence of the rotor, would initially be a distance GAP downstream from the centre of the rotor. Figure 7.9 illustrates this concept. This wavefront and the associated series of turbulent velocities is considered to move downwind with the ambient mean wind speed, V . It is, therefore, possible to calculate which element of the time series is located at the upwind actuator disk at any specified time; the windspeed index KV for blade #1 is then given by

$$KV = \frac{GAP + R\sin\theta + t\,\bar{V}_z}{\bar{V}_z\,\Delta T},$$

where $t = \theta/\Omega$

and where Ω = rotor speed, ΔT = DELT = time interval for time series. For blade #2, the angle is increased by 180°.

A similar calculation is carried out for blades passing through the downstream actuator disk. However,

the actual mean velocity of the air within the rotor is less than the ambient mean and correction must be made for this period of lower velocity. For blade #1 passing through the downstream disk

$$KV = \frac{GAP - R \sin\theta + t\,\bar{V}_z - 2R \sin\theta\,(\bar{V}_z/V_1 + 1)}{\bar{V}_z\,\Delta T},$$

where V_1 = mean wind speed within the rotor.

At each actuator disk, the mean wind speed is combined with the longitudinal and lateral turbulence to produce a total incident wind speed and its angle of incidence, ϕ. This information is passed through common block AERO to the subroutine DMST, which calculates the aerodynamic forces on the blade (see Section 7.3.14).

The call to subroutine FMODAL transforms the aerodynamic loads in physical coordinates for the current stream tube, actuator disk and rotor revolution, into their contribution to the modal coordinate load time series (see Section 7.3.18).

If the upstream actuator disk is immediately upwind of the central column, then the aerodynamic loading on that column is calculated (if ICL = 1). The current index of the load series, KL, and the index of the turbulent time series are calculated in a manner similar to that for the blades. Likewise, the combined magnitude and direction of the mean wind speed and turbulent components are calculated so that the magnitude and direction of the column load may be calculated. This drag-per-unit length of column in the X-and Y-directions of the rotating frame is given by

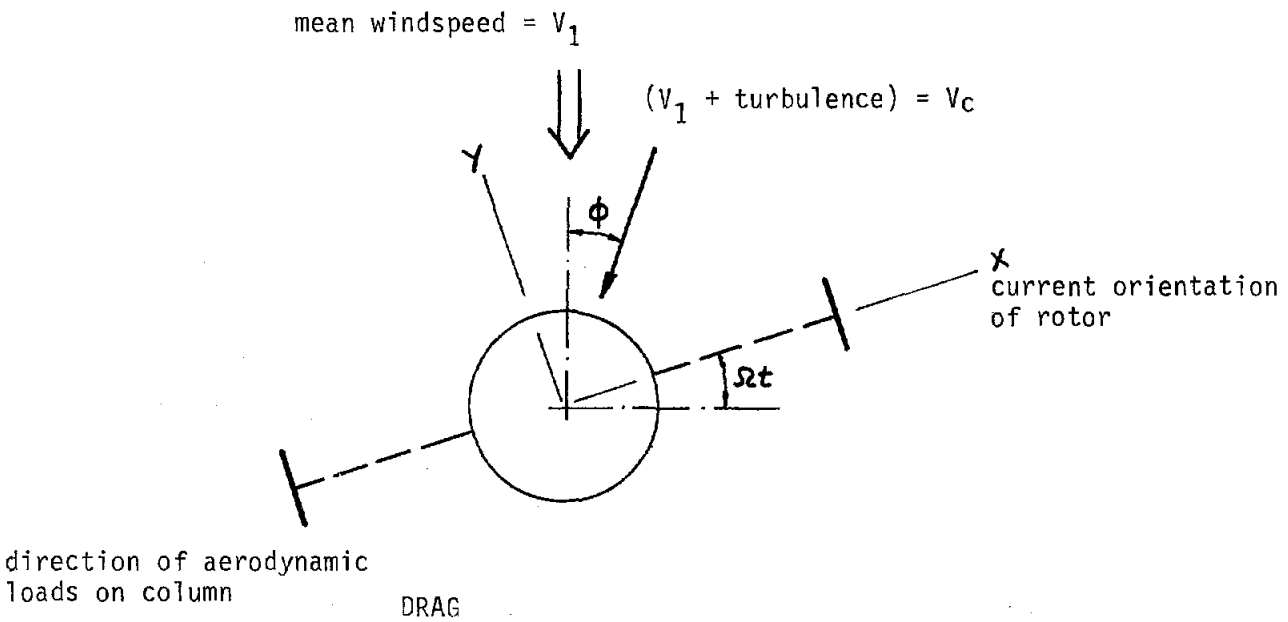


Figure 7.10 Aerodynamic Loading of Central Column

$$DRAG(X) = -Cd*diameter*V_c^2*\sin(\Omega t+\phi)*1/2*\rho$$

$$DRAG(Y) = -Cd*diameter*V_c^2*\cos(\Omega t+\phi)*1/2*\rho$$

where V_c is the current wind speed at the column, and ϕ is the angle of incidence, as indicated in Figure 7.10. The value of the drag coefficient, Cd, is 1.0 at present.

Once the nearest column node has been located, the physical loads are transformed into contributions to the modal load time series in subroutine CMODAL (see Section 7.3.19).

A list of some of the internal variables used in STUBE is given below.

GAP	initial position of imaginary wave front; it has been set = 1 rotor diameter
NL	total length of load time series
DZ	vertical width of current stream tube
KK	current airfoil type number
INIT	= 0 for first application of DMST to stream tube
	= 1 for subsequent application of DMST to stream tube
ITURB	= 0 for no turbulence
	= 1 for turbulence
IREV	current rotor revolution number
KV	current index of velocity time series
KL	current index of loading time series
II	current vertical stream tube location
JJ	current lateral stream tube location

7.3.14 Subroutine DMST

Subroutine DMST calculates the aerodynamic forces

on the current blade and stream tube. It is based on the double multiple stream tube with dynamic stall, as proposed by Templin (6). The version included in this program incorporates modifications to accept the direction changes resulting from lateral turbulence and modifications to the dynamic stall calculation.

A schematic flow chart of the subroutine is shown in Figure 7.11 and a diagram of the flow through the rotor is included as Figure 7.12. It can be shown that the effective wind velocity relative to the (upwind) blade is

$$V_R^2 = (R\Omega + V \cos\beta)^2 + (V \sin\beta \cos\delta)^2, \qquad (1)$$

where $\beta = \theta + \phi$,

and where V = current wind velocity, ϕ = orientation of current wind velocity and δ = inclination to the vertical of the blade. For the downwind blades ($+\phi$) becomes ($-\phi$).

The theory of the momentum balance at the actuator disk may be found in references such as Templin (6) where it is shown that the ambient windspeed, V_∞, the disk windspeed, V, and the downstream windspeed, V_1, are related by

$$\frac{V_\infty}{V} = 1 + C_{DD}/4, \qquad (2)$$

$$\frac{V_1}{V} = 1 - C_{DD}/4 \qquad (3)$$

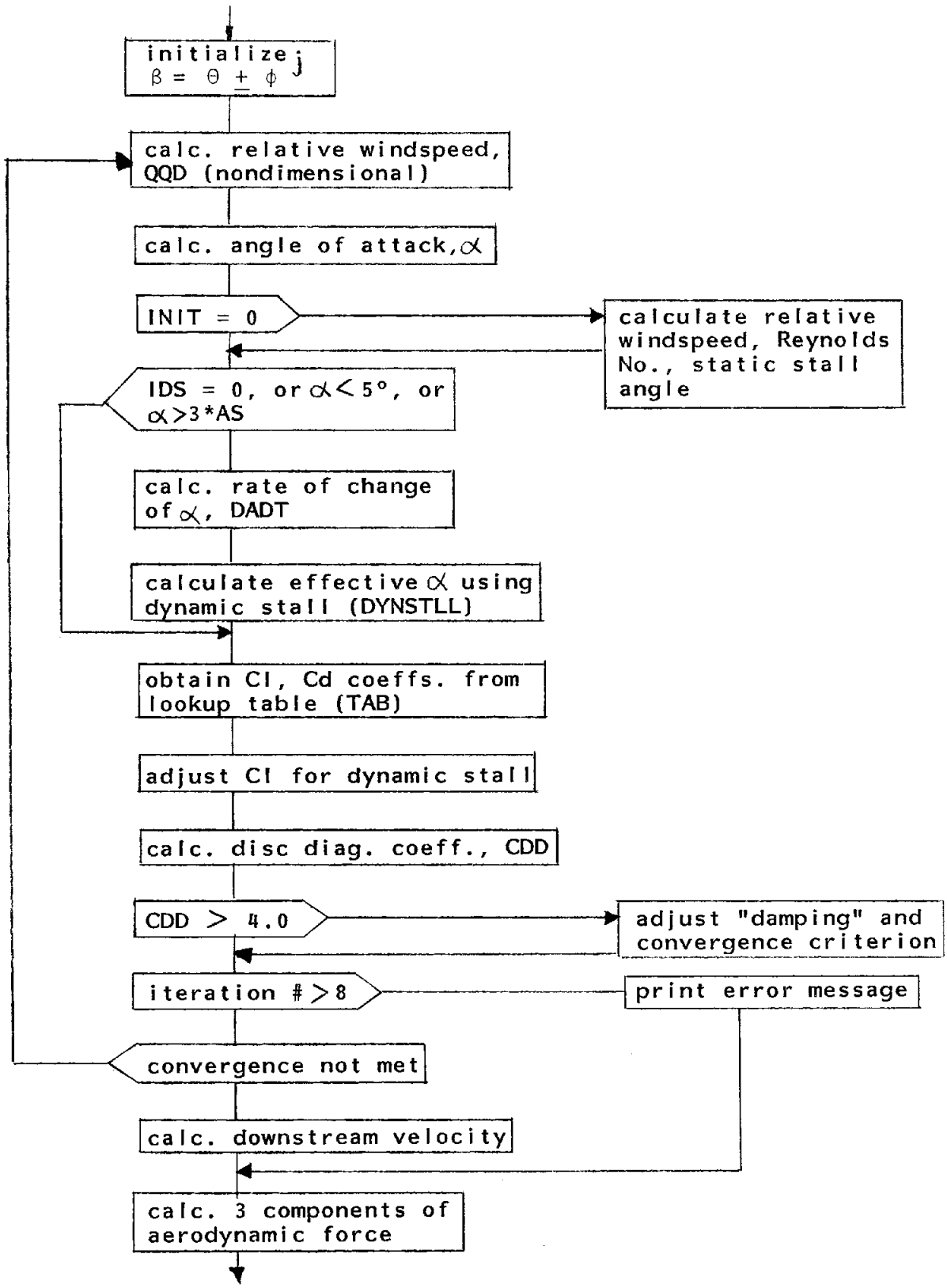


Figure 7.11. Schematic Flowchart of Subroutine DMST

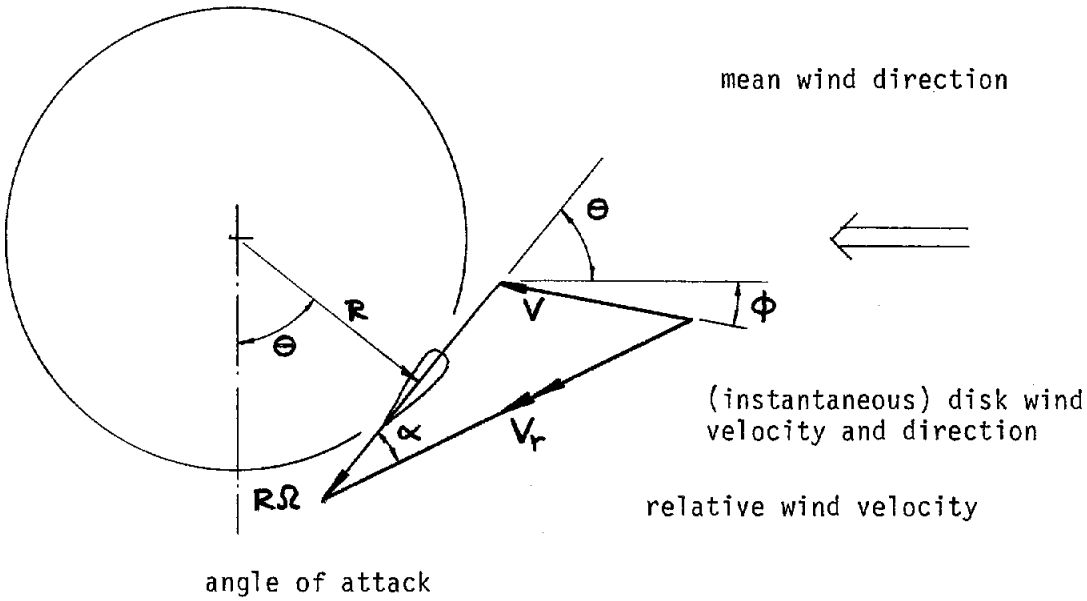


Figure 7.12 Velocity Vectors at Actuator Disk

where CDD, the disk drag coefficient is defined as

$$C_{DD} = (\text{total drag})/(\tfrac{1}{2}\rho V^2 A), \tag{4}$$

and the total drag is obtained from a resolution of the aerodynamic blade forces.

These equations must be solved by an iterative process. In subroutine DMST, an initial value of V = 0.9V is used and convergence is complete when Eq. (2) above is satisfied. A maximum of eight iterations is allowed to achieve adequate convergence.

For low ambient wind speeds, the numerical solution can easily become unstable and hence a "damping factor", DMP, is introduced. This factor initially has the value of 0.75 but it is reduced if, in the course of the solution, CDD > 4.

Dynamic stall is a phenomenon that, due to unsteady effects, delays stall beyond the static stall angle when the angle of attack is increasing. In a similar manner the lift coefficient can be depressed when the angle of attack is decreasing. References are given in Section 7.3.16.

To predict the extent of dynamic stall, it is necessary to calculate the rate of change of the angle of attack, $d\alpha/dt$. This may be accomplished by noting from Figure 7.12 that

$$\tan \alpha = \frac{V \sin(\theta + \phi) \cos\delta}{R\Omega + V \cos(\theta + \phi)}.$$

Differentiation of this expression is made more complicated by the variable nature of V and ϕ as well as θ but leads finally to

$$\frac{d\alpha}{dt} = \frac{(\Omega + \dot{\phi}) \left[\frac{R\Omega}{V} \cos(\theta + \phi) + 1\right] \cos\delta + \dot{V} \cos\delta \sin(\theta + \phi) \frac{R\Omega}{V^2}}{\left[\frac{R\Omega}{V} + \cos(\theta + \phi)\right]^2 + [\sin(\theta + \phi) \cos\delta]^2}.$$

The values of $\dot{V}$ and $\dot{\phi}$ may be evaluated using a finite difference expression of the kind

$$\dot{V}_k = \frac{V_{k+1} - V_{k-1}}{2\ \Delta T},$$

where V_{k+1} and V_{k-1} are the values of the velocity magnitude "upstream" and "downstream" of the current time series value. These values must be adjusted for the decrease between the velocity upstream of the disk and the disk velocity.

Once $d\alpha/dt$ has been calculated, a call is made to subroutine DYNSTLL (see Section 7.3.16) which returns a "reference" angle of attack used in adjusting the final lift coefficient. The reference angle is the angle used by subroutine TAB to look up appropriate values of Cl and Cd for the current airfoil type and Reynolds number.

List of Argument Variables

ISIGN	= 1 for upstream blade, = -1 for downstream blade
II	current vertical index for stream tube location
JJ	current lateral index for stream tube location
KK	index of current airfoil type
KV	index of current velocity series value
ITURB	= 0 for no turbulence, = 1 for inclusion of turbulence

INIT	= 0 for first iteration, = 1 for subsequent iterations
IDS	= 0 for no dynamic stall, = 1 for inclusion of dynamic stall

Partial List of Internal Variables

DMP	"damping" to assist convergence of iterative solution
CRIT	convergence criterion
IC	iteration count number
BETA	= $\theta + \phi$ (upstream blade), = $\theta - \phi$ (downstream blade)
QQD	(ratio of relative windspeed to disk windspeed) **2
ALPH	angle of attack (radians)
VR	relative windspeed (in/s)
CL	lift coefficient
CD	drag coefficient
CDD	disk drag coefficient
VRW	upstream windspeed (non dimensionalized)
VDRW	disk windspeed (non dimensionalized)
VIRW	downstream windspeed (non dimensionalized)
FNODE(1)	X direction (in-plane horizontal) force on blade node
FNODE(2)	Y direction (out-of-plane vertical) force on blade node
FNODE(3)	Z direction (in-plane vertical) force on blade node

7.3.15 Subroutine TAB

This subroutine accesses the appropriate stored airfoil data and interpolates to obtain the correct lift and drag coefficients for the current angle of attack and for the current Reynolds number. A schematic flow chart is shown in Figure 7.13.

For all but the first iteration at a particular streamtube, the program uses the previously calculated Reynolds number and set of possible Cl and Cd values (DSET1). For initial iterations, the routine checks for Reynolds numbers outside of the tabulated range and, if necessary, allocates the highest or lowest Reynolds number that is tabulated. There is no extrapolation of tabulated values.

The selection of lift and drag coefficients for the current angle of attack is done by linear interpolation.

List of Arguments

ALPHR	current angle of attack
CL	lift coefficient (output)
CD	drag coefficient (output)
CDM	current Cd (min) for zero angle of attack
INIT	= 0 for initial iteration, = 1 for subsequent iterations
KK	index of airfoil type

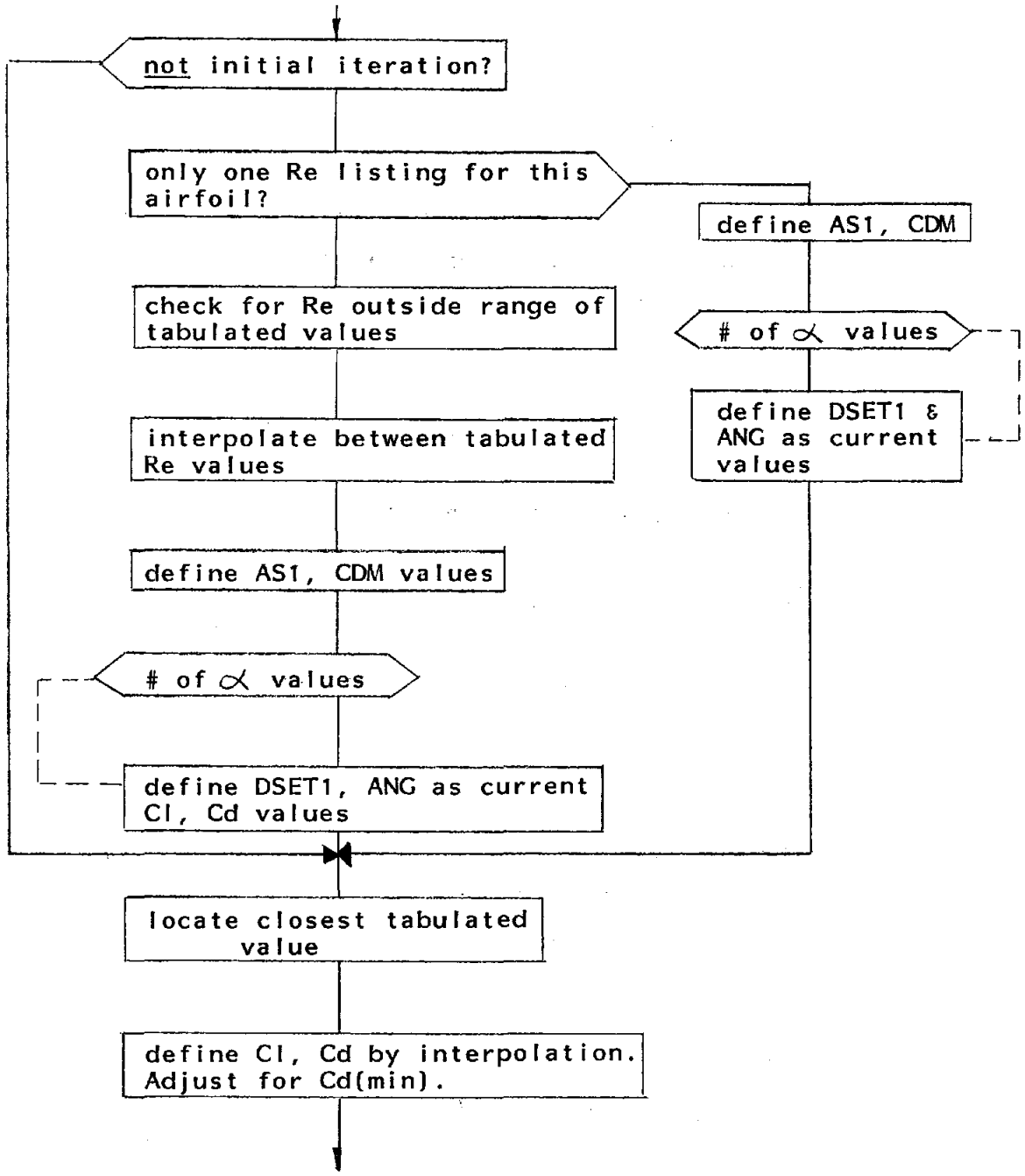


Figure 7.13. Schematic Flowchart of Subroutine TAB

7.3.16 Subroutine DYNSTLL

Subroutine DYNSTLL uses a Masse-Templin modification of the Gormont (23) dynamic stall model to adjust lift coefficients for the varying nature of the angle of attack.

The effect of dynamic stall and the method of calculating it are illustrated in Figure 7.14. The delay, $\Delta\alpha$, of dynamic stall is given by

$$\Delta\alpha = \gamma_1 S_{crit} + \gamma_2 (S - S_{crit}),$$

where γ_1 and γ_2 are determined experimentally, and

$$S = \sqrt{\frac{c\dot{\alpha}}{2 V_R}},$$

where c = blade chord, $\dot{\alpha}$ = rate of change of angle of attack and V_R = relative wind velocity. S_{crit}, γ_1 and γ_2 vary with the thickness/chord ratio, t/c, and the Mach number, M, according to

$$S_{crit} = 0.06 + 1.5\ (0.06 - t/c)$$
$$\gamma_2 = \gamma_{2max} = 1.4 - 6.0\ (0.06 - t/c) \quad \text{for } M < M_1$$
$$\gamma_2 = 0 \quad \text{for } M > M_2$$
$$M_1 = 0.4 + 5.0\ (0.06 - t/c)$$
$$M_2 = 0.9 + 2.5\ (0.06 - t/c)$$
$$\gamma_1 = \gamma_2 / 2$$

and γ_2 is given by linear interpolation between $M = M_1$ and $M = M_2$.

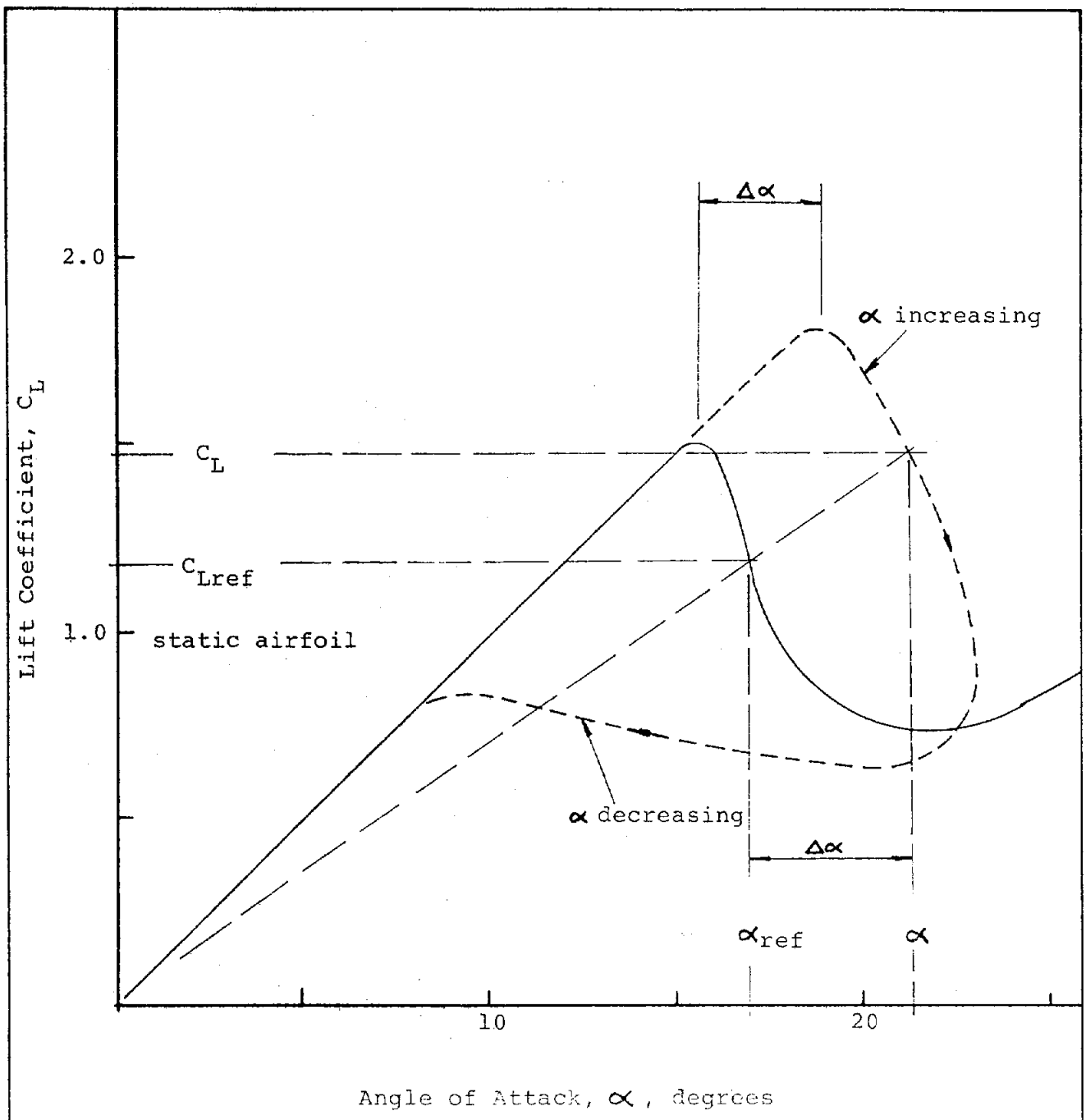


Figure 7.14 Typical Lift Coefficient vs. Angle of Attack and the Influence of Dynamic Stall

For t/c values used in Darrieus rotors it was found that S usually has negative values according to the above expression. This was considered unrealistic and S has, therefore, been put equal to zero in the program.

The reference angle of attack is calculated from

$$\alpha_{ref} = \alpha - k\ \Delta\alpha,$$

where has the value of +1.0 for increasing values of and -0.5 for decreasing values. The Masse-Templin modification considers that the Gormont treatment of dynamic stall is inapplicable to large angles of attack. The present routine assumes that dynamic stall is zero at angles of attack greater than 3.0 times the static stall angle. Between these two values the effect is decreased in a linear manner.

List of Arguments

DADT	rate of change of angle of attack (radians/s)
CH(KK)	current chord value (in)
ALPH	current angle of attack (radians)
ALPHR	reference angle of attack returned by DYNSTLL
KK	current airfoil type no.
TC(KK)	current airfoil aspect ratio

7.3.17 Subroutine VSERIES

This routine selects the appropriate time series for longitudinal and lateral turbulence for the current stream tube from the available spatial array of time series. The current version of the routine selects the

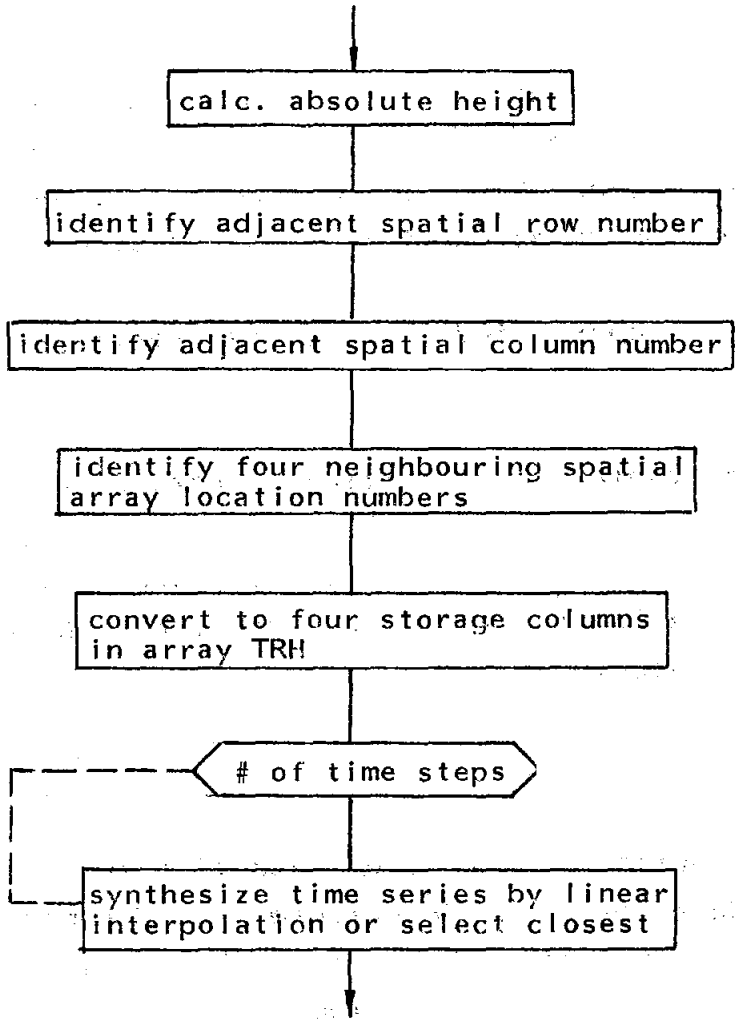


Figure 7.15. Schematic Flowchart of Subroutine VSERIES

time series of that spatial point that is closest to the particular stream tube. Alternatively, a process of linear interpolation between the time series associated with the four neighboring points may be used; however, this process will reduce the rms, especially if the turbulence is uncorrelated and a coarse spatial array is used.

The horizontal and vertical coordinates of the stream tube are used to identify the four neighboring spatial array points (see Figure 7.5) and their corresponding storage locations in the array TRH. The closest point is then selected.

7.3.18 Subroutine FMODAL

This routine is called each time that physical loads on blade #1 or 2 are determined. It decomposes the physical loads into contributions to the modal (generalized) time-series vectors according to the relationship

$$P(t) = \phi^T p(t).$$

List of Arguments

IBLADE	= 1 for blade #1, = 2 for blade 2
II	blade node no.
KL	index for loading time series

7.3.19 Subroutine CMODAL

Subroutine CMODAL calculates the contributions to the modal (generalized) load vectors of the physical

loads on the central column. The load corresponds to the current stream tube (that passes through the central column) and is apportioned between the two neighboring column nodes.

The same transformation relationship as given in 7.3.18 is used in this routine.

List of Arguments

II	blade node number
KV	index for velocity time series
KL	index for load time series
IC	adjacent column node number
PRESS	dynamic air pressure
THETAC	angle describing current orientation of rotor
PHIC	angle to which turbulent airstream differs from longitudinal

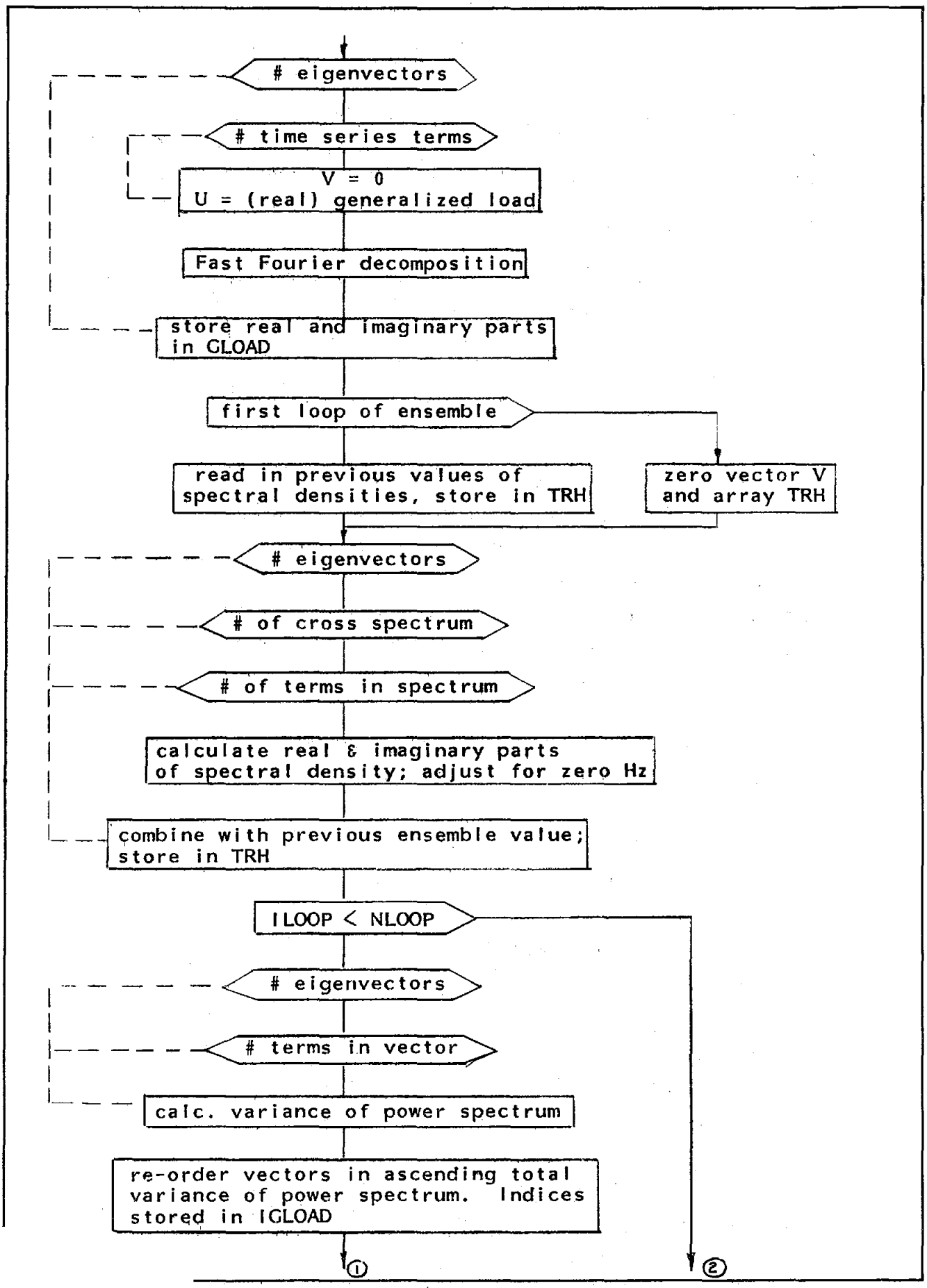
The loads in the in-plane and out-of-plane directions are calculated from (see Figure 7.10):

$$\text{in-plane} = \text{DRAG} \sin(\theta + \phi)$$
$$\text{out-of-plane} = \text{DRAG} \cos(\theta + \phi).$$

7.3.20 Subroutine SPECTRA

This subroutine transforms the time series of generalized loads into the frequency domain and prepares them in spectral density form for later printing. A schematic flow chart is shown in Figure 7.16.

The time series is purely real and of length NL. The resulting Fourier transforms are stored in the same


# eigenvectors
# time series terms
V = 0
U = (real) generalized load
Fast Fourier decomposition
store real and imaginary parts in GLOAD
first loop of ensemble
read in previous values of spectral densities, store in TRH
zero vector V and array TRH
eigenvectors
of cross spectrum
# of terms in spectrum
calculate real & imaginary parts of spectral density; adjust for zero Hz
combine with previous ensemble value; store in TRH
ILOOP < NLOOP
eigenvectors
terms in vector
calc. variance of power spectrum
re-order vectors in ascending total variance of power spectrum. Indices stored in IGLOAD
1
2

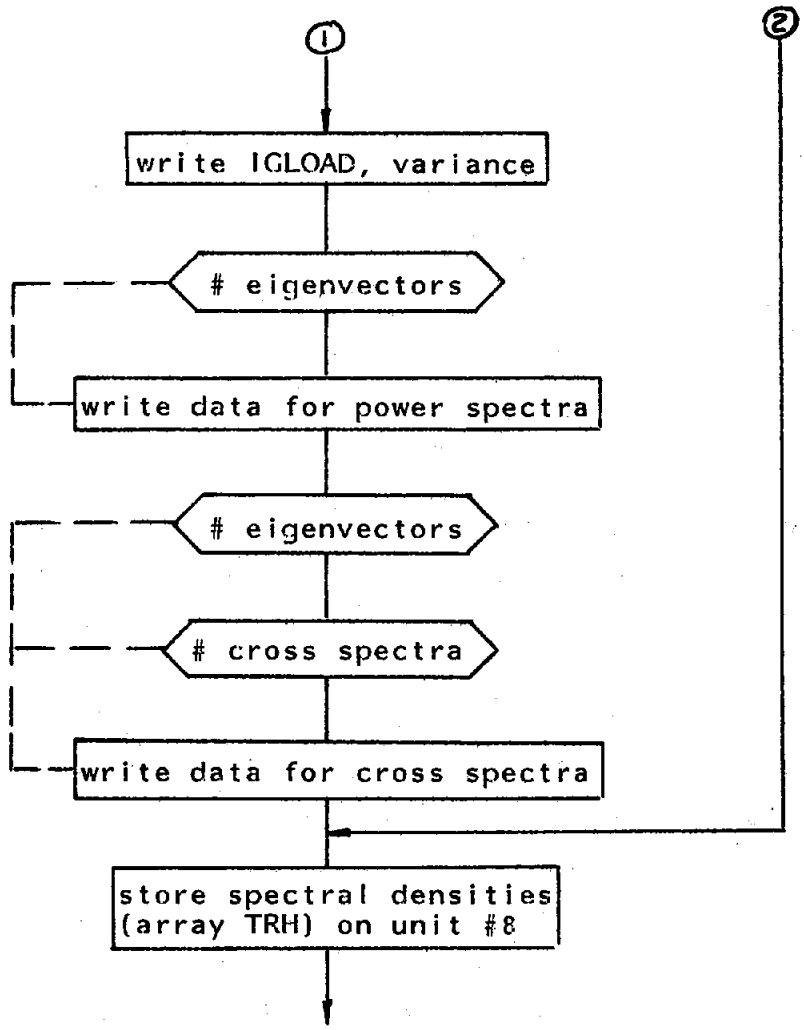


Figure 7.16. Schematic Flowchart of Subroutine SPECTRA

vectors (GLOAD) with the real and imaginary parts of the first half (length NL/2) occupying alternating spaces.

The terms of the spectral density matrix are formed according to

$$S_{xy} = Y^{*}X,$$

where X and Y are the Fourier transforms of the vectors x and y respectively, and * denotes a complex conjugate. In this manner, the upper triangle of the matrix S is formulated and is stored in the matrix TRH.

The correlation coefficient of cross-spectral terms formed in this manner is always unity, and in order to obtain a statistically valid spectral density it is necessary either to average neighboring values or to average the values from an ensemble of spectra. The present program uses the second method so that the currently calculated spectral densities are added to the mean of the previous spectra.

The remaining sections of subroutine SPECTRA are performed only following the last ensemble loop. First, the generalized coordinates are reordered according to the total variance of their associated power spectral densities. The new order is stored in the vector IGLOAD. This reordering allows later deletion of those coordinates associated with the lowest loading spectra.

The final sections are not necessary but organize output concerning the relative magnitude of the random and deterministic components.

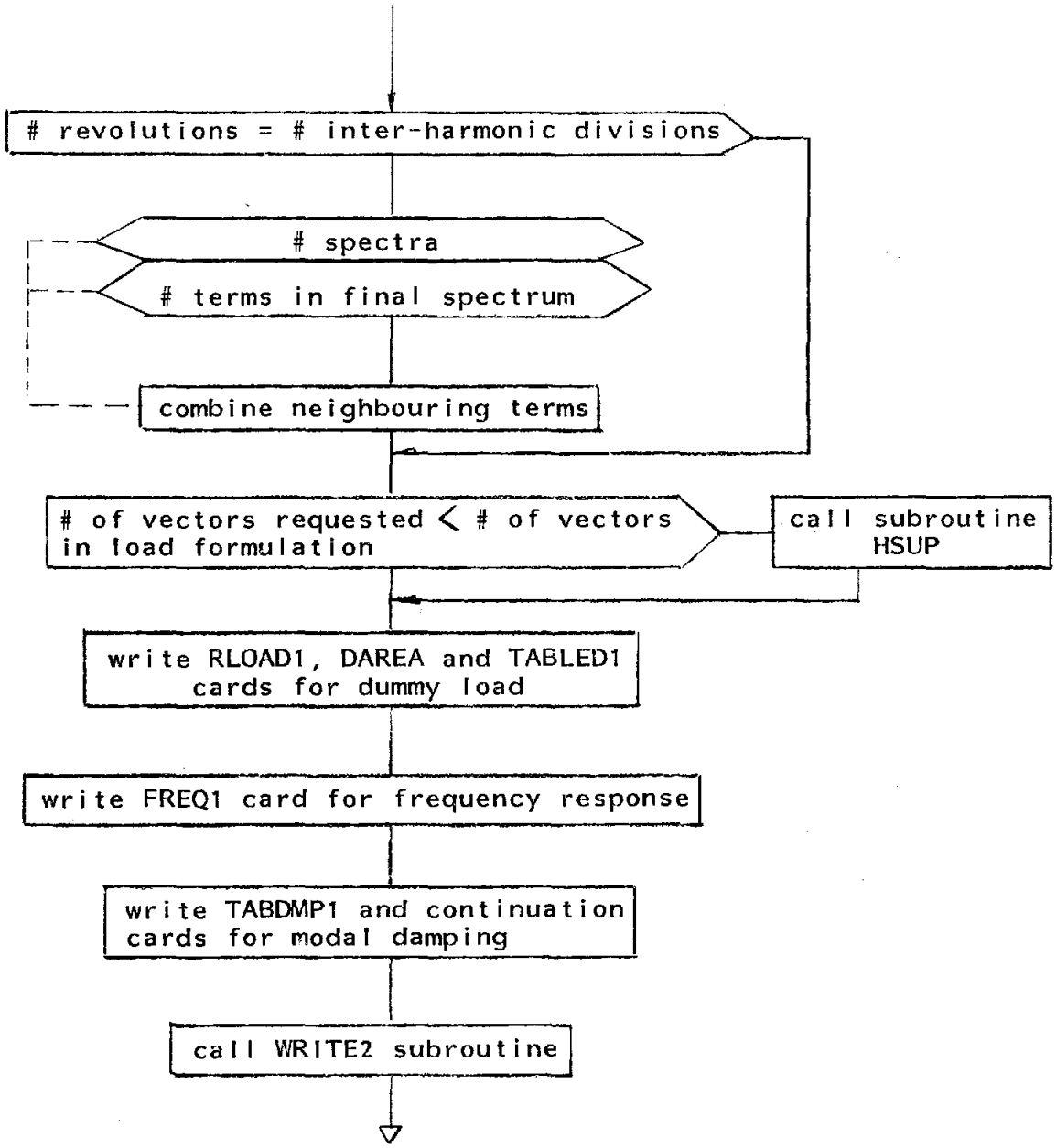


Figure 7.17 . Schematic Flowchart of Subroutine WRITE1

List of Arguments and Important Parameters

ILOOP	counter of no. of ensemble loops
IOUT	counter for determining output of ensemble
NL	length of time series
NSP	number of spectral densities generated

7.3.21 Subroutine WRITE1

This routine formulates some of the required NASTRAN input cards and calls other routines that prepare the remaining cards. A schematic flow chart is shown in Figure 7.17.

If NDIV, the number of divisions to be used between harmonic frequencies in the NASTRAN solution is less than NREV, the number of existing intervals in the current spectra, then some condensation of each spectrum is required. This is done by combining an appropriate number of the neighboring discrete spectral terms into one term. The only term not affected is the initial (zero frequency) term.

It should be noted that both NDIV and NREV must be powers of 2.

If the number of eigenvectors requested for the NASTRAN solution (NVECT) is less than the number of eigenvectors used in the load formulation (NEIG) then certain modes are suppressed by a call to subroutine HSUP (see Section 7.3.23).

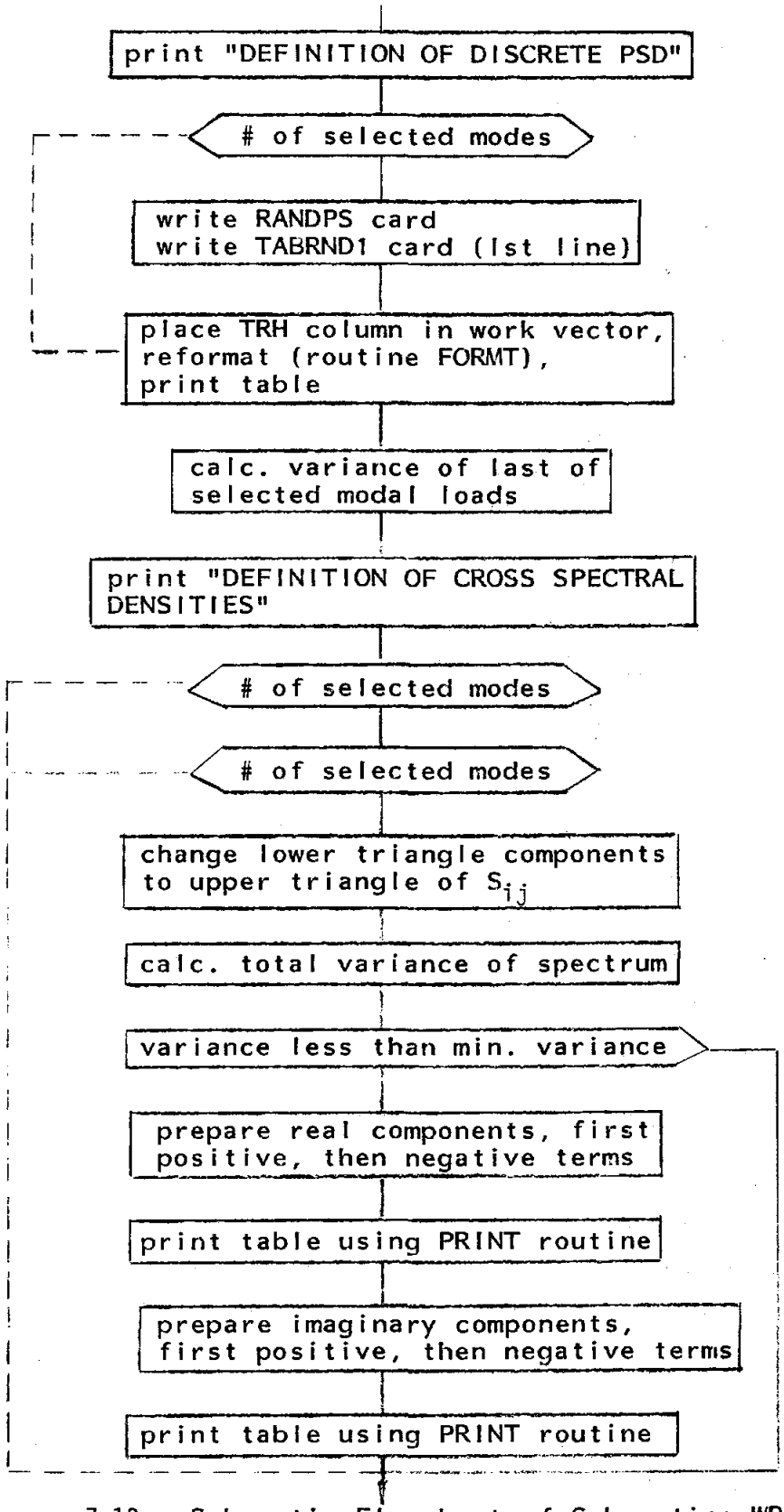


Figure 7.18. Schematic Flowchart of Subroutine WRITE2

7.3.22 Schematic WRITE2

This subroutine prepares the power and cross-spectral densities in an appropriate NASTRAN format. A schematic flow chart for this routine is included as Figure 7.18.

The spectra are prepared in the format required by the RANDPS and the TABRND1 cards. The former identifies the random-loading set number and the values of X and Y in the expression

$$S_{ab}(f) = (X + iY)\ G(f),$$

and TABRND1 gives the look-up table for G(f).

A power spectral density has only real positive values so that the value of Y is always zero. However, cross-spectral densities may in general be complex and of any phase, so that it is necessary to input the real and imaginary parts in separate tables.

Although the NASTRAN manual does not mention it, the values listed in the table of TABRND1 must be positive; any negative values will be interpreted as zero. It is, therefore, necessary to separate both real and imaginary parts into positive and negative contributions and to input them in separate tables (associating an appropriate negative sign with X or Y on RANDPS).

A more general limitation of NASTRAN input format is that use of the 8-character field length limits values in exponential format to three significant numbers. This

may be increased to four significant numbers if the "E" of the exponential form is removed. This is carried out by calls to the subroutine FORMT.

Before being included in the output, the total variance of a cross-spectral density is calculated. If this variance is less than that of the minimum variance of those power-spectral densities which are being included, then that cross spectrum is entirely ignored. The reason is that if certain power-spectral densities (and associated degrees of freedom) are to be neglected due to their low contribution to overall loading, then there is no reason to include cross-spectral densities, which will contribute no more to the spectral response. In this way the size of the input file is reduced.

The output is further reduced in size by testing each of the individual tables against a similar criterion. If the sum of the terms in each table is less than one-half of the minimum psd variance, then that table is omitted.

The printing of the power-spectral densities is carried out by the routine WRITE2, whereas the output of the cross-spectral densities is organized with subroutine PRINT. This is largely due to the three different options that are available for the latter (see Section 7.3.24).

7.3.24 Subroutine HSUP

This subroutine is called when the number of modes requested for the NASTRAN solution (NVECT) is less than

the number of modes in the load formulation (NEIG). HSUP will suppress those modes that have the lowest variance of their modal load power spectral densities.

Once the modes to be suppressed have been identified, they are transmitted to NASTRAN through a DMI (direct matrix input) named HSUP, which is interpreted through the DMAP modifications (see Appendix E).

7.3.25 Subroutine PRINT

This routine prints the cross spectral density tables in a format for TABRND1 cards of NASTRAN. Three alternative versions can be selected through the value of IPRINT.

IPRINT = 1 prints the full spectrum

IPRINT = 2 the spectral values at harmonic frequencies are printed but all intermediate values are put equal to zero. This version reduces the total file length and allows examination of the influence of non-harmonic terms.

IPRINT = 3 this version also writes harmonic frequency values but can only be used if the solution is limited to those frequencies.

List of Arguments

WORK	vector of current table values (Mantissa only)
SC	vector of exponential signs for table values
NC	vector of exponents for table values

NPMAX	maximum harmonic frequency requested
NDIV	number of intervals in spectrum between harmonic frequencies (must be a power of 2)
KTAB	current index value for continuation cards
KRAN	index for current id of TABRND1 card
DELF	basic frequency interval
IPRINT	= 1, 2 or 3; key to type of cross spectrum printing

7.4 Input Files

A total of four input files is required by the program TRES. They are

basic data
airfoil data
eigenvectors
NASTRAN bulk data

They are described in the following sections, and sample listings are included in Appendix B.

7.4.1 Basic Input Data File

This file contains all necessary information about the overall rotor configuration, the spatial array of turbulent vectors, the turbulence parameters, the number and types of airfoils, the number of eigenvectors to be used, the type of output and the extent of modal damping. All of this file is read by subroutine READ1 and information on the meaning of variables may be obtained from Sections 7.2.1 and 7.3.2.

Format. All comment cards must have a "$" in column one. All variables are in free format except where noted.

Variable	Dimensions	Meaning	Common Block
Line 1			
HT	in	height of rotor	GEOM
DIA	in	diameter of rotor	GEOM
HMR	in	mid-rotor height	GEOM
RPM	rpm	rotor speed	ROTOR
VBAR	mph	mid-rotor windspeed	WND
WSE	-	vertical wind shear exponent	WND
DELT	s	time interval for time series	WND
ARHO	lb/ft	air density	WND
Line 2			
C1X		coefficients C1 and C2 for	WND
C2X		use in Frost & Turner	
C1Y		turbulence spectrum.	
C2Y		X = longitudinal, Y = lateral	
Z0	m	roughness height	WND
DECAY		decay coefficient to define coherence of cross-spectra of wind	WND
Line 3			
NHT	-	no. of vertical divisions in spatial array	GEOM
NDIA	-	no. of lateral divisions in spatial array	GEOM
NEIG	-	no. of eigenvectors in load formulation	GEOM

Variable	Dimensions	Meaning	Common Block
NT	-	no. of intervals per rotor revolution; must be a power of 2	GEOM
NREV	-	no. of revolutions of rotor; must be a power of 2	GEOM
NFOIL	-	no. of different airfoils used	ROTOR
NLOOP	-	no. of loops used to generate ensemble of load spectra	GEOM
NPMAX	-	max. per-rev frequency in output spectra	GEOM
NDIV	-	no. of divisions between per-rev frequencies in output spectra; must be power of 2	GEOM
NVECT	-	no. of eigenvectors to be used in NASTRAN modal solution	GEOM
Line 4			
"YES/NO"		Dynamic stall included? A3 format	
Line 5			
"YES/NO"		Column loading included? A3 format	
Line 6			
IPRINT	-	1 = full cross spectra for output 2 = cross spectra at harmonics only 3 = solution at harmonics only	

Variable	Dimensions	Meaning	Common Block
Line 7			
TYPE(i)	-	airfoil type name, A8 format	ALPHA
CH(i)	in	chord length of airfoil #i	ROTOR
FHT(i)	in	height from mid-rotor for start of airfoil #i Note: the location of airfoils is assumed to be symmetric about the mid-rotor.	ROTOR
Line 8			
ILAM	-	eigenvector no.	
DAMP(ILAM)	-	non-default critical damping for mode ILAM	ROTOR

7.4.2 Airfoil Data File

All the necessary airfoil data are read in by subroutine READAIR (Section 7.3.4), and a sample of an input file is included as Appendix B.2. This input file must adhere to the following format restrictions:

(1) The file may contain lift and drag coefficients for any number of airfoil shapes but no more than five can be read by one job.

(2) Each airfoil may have coefficients listed at up to five Reynolds numbers.

(3) Up to 50 angles of attack may be listed for each block.

(4) If data at more than one Reynolds number are given for a certain airfoil then the blocks must be placed in order of ascending Reynolds number.

(5) The last angle of attack in each block must be 180.0 (exactly).

(6) The angles of attack used for different airfoils or for different Reynolds numbers of the same airfoil do not have to be the same (in value or total number).

(7) The file must end with "ENDFILE".

(8) Each block or group of data must begin with a line having the eight-character alphanumeric airfoil identifier in the first field.

(9) The second line of each block contain the following, in F10.0, F10.2, 2F10.4 format.

RE(i,j)	Reynolds number #j for airfoil #i
AS(i,j)	static stall angle
CDMIN(i,j)	Cd at zero angle of attack to be added to all values listed
TC(i)	aspect ratio for airfoil #i

(10) Subsequent lines contain in 3F10.4 format.

A	angle of attack (degrees)
CL	lift coefficient
CD	drag coefficient

7.4.3 Eigenvector Data File

This file is created by a NASTRAN real eigenvalue solution (such as 03, 30 or 63). It is generated as "punched" output by the control cards described in Section 3.1. A sample of such a file is included as Appendix B.3.

Subroutine READEIG is written especially to read this type of file. It searches for a line beginning with the characters "$EIGENVALUE", records the mode number and eigenvalue and proceeds to read the grid point displacements. These points are output in ascending order of the associated NASTRAN GRID id numbers.

7.4.4 NASTRAN Bulk Data File

The NASTRAN Bulk Data File is used to supply the necessary information on the configuration of the rotor. The file is read in by subroutine READ2, which is described in Section 7.3.3. A sample bulk data file is included as Appendix B.4.

The bulk data file is a standard NASTRAN input deck except for the GRID cards associated with the column nodes. In order to transmit the value of the column diameter, field number 10, which is normally blank and is ignored by NASTRAN, is used for this value.

7.5 Output Files

7.5.1 Output File TRES.OUT

The program TRES generates a file TRES.OUT which is largely an echo of the data contained in the basic

input data file. It also lists the length of the time series vectors, the number of elements in the blades and in the column, and the eigenvalues.

In addition, the rms and intensity of the longitudinal and lateral turbulence are given, together with the ordering of the modal loads according to their variances. The percentage of stochastic variance is listed for all spectra and cross spectra.

A sample output file is included as Appendix C.1.

7.5.2 Output File TRES1.OUT

A file with the name TRES1.OUT is also generated by program TRES and contains all cards that must be attached to the NASTRAN bulk data for the Solution 30 frequency response analysis.

This file can be long. For modal input from 20 modes at 40 frequency values, the total length can be limited to about 2,500 lines by deleting tables which contribute less than a certain minimum variance. An abbreviated sample of such a file is attached as Appendix C.2.

7.5.3 Output File TRES.STR

This file is used as secondary storage by the program TRES. The file stores the matrix of auto- and cross-spectral densities of the modal loads between ensemble loops. The file is retrieved when a loop is complete to allow the new ensemble mean to be calculated.

APPENDIX A

Program Listing

Note; Main routine is listed first and subroutines follow in alphabetical order.

```
      PROGRAM TRESM
      WRITE(*,*)' enter basic input data file name'
      OPEN(1,FILE='TRES.DAT')
      WRITE(*,*)' enter airfoil data file name'
      OPEN(2,FILE='AIR2.DAT')
      WRITE(*,*)' enter file containing eigenvectors'
      OPEN(3,FILE='PSVECT.DAT')
      WRITE(*,*)' enter NASTRAN bulkdata filename'
      OPEN(5,FILE='PSBULK.DAT')
      OPEN(6,FILE='TRES.OUT',STATUS='NEW')
      OPEN(7,FILE='TRES1.OUT',STATUS='NEW')
      OPEN(8,FILE='TRES.STR',STATUS='NEW')
      OPEN(9,FILE='VTIME.OUT',STATUS='NEW')
      WRITE(6,111)
111   FORMAT(' TRESM. CALCULATION OF ROTOR AERODYNAMIC LOADS UNDER',
     1' TURBULENT WINDS',/,' D.J.MALCOLM, APRIL 1986',/)
C
      CALL READ1(IDS,ICL,IPRINT)
      CALL READ2
      CALL READAIR
      CALL READEIG
      CALL SMOOTH(IDS,ICL)
      CALL WRITE1(IPRINT)
      END
C
```

```
C
      SUBROUTINE CMODAL(II,KV,KL,IC,PRESS,THETAC,PHIC)
C
C  contributes column loads to modal loads
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1                ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
C  sharing between column nodes
      G=(ZCOL(IC)-Z(II))/(ZCOL(IC)-ZCOL(IC-1))
C  identify column in EIGV matrix
      ICOL=INDEXC(IC)
      DRAG2=PRESS*DCOL(IC-1)*1.0*G
      DRAG1=PRESS*DCOL(IC)*1.0*(1.-G)
C  loop on eigenmodes
        DO 10 I=1,NEIG
10      GLOAD(KL,I)=GLOAD(KL,I)-(EIGV(ICOL,1,I)*DRAG1+EIGV(ICOL-1,1,I)*
     1                DRAG2)*SIN(THETAC-PHIC)  - COS(THETAC+PHIC)*(EIGV(
     2                ICOL,2,I)*DRAG1+EIGV(ICOL-1,2,I)*DRAG2)
      RETURN
      END
```

```
C
      SUBROUTINE DECOMP(IXY)
C
C  decomposes csd's into transfer matrix according to S=H*(H)t.
C  results are stored in same locations in TRH.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
      NN=(NHT+1)*(NDIA+1)
      NSP=NN*(NN+1)/2
C  loop on frequencies
      DO 10 M=1,NTRAN/2
       IROW=2*M-1
C  initialize first column
       TRH(IROW,1,IXY)=SQRT(TRH(IROW,1,IXY))
       DO 20 IND=2,NN
        ICOL=IND*(IND-1)/2+1
        TRH(IROW,ICOL,IXY)=TRH(IROW,ICOL,IXY)/TRH(IROW,1,IXY)
20     CONTINUE
C  solve for each IND1 row
       DO 30 IND1=2,NN
         DO 30 IND2=2,IND1
           INDX=IND1*(IND1-1)/2+IND2
           SUM=0.0
           DO 40  K=1,IND2-1
             INDX1=IND1*(IND1-1)/2+K
             INDX2=IND2*(IND2-1)/2+K
40           SUM=SUM+TRH(IROW,INDX1,IXY)*TRH(IROW,INDX2,IXY)
           IF(IND2.LT.IND1) THEN
             TRH(IROW,INDX,IXY)=(TRH(IROW,INDX,IXY)-SUM)
     1                          /TRH(IROW,INDX2+1,IXY)
           ELSE
             TRH(IROW,INDX,IXY)=SQRT(TRH(IROW,INDX,IXY)-SUM)
           ENDIF
30       CONTINUE
10     CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE DFT(XSEED,IXY)
C
C  this routine adds a random phase to the columns of H, performs
C  an inverse Fourier transform on each spectrum, and obtains the
C  time series at each point by summing the rows.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
      DIMENSION WORK1(512),WORK2(512)
      NN=(NHT+1)*(NDIA+1)
      PI=ACOS(-1.)
C  loop on frequencies
      DO 10 M=1,NTRAN/2
      M1=2*M-1
      M2=2*M
C  loop on columns
        DO 20 IND2=1,NN
        PHASE=RANDOM(XSEED)*2.*PI
C  loop on rows
          DO 20 IND1=IND2,NN
          INDX=IND1*(IND1-1)/2+IND2
          TRH(M2,INDX,IXY)=TRH(M1,INDX,IXY)*SIN(PHASE)
          TRH(M1,INDX,IXY)=TRH(M1,INDX,IXY)*COS(PHASE)
20      CONTINUE
10    CONTINUE
C  loop on spectra
      DO 30 IND1=1,NN
      DO 30 IND2=1,IND1
      INDX=IND1*(IND1-1)/2+IND2
C  transfer to working vectors and add conjugate to 2nd half
        DO 40 M=2,NTRAN/2
        M1=2*M-1
        M2=2*M
        WORK1(M)=TRH(M1,INDX,IXY)
        WORK2(M)=-TRH(M2,INDX,IXY)
        WORK1(NTRAN-M+2)=TRH(M1,INDX,IXY)
40      WORK2(NTRAN-M+2)=TRH(M2,INDX,IXY)
      WORK1(NTRAN/2+1)=0.0
      WORK2(NTRAN/2+1)=0.0
C  remove zero frequency (mean wind)
      WORK1(1)=0.
      WORK2(1)=0.
C  carry out Fourier transform
      IN=0
      CALL FFT842(IN,NTRAN,WORK1,WORK2)
C  store (real part of) output back into  TRH,(* by N)
        DO 50 M=1,NTRAN
50      TRH(M,INDX,IXY)=WORK1(M)
30    CONTINUE
C  sum across rows to obtain final time series. Store in TRH
      DO 60 M=1,NTRAN
C  loop on rows
        DO 70 IND1=2,NN
        ICOL=IND1*(IND1-1)/2+1
         DO 70 IND2=2,IND1
         INDX=IND1*(IND1-1)/2+IND2
70      TRH(M,ICOL,IXY)=TRH(M,ICOL,IXY)+TRH(M,INDX,IXY)
60    CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
C
C iterative solution to momentum balance based on method by R J Templin
C  Programmed by D J Malcolm
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1                ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/AIRFOIL/DSET(5,50,11),DSET1(50,2),RE(5,5),AS(5,5),
     1CDMIN(5,5),NRE(5),TC(5),NA(5),ANG(50)
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
      VDRW=VRW*.90
      DMP=.75
      CRIT=0.02
      JDS=1
      IF(IDS.EQ.0) JDS=0
      IC=0
      BETA=THETA+ISIGN*PHI
C   iterate to converge on disc drag coefficient
2006  QQD=(RR/VDRW+COS(BETA))**2+(SIN(BETA)*COSD)**2
      IC=IC+1
      ALPH=ACOS((COS(BETA)+RR/VDRW)/SQRT(QQD))
C relative velocity, stall angle, local Reynolds number (initial pass only)
      IF(INIT.EQ.0) THEN
        VR=VDRW*DIA/2.*OMEGA*SQRT(QQD)
        RE1=VR*CH(KK)*6394./144.
        AS1=AS(KK,1)
      ENDIF
C  dynamic stall
      IF(QQD.LT.0.01.OR.VR.LT.DIA*OMEGA/20.) JDS=0
      IF(ALPH.LT.5./57.3.OR.ALPH.GT.3.*AS1/57.3) JDS=0
      DADT=0.0
      ALPHR=ALPH
      IF(JDS.EQ.1) THEN
          DADT=ISIGN*OMEGA*COSD*(1.+RR/VDRW*COS(BETA))/QQD
          IF(ITURB.EQ.1) THEN
            VDEF1=1.0
            IF(ISIGN.EQ.-1) VDEF1=VDEF
            VP1=SQRT((VBARZ+VTUBE(KV+1,1))**2+VTUBE(KV+1,2)**2)
            VM1=SQRT((VBARZ+VTUBE(KV-1,1))**2+VTUBE(KV-1,2)**2)
            DADT=DADT+(VP1-VM1)*VDEF1/2./DELT
     1            *SIN(BETA)*COSD*RR/DIA*2./OMEGA/VRW/VDRW/QQD
            PHIP1=ASIN(VTUBE(KV+1,2)/VP1)
            PHIM1=ASIN(VTUBE(KV-1,2)/VM1)
            DADT=DADT+(PHIP1-PHIM1)/2./DELT*COSD*(1.+RR/VDRW*
     1             COS(BETA))/QQD*ISIGN
```

```
          ENDIF
          CALL DYNSTLL(DADT,CH(KK),ALPH,ALPHR,KK,TC(KK))
        ENDIF
C  interpolate between data to obtain lift and drag coeffs.
        CALL TAB(ALPHR,CL,CD,CDM,INIT,KK)
        INIT=1
        IF(ALPH.NE.0.0) CL=CL*ALPH/ALPHR
        CN=CL*COS(ALPH)+CD*SIN(ALPH)
        CT=CL*SIN(ALPH)-CD*COS(ALPH)
        CDD=2.*CH(KK)*QQD/2./PI/SIN(THETA)/R(II)*(CN*SIN(THETA)-
     1     CT*COS(THETA)/COSD)
        IF(CDD.GE.4.0) THEN
          DMP=DMP*.67
          CRIT=CRIT*1.5
        ENDIF
        IF(IC.GT.8) THEN
          WRITE(6,100)II,JJ,KK,IC,ISIGN,CDD,CRIT
          V1RW=VDRW
        ELSE
          VRWA=VDRW*(1.+CDD/4.)
          VDRW=VDRW-DMP*(VRWA-VRW)
          IF(ABS((VRWA-VRW)/VRW).LE.CRIT) THEN
            V1RW=VDRW*(1.-CDD/4.)
          ELSE
            GO TO 2006
          ENDIF
        ENDIF
        TEMP=CH(KK)*QQD*(DIA/2.*OMEGA*VDRW)**2*ARHOG/2.*DZ/COSD
        FNODE(1)=-CN*TEMP*COSD*ISIGN
        FNODE(2)=CT*TEMP
        FNODE(3)=CN*TEMP*SIN(DEL)*ISIGN
        POWER=POWER+2.*FNODE(2)*R(II)*RPM/NT/84484.
100     FORMAT(' CONVERGENCE NOT MET, II=',I3,' JJ=',I3,' KK=',
     1I3,' IC=',I3,' ISIGN=',I3,' CDD=',F7.3,'CRIT=',F6.3)
        RETURN
        END
```

```
C
      SUBROUTINE DYNSTLL(DADT,C,ALPH,ALPHR,KK,TC)
C
C  Uses the dynamic stall model of Gormont (Boeing-Vertol) modified by
C  B.Masse and by R.J. Templin (notes of 21 Nov 1983)
C  Returns the value of ALPHR
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      REAL M,M2,M1
      A=ALPH*57.296
C  correct for Mach no
      M1=0.4+5.*(.06-TC)
      M2=.9+2.5*(.06-TC)
      M=VR/1080./12.
      GAM2=(1.4-6.*(.06-TC))*(M2-M)/(M2-M1)
C  Gormont stall delay parameter
      AB=SQRT(ABS(DADT*C/2./VR))
C  dynamic stall breakpoint
      ABCRIT=.06+1.5*(.06-TC)
      ABCRIT=0.0
C  RJT weighting of dynamic stall effect
      P=(A-5.)/(AS1-5.)
      IF(A.GT.AS1) P=1.-(A-AS1)/2./AS1
C  correction for sign of DADT
      G=.75+SIGN(1.,DADT)*.25
C  calculate reference angle
      ALPHR=ALPH-GAM2*(AB-.5*ABCRIT)*G*SIGN(1.,DADT)*P
      IF(ALPHR.LT.0.1) ALPHR=0.1
      RETURN
      END
```

```
C
C-----------------------------------------------------------------------
C SUBROUTINE:  FFT842
C FAST FOURIER TRANSFORM FOR N=2**M
C COMPLEX INPUT
C-----------------------------------------------------------------------
C
      SUBROUTINE FFT842(IN, N, X, Y)
C
C THIS PROGRAM REPLACES THE VECTOR Z=X+IY BY ITS  FINITE
C DISCRETE, COMPLEX FOURIER TRANSFORM IF IN=0.  THE INVERSE TRANSFORM
C IS CALCULATED FOR IN=1.  IT PERFORMS AS MANY BASE
C 8 ITERATIONS AS POSSIBLE AND THEN FINISHES WITH A BASE 4 ITERATION
C OR A BASE 2 ITERATION IF NEEDED.
C
C THE SUBROUTINE IS CALLED AS SUBROUTINE FFT842 (IN,N,X,Y).
C THE INTEGER N (A POWER OF 2), THE N REAL LOCATION ARRAY X, AND
C THE N REAL LOCATION ARRAY Y MUST BE SUPPLIED TO THE SUBROUTINE.
C
      DIMENSION X(2), Y(2), L(15)
      EQUIVALENCE (L15,L(1)), (L14,L(2)), (L13,L(3)), (L12,L(4)),
     *   (L11,L(5)), (L10,L(6)), (L9,L(7)), (L8,L(8)), (L7,L(9)),
     *   (L6,L(10)), (L5,L(11)), (L4,L(12)), (L3,L(13)), (L2,L(14)),
     *   (L1,L(15))
C
C
C IW IS A MACHINE DEPENDENT WRITE DEVICE NUMBER
C
      IW = 6
C
      PI2 = 2.*3.141593
      P7 = 1./SQRT(2.)
      DO 10 I=1,15
      M = I
      NT = 2**I
      IF (N.EQ.NT) GO TO 20
   10 CONTINUE
      WRITE (IW,9999)
 9999 FORMAT (35H N IS NOT A POWER OF TWO FOR FFT842)
      STOP
   20 N2POW = M
      NTHPO = N
      FN = NTHPO
      IF (IN.EQ.1) GO TO 40
      DO 30 I=1,NTHPO
      Y(I) = -Y(I)
   30 CONTINUE
   40 N8POW = N2POW/3
      IF (N8POW.EQ.0) GO TO 60
C
C RADIX 8 PASSES,IF ANY.
C
      DO 50 IPASS=1,N8POW
      NXTLT = 2**(N2POW-3*IPASS)
      LENGT = 8*NXTLT
      CALL R8TX(NXTLT, NTHPO, LENGT, X(1), X(NXTLT+1), X(2*NXTLT+1),
     *    X(3*NXTLT+1), X(4*NXTLT+1), X(5*NXTLT+1), X(6*NXTLT+1),
     *    X(7*NXTLT+1), Y(1), Y(NXTLT+1), Y(2*NXTLT+1), Y(3*NXTLT+1),
     *    Y(4*NXTLT+1), Y(5*NXTLT+1), Y(6*NXTLT+1), Y(7*NXTLT+1),PI2,P7)
   50 CONTINUE
```

```
C
      SUBROUTINE FMODAL(IBLADE,II,KL)
C
C  this routine adds contributions to the modal load time series
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
C  identify column in matrix EIGV corresponding to blade node II and blade # IBLADE
      ICOL=(NZH-1)*(IBLADE-1)+II +NCOL
C  calc contribution to each of NEIG eigenvectors
      DO 10 I=1,NEIG
      SUM=0.0
        DO 20 J=1,3
20      SUM=SUM+EIGV(ICOL,J,I)*FNODE(J)
10    GLOAD(KL,I)=GLOAD(KL,I)+SUM
      RETURN
      END
```

```
C
      SUBROUTINE FORMT(E,SE,NE,NN)
C reformats vector E into exponential form
      CHARACTER SE(256)
      DIMENSION E(256),NE(256)
      DO 50 I=1,NN
      NE(I)=0
      SE(I)=' +'
      IF(ABS(E(I)).EQ.0.) GO TO 50
      IF(ABS(E(I)).LT.1.0) GO TO 20
      SE(I)=' +'
   10 CONTINUE
      NE(I)=NE(I)+1
      E(I)=E(I)/10
      IF(ABS(E(I)).GT.1.0) GO TO 10
      GO TO 50
   20 CONTINUE
      SE(I)=' -'
   30 CONTINUE
      NE(I)=NE(I)+1
      E(I)=E(I)*10
      IF(ABS(E(I)).LT.1.0) GO TO 30
      NE(I)=NE(I)-1
      E(I)=E(I)/10
      IF(NE(I).LE.9) GO TO 50
      NE(I)=0
      E(I)=0.
   50 CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE HSUP(NEIG,NVECT,IGLOAD)
C
C  supress omitted subcases (modes)
      DIMENSION IGLOAD(22),ISUP(30)
      WRITE(7,118)0,2,1,0,NEIG,1
118   FORMAT('$',/,'$ DE-ACTIVATE UNWANTED MODES',/,'$',/,
     1          'DMI     HSUP    ',4I8,8X,2I8)
      NSUP=NEIG-NVECT
C  re-order suppressed vectors (ascending order)
      K=0
        DO 54 I=1,NEIG
          DO 55 J=NVECT+1,NEIG
          IF(I.EQ.IGLOAD(J)) THEN
            K=K+1
            ISUP(K)=IGLOAD(J)
            GO TO 54
          ENDIF
55        CONTINUE
54      CONTINUE
C  write DMI cards for HSUP
      IF(NSUP.LE.3) THEN
        WRITE(7,119)1,(ISUP(I),1.0,I=1,NSUP)
119     FORMAT('DMI     HSUP    ',I8,3(I8,F8.1))
      ELSE
        WRITE(7,120)1,(ISUP(I),1.0,I=1,3),1
120     FORMAT('DMI     HSUP    ',I8,3(I8,F8.1),'+HSUP',I1)
        NSUP1=NSUP+1
        I1=0
        K=1
56      NSUP1=NSUP1-4
        I1=I1+4
        IF(NSUP1.LE.4) THEN
          WRITE(7,121)K,(ISUP(I),1.0,I=I1,NSUP)
121       FORMAT('+HSUP',I1,2X,4(I8,F8.1))
        ELSE
          K=K+1
          WRITE(7,122)K-1,(ISUP(I),1.0,I=I1,I1+3),K
122       FORMAT('+HSUP',I1,2X,4(I8,F8.1),'+HSUP',I1)
          GO TO 56
        ENDIF
      ENDIF
      RETURN
      END
```

```
C
      SUBROUTINE INPUT(J)
C  reads from unit J, checks for initial $ sign
      CHARACTER AA
1     READ(J,100)AA
100   FORMAT(A1)
      IF(AA.EQ.'$') GO TO 1
9     BACKSPACE J
      RETURN
      END
```

```
C
      SUBROUTINE MODEL(H,V,WORK,IXY)
C
C  uses Frost & Turner expression for the (continuous) psd of wind turbulence.
c  Units must be S.I.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      DIMENSION WORK(256)
      HM=H/39.37
      HM=10.
      VM=V*.447
      IF(IXY.EQ.1) THEN
        C1=C1X
        C2=C2X
      ELSE
        C1=C1Y
        C2=C2Y
      ENDIF
      DELF=1./NTRAN/DELT
      DUM1=ALOG(10./ZO+1.)*ALOG(HM/ZO+1.)
      DUM1=VM*C1*HM/DUM1
      DUM2=HM*ALOG(10./ZO+1.)/(VM*ALOG(HM/ZO+1.))
        DO 10 M=2,NTRAN/2
        MM=M-1
10      WORK(M)=DUM1/(1.+C2*(MM*DELF*DUM2)**1.67)
      WORK(1)=WORK(2)
      RETURN
      END
```

```
C
      SUBROUTINE PRINT(WORK,SC,NC,NPMAX,NDIV,KTAB,KRAN,DELF,IPRINT)
C
C  writes NASTRAN TABLE for cross spectra using chosen option
      CHARACTER SC(256)
      DIMENSION WORK(256),NC(256),FREQ(128)
      WRITE(7,100)KRAN,KTAB
100   FORMAT('TABRND1 ',I8,56X,'+TAB',I4)
      NTOT=NPMAX*NDIV+1
      IF(IPRINT.EQ.1) THEN
C  print full cross spectra (assuming a multiple of 4)
        NCARD=NPMAX*NDIV/4
          DO 20 IC=1,NCARD
          WRITE(7,101)KTAB,(DELF*(II-1),WORK(II),SC(II),NC(II),
     1                II=IC*4-3,IC*4),KTAB+1
101       FORMAT('+TAB',I4,4(F8.3,F6.4,A1,I1),'+TAB',I4)
20        KTAB=KTAB+1
        WRITE(7,103)KTAB,DELF*(NTOT-1),WORK(NTOT),SC(NTOT),NC(NTOT)
103     FORMAT('+TAB',I4,F8.3,F6.4,A1,I1,'     ENDT')
      ELSEIF(IPRINT.EQ.2) THEN
C  write cross spectra at harmonic frequencies only with intermediate zeros
C  reorder vectors onto harmonics only with adjacent zeros
          DO 10 IP=1,NPMAX
          II=IP*3+1
          JJ=IP*NDIV+1
          WORK(II)=WORK(JJ)
          WORK(II-1)=0.0
          WORK(II-2)=0.0
          NC(II)=NC(JJ)
          NC(II-1)=0
          NC(II-2)=0
          FREQ(II)=DELF*(JJ-1)
          FREQ(II-2)=DELF*(JJ-NDIV)
10        FREQ(II-1)=DELF*(JJ-2)
C  print TABLE in groups of 4
        NF=NPMAX*3+1
        NCARD=NF/4
        NREM=NF-NCARD*4
          DO 30 IC=1,NCARD
          WRITE(7,104)KTAB,(FREQ(II),WORK(II),SC(II),NC(II),II=IC*4-3,
     1                IC*4),KTAB+1
104       FORMAT('+TAB',I4,4(F8.3,F6.4,A1,I1),'+TAB',I4)
30        KTAB=KTAB+1
        IF(NREM.EQ.0) THEN
          WRITE(7,105)KTAB
105       FORMAT('+TAB',I4,'     ENDT')
        ELSEIF(NREM.EQ.1) THEN
          WRITE(7,106)KTAB,FREQ(NF),WORK(NF),SC(NF),NC(NF)
106       FORMAT('+TAB',I4,F8.3,F6.4,A1,I1,'     ENDT')
        ELSEIF(NREM.EQ.2) THEN
          WRITE(7,107)KTAB,(FREQ(I),WORK(I),SC(I),NC(I),I=NF-1,NF)
107       FORMAT('+TAB',I4,2(F8.3,F6.4,A1,I1),'     ENDT')
        ELSE
          WRITE(7,108)KTAB,(FREQ(I),WORK(I),SC(I),NC(I),I=NF-2,NF)
108       FORMAT('+TAB',I4,3(F8.3,F6.4,A1,I1),'     ENDT')
```

```
        ENDIF
C  writes cross spectra at 5 harmonic frequencies only (no intermediate zeros)
      ELSEIF(IPRINT.EQ.3) THEN
        WRITE(7,109)KTAB,(DELF*(II-1),WORK(II),SC(II),NC(II),II=1,
     1              3*NDIV+1,NDIV),KTAB+1
109     FORMAT('+TAB',I4,4(F8.3,F6.4,A1,I1),'+TAB',I4)
        KTAB=KTAB+1
        WRITE(7,110)KTAB,(DELF*(II-1),WORK(II),SC(II),NC(II),II=4*NDIV+1
     1            ,NTOT,NDIV)
110     FORMAT('+TAB',I4,2(F8.3,F6.4,A1,I1),'     ENDT')
      ENDIF
      KTAB=KTAB+1
      RETURN
      END
```

```
C
      FUNCTION RANDOM(XSEED)
C
C generates a random number based on Ang & Tang p. 279
C       IA=101
C       IC=1
C       M=256
C       DO 1 I=1,3
C1      XSEED=IA*XSEED+IC-M*INT((IA*XSEED+IC)/M)
C       RANDOM=XSEED/M
C  based on HP-35 applications manual (S. MIKAIL)
      X=EXP(5.*ALOG(XSEED+3.1415926))
      XSEED=X-INT(X)
      RANDOM=XSEED
      RETURN
      END
```

```
C
      SUBROUTINE READAIR
C
C  reads and stores the required airfoil datasets with corresponding Reynolds
C  numbers, static stall, and Cdmin
      CHARACTER*8 AA,TYPE
      COMMON/ALPHA/TYPE(5)
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1              ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/AIRFOIL/DSET(5,50,11),DSET1(50,2),RE(5,5),AS(5,5),
     1CDMIN(5,5),NRE(5),TC(5),NA(5),ANG(50)
C
C loop on no of airfoils. Sections identical to previous sections are
C allocated identical coefficients.
      DO 9 I=1,NFOIL
      J1=0
11    J1=J1+1
      IF(J1.LT.I) THEN
        IF(TYPE(J1).EQ.TYPE(I)) THEN
          NRE(I)=NRE(J1)
          NA(I)=NA(J1)
            DO 13 KK=1,NA(J1)
              DO 14 K1=1,2*NRE(J1)+1
14            DSET(I,KK,K1)=DSET(J1,KK,K1)
13          CONTINUE
          TC(I)=TC(J1)
            DO 15 K2=1,NRE(I)
            RE(I,K2)=RE(J1,K2)
            AS(I,K2)=AS(J1,K2)
15          CDMIN(I,K2)=CDMIN(J1,K2)
        ELSE
          GO TO 11
        ENDIF
      ENDIF
10    ANG(1)=0.
      DSET1(1,1)=0.
      INIT=0
C  read first 8 letters of lines and check for airfoil description
      J=0
1     READ(2,100)AA
100   FORMAT(A8)
      IF(AA.EQ.'ENDFILE ') THEN
        REWIND 2
        GO TO 9
      ELSEIF(AA.NE.TYPE(I)) THEN
        GO TO 1
      ENDIF
      J=J+1
      NRE(I)=J
C  read Reynolds no., static stall angle, Cdmin, aspect ratio
      READ(2,101)RE(I,J),AS(I,J),CDMIN(I,J),TC(I)
101   FORMAT(F10.0,F10.2,2F10.4)
C  read angle of attack, Cl and Cd
      K=0
4     K=K+1
      READ(2,102)A,CL,CD
102   FORMAT(3F10.4)
      IF(INIT.EQ.0.OR.K.EQ.1) THEN
```

```
          DSET(I,K,1)=A
          DSET(I,K,2*J)=CL
          DSET(I,K,2*J+1)=CD
          DSET1(1,2)=CD
          IF(A.GE.180.) THEN
            NA(I)=K
            INIT=1
            GO TO 1
          ELSE
            GO TO 4
          ENDIF
        ELSE
C use ANG and DSET1as buffers for non-initial data sets
          ANG(K)=A
          DSET1(K,1)=CL
          DSET1(K,2)=CD
          IF(A.LT.180.) THEN
            GO TO 4
          ELSE
C interpolate cl and cd values to fit initial angle set
            DO 5 KK=2,NA(I)
            K=1
6           K=K+1
            IF(DSET(I,KK,1).LE.ANG(K)) THEN
              G=(DSET(I,KK,1)-ANG(K-1))/(ANG(K)-ANG(K-1))
              DSET(I,KK,2*J)=(1.-G)*DSET1(K-1,1)+G*DSET1(K,1)
              DSET(I,KK,2*J+1)=(1.-G)*DSET1(K-1,2)+G*DSET1(K,2)
            ELSE
              IF(ANG(K).GE.180.)WRITE(6,103)I,J,K,KK,ANG(K),DSET(I,KK,1)
              IF(ANG(K).GE.180.) STOP
              GO TO 6
            ENDIF
5           CONTINUE
          ENDIF
        ENDIF
        GO TO 1
9       CONTINUE
103     FORMAT(' I J K KK ANG(K) DSET(I,KK,1)',4I4,2E10.3)
        RETURN
        END
```

```
C
      SUBROUTINE READEIG
C
C  reads in eigenvalues and stores in EVALUE().
C  reads in the translational degrees of freedom of the blade and column nodes.
C  these nodes must start at NASTRAN grid no. 100.  Eigenvectors stored
C  in EIGV(I,J,K) .
C  Unit #5 is formatted according to the punched output of NASTRAN.
      CHARACTER*10 AA
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1              ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      DIMENSION DISP(3)
C  loop on the no of eigenvectors and eigenvalues required
        DO 10 I=1,NEIG
1       READ(3,102)AA
        IF(AA.NE.'$EIGENVALU')  GO TO 1
        BACKSPACE 3
        READ(3,103)B
        EVALUE(I)=SQRT(B)/6.28319
C  read in column components
3       READ(3,102)AA
        IF(AA.NE.'          2')  GO TO 3
        BACKSPACE 3
          DO 50 J=1,NCOL+1
          READ(3,100)NODE,(EIGV(J,K,I),K=1,3)
50        READ(3,100)
C  locate node no.=100
2       READ(3,102)AA
        IF(AA.NE.'        100')  GO TO 2
        BACKSPACE 3
C  loop on no. of (both) blade nodes
          DO 30 J=NCOL+2,2*(NZH-1)+NCOL+1
          READ(3,100)NODE,(EIGV(J,K,I),K=1,3)
30        READ(3,100)
10      CONTINUE
      WRITE(6,104)
104   FORMAT(/,' MODE  EIGENVALUE')
      WRITE(6,105)(I,EVALUE(I),I=1,NEIG)
105   FORMAT(I4,F9.3)
100   FORMAT(I10,8X,3E18.6)
102   FORMAT(A10)
103   FORMAT(16X,E12.7)
      RETURN
      END
```

```
C
      SUBROUTINE READ1(IDS,ICL,IPRINT)
C
C  reads in some basic data from unit #1 and writes to unit #6
C
      CHARACTER AA
      CHARACTER*8 TYPE,ADS,ACL
      COMMON/ALPHA/TYPE(5)
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1                ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      CALL INPUT(1)
      READ(1,*)HT,DIA,HMR,RPM,VBAR,WSE,DELT,ARHO
      CALL INPUT(1)
      READ(1,*)C1X,C2X,C1Y,C2Y,ZO,DECAY
      CALL INPUT(1)
      READ (1,*)NHT,NDIA,NEIG,NT,NREV,NFOIL,NLOOP,NPMAX,NDIV,NVECT
      CALL INPUT(1)
      READ(1,103)ADS
      CALL INPUT(1)
      READ(1,103)ACL
103   FORMAT(A3)
      IDS=0
      IF(ADS.EQ.'YES') IDS=1
      ICL=0
      IF(ACL.EQ.'YES') ICL=1
      CALL INPUT(1)
      READ(1,*)IPRINT
      WRITE(6,104)HT,HT/39.37
      WRITE(6,108)DIA,DIA/39.37
      WRITE(6,110)HMR,HMR/39.37
      WRITE(6,109)RPM,RPM/9.549
      WRITE(6,117)VBAR,VBAR/2.237
      WRITE(6,111)WSE
      WRITE(6,112)ARHO
      WRITE(6,121)DELT
      WRITE(6,116)NHT
      WRITE(6,115)NDIA
      WRITE(6,122)C1X
      WRITE(6,123)C2X
      WRITE(6,128)C1Y
      WRITE(6,129)C2Y
      WRITE(6,124)ZO
      WRITE(6,125)DECAY
      WRITE(6,113)NEIG
      WRITE(6,132)NVECT
      WRITE(6,114)NT
      WRITE(6,118)NREV
      WRITE(6,119)NPMAX
      WRITE(6,130)NDIV
      WRITE(6,120)NLOOP
      WRITE(6,131)ADS
      WRITE(6,133)ACL
      WRITE(6,134)IPRINT
104   FORMAT(' ROTOR HEIGHT                    =',F6.1,' INS  =',F5.1,' M')
108   FORMAT(' ROTOR DIAMETER                  =',F6.1,' INS  =',F5.1,' M')
109   FORMAT(' ROTOR SPEED                     =',F6.1,' RPM  =',F5.3,' RAD/S'
     1)
```

```
110   FORMAT(' MID-ROTOR HEIGHT            =',F6.1,' INS  =',F5.1,' M')
111   FORMAT(' WIND SHEAR EXPONENT         =',F6.3)
112   FORMAT(' AIR DENSITY                 =',F6.4,' LB/FT3')
113   FORMAT(' NO OF EIGENVECTORS USED     =',I6)
114   FORMAT(' NO OF DIVISIONS IN CYCLE    =',I6)
115   FORMAT(' # LAT DIV IN WIND ARRAY     =',I6)
116   FORMAT(' # VERT DIV IN WIND ARRAY    =',I6)
117   FORMAT(' MID ROTOR WINDSPEED         =',F6.1,' MPH  =',F5.1,' M/S')
118   FORMAT(' NO OF ROTOR REVOLUTIONS     =',I6)
119   FORMAT(' MAX PER-REV MULTIPLE        =',I6)
120   FORMAT(' # ENSEMBLE VALUES           =',I6)
121   FORMAT(' TIME SERIES: DELTA T        =',F6.3,' SECS')
122   FORMAT(' FROST & TURNER: C1X         =',F6.3)
123   FORMAT(' FROST & TURNER: C2X         =',F6.1)
128   FORMAT(' FROST & TURNER: C1Y         =',F6.3)
129   FORMAT(' FROST & TURNER: C2Y         =',F6.1)
124   FORMAT(' SURFACE ROUGHNESS           =',F6.3,' M')
125   FORMAT(' DECAY COEFFICIENT FOR CSDs=',F6.3)
126   FORMAT(/,' LENGTH OF WINDSPEED SERIES=',I6)
127   FORMAT(' LENGTH OF LOAD SERIES       =',I6)
130   FORMAT(' OUTPUT: # DIVISIONS/CYCLE =',I6)
131   FORMAT(' DYNAMIC STALL?                  ',A3)
133   FORMAT(' COLUMN LOADING?                 ',A3)
134   FORMAT(' PRINT OPTION # FOR CSDs     =',I6)
132   FORMAT(' # EIGENVECTORS IN SOLUTION=',I6)
C  select length of time series (to nearest power of 2)
      TIME=NREV*60./RPM
      NTRAN=(TIME+DIA*1.0/VBAR/17.6)/DELT
      NB=0
1     NB=NB+1
      IF(2**NB.LT.NTRAN) GO TO 1
      NTRAN=2**NB
      WRITE(6,126)NTRAN
      WRITE(6,127)NREV*NT
C
C  read data on airfoil names,chords, densities, conc. masses, ht from mid-rotor
C
      CALL INPUT(1)
      WRITE(6,105)
105   FORMAT(/,'AIRFOIL TYPE   CHORD(IN)   START-HT(IN)')
       DO 2 I=1,NFOIL
       READ(1,107)TYPE(I),CH(I),FHT(I)
2      WRITE(6,107)TYPE(I),CH(I),FHT(I)
107   FORMAT(A8,F10.2,F10.2)
C  read in mode numbers and critical damping factors (default = 0.01)
        DO 4 I=1,NEIG
4       DAMP(I)=0.01
      WRITE(6,102)
102   FORMAT(/,' MODE  CRITICAL DAMPING')
      CALL INPUT(1)
3     READ(1,*)ILAM,CRIT
      DAMP(ILAM)=CRIT
      WRITE(6,101)ILAM,DAMP(ILAM)
101   FORMAT(I4,F10.2)
      READ(1,100)AA
100   FORMAT(A1)
      IF(AA.NE.'$') THEN
        BACKSPACE 1
        GO TO 3
      ENDIF
      RETURN
      END
```

```
C
      SUBROUTINE READ2
C
C reads geometry data and writes to unit #6
      CHARACTER*8 TYPE
      CHARACTER*4 AA
      COMMON/ALPHA/TYPE(5)
      COMMON/GEOM/HT, DIA, HMR, NHT, NDIA, NZH, NT, NREV, NEIG, NLOOP, NPMAX, NDIV
     1, NVECT, NCOL
      COMMON/ROTOR/R(40), Z(40), RPM, CH(5), FHT(5), NFOIL, INDEX(40), DAMP(30)
     1                , INDEXC(20), ZCOL(20), DCOL(20)
      NZH=1
      NCOL=-1
1     READ(5,100)AA
100   FORMAT(A4)
      IF(AA.NE.'ENDD') THEN
        IF(AA.NE.'GRID') GO TO 1
3       BACKSPACE 5
        READ(5,101)II, RR, ZZ, DC
101     FORMAT(8X, I8, 8X, F8.2, 8X, F8.2, 24X, F8.2)
        IF(II.GE.100.AND.II.LT.200) THEN
C  blade no 1 coords
          NZH=NZH+1
          INDEX(NZH)=II
          R(NZH)=RR
          Z(NZH)=ZZ
          IF(RR.GT.DIA/2.) WRITE(6,*)' READ2: R > RADIUS'
C  column coordinates
        ELSEIF(II.GE.2.AND.II.LT.100) THEN
          NCOL=NCOL+1
          INDEXC(NCOL+1)=II
          ZCOL(NCOL+1)=ZZ
          DCOL(NCOL+1)=DC
        ENDIF
        GO TO 1
      ENDIF
C  top and bottom blade nodes
      R(1)=0.
      R(NZH+1)=0.
      Z(1)=-HT/2.
      Z(NZH+1)=HT/2.
C  fill in missing column diameters using linear interpolation
      JJ1=0
62    JJ1=JJ1+1
63    II=JJ1
64    II=II+1
      IF(II.LE.NCOL+2) THEN
        IF(DCOL(II).EQ.0.0) GO TO 64
        IF(II.LE.JJ1+1) GO TO 62
        JJ2=II
```

```
          G=(DCOL(JJ2)-DCOL(JJ1))/(ZCOL(JJ2)-ZCOL(JJ1))
          K1=JJ1+1
          K2=JJ2-1
          DO 61 KK=K1,K2
61        DCOL(KK)=DCOL(JJ1)+G*(ZCOL(KK)-ZCOL(JJ1))
          IF(JJ2.LT.NCOL) THEN
            JJ1=JJ2
            GO TO 63
          ENDIF
        ENDIF
C  write geometry details
        WRITE(6,103)NZH
        WRITE(6,102)NCOL
103     FORMAT(/,' # OF ELEMENTS PER BLADE    =',I6)
102     FORMAT(' TOTAL # OF COLUMN ELEMENTS   =',I6)
        RETURN
        END
```

```
C
      SUBROUTINE SIJ(ILOOP,IXY)
C
C  generates the spectral densities of turbulence for the rectangular spatial
C  array based on the coherence function given by Frost & Turner and used
C  by P Veers. Note: csd is assumed real. Values are stored in columns
C  of TRH using alternate rows. This routine uses S.I. units.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,Z0,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
      DIMENSION WORK(256)
      NN=(NHT+1)*(NDIA+1)
      NSP=NN*(NN+1)/2
      DELHT=HT/NHT
      DELF=1./NTRAN/DELT
C  determine  turbulence intensity at mid-rotor
      IF(ILOOP.EQ.1) THEN
        H=HMR
        V=VBAR
        CALL MODEL(H,V,WORK,IXY)
        RMS=0.0
          DO 70 M=2,NTRAN/2
70        RMS=RMS+WORK(M)
        RMS=SQRT(RMS*DELF)*2.237
        IF(IXY.EQ.1) THEN
          WRITE(6,100)RMS,RMS/VBAR
100       FORMAT(/,'MID-ROTOR LONGITUDINAL TURBULENCE',/,' STANDARD',
     1       ' DEVIATION =',F6.2,' MPH',/,' COEFF OF VARIATION =',F6.2)
        ELSE
          WRITE(6,101)RMS,RMS/VBAR
101       FORMAT(/,'MID-ROTOR LATERAL TURBULENCE',/,' STANDARD ',
     1        'DEVIATION =',F6.2,' MPH',/,' COEFF OF VARIATION =',F6.2)
        ENDIF
      ENDIF
C  establishes the (continuous 1-sided) power spectral densities for NHT+1
C  vertical levels. PSD stored in S(i,j).
        DO 30 I=1,NHT+1
        H=HMR-HT/2.+(I-1)*DELHT
        V=VBAR*(H/HMR)**WSE
C
        CALL MODEL(H,V,WORK,IXY)
C
          DO 40 J=1,NTRAN/2
40        S(J,I)=WORK(J)
30      CONTINUE
C  loop on frequencies
      DO 10 M=1,NTRAN/2
      FR=(M)*DELF
      IROW=2*M-1
C  loop on array height
        DO 20 I=1,NHT+1
C  loop on array width
        DO 20 J=1,NDIA+1
C  location index
        IND1=(I-1)*(NDIA+1)+J
C  loop for 2nd location
          DO 20 K=1,I
          DO 20 L=1,NDIA+1
```

```
          IF(IND2.LE.IND1) THEN
C  index for storage in TRH columns
          INDX=IND1*(IND1-1)/2+IND2
C  distance between pairs of points
          DX=DIA/NDIA
          DZ=HT/NHT
          DIST=SQRT((DZ*(I-K))**2+(DX*(J-L))**2)/39.37
C  coherence function. Note, DELF/2 factor converts 1-sided continuous
C  spectrum to 2-sided disrete spectrum.
          GAMMA=EXP(-DECAY*FR*DIST/VBAR/.477)
          IF(GAMMA.LT.1.E-10) GAMMA=0.0
          TRH(IROW,INDX,IXY)=SQRT(GAMMA*S(M,I)*S(M,K))*DELF/2.
          ENDIF
20      CONTINUE
10    CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE SMOOTH(IDS,ICL)
C
C  This routine organizes an ensemble of spectra for modal loads
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1                ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      DIMENSION WORK(256),WORK2(32)
      NL=NT*NREV
C  loop on whole process to generate ensemble
      XSEED=0.5
      IOUT=0
        DO 10 ILOOP=1,NLOOP
        XRAN=RANDOM(XSEED)
C  generate longitudinal (IXY=1) and lateral (IXY=2) time series
          DO 60 IXY=1,2
          CALL SIJ(ILOOP,IXY)
          CALL DECOMP(IXY)
          CALL DFT(XSEED,IXY)
60        CONTINUE
C  DMST aerodynamics
        CALL STUBE(IDS,ICL)
        CALL SPECTRA(ILOOP,IOUT)
        WRITE(*,*)' COMPLETED LOOP #',ILOOP
10      CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE SPECTRA(ILOOP,IOUT)
C
C  generates the auto and cross spectral densities of modal loads
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(256,3),TRH(256,136,2),VTUBE(512,2)
      DIMENSION U(256),V(256)
      NL=NREV*NT
      NSP=NEIG*(NEIG+1)/2
c  loop for FFTS of modal loads
        DO 10 I=1,NEIG
          DO 11 M=1,NL
          V(M)=0.0
11        U(M)=GLOAD(M,I)
        IN=0
        CALL FFT842(IN,NL,U,V)
          DO 12 M=1,NL/2
          GLOAD(2*M-1,I)=U(M)/NL
12        GLOAD(2*M,I)=V(M)/NL
10      CONTINUE
C  read in previous CSDs ( or zero)
      REWIND 8
      IF(ILOOP.GT.1) THEN
        DO 70 M=1,NL/2
          DO 70 I=1,NSP
70          READ(8,106)(TRH(I,M,K),K=1,2)
      ELSE
        DO 80 M=1,NL/2
        V(M)=0.0
          DO 80 I=1,NSP
            DO 80 K=1,2
80          TRH(I,M,K)=0.0
      ENDIF
C   generate and store psds and csds in TRH matrix.
      DO 20 J=1,NEIG
        DO 20 I=1,J
        ICOL=J*(J-1)/2+I
C  loop on frequency intervals; generate 1-sided discrete power spectrum
          DO 30 M=1,NL/2
          M1=2*M-1
          M2=2*M
          CSD1=2.*(GLOAD(M1,J)*GLOAD(M1,I)+GLOAD(M2,J)*GLOAD(M2,I))
          CSD2=2.*(GLOAD(M1,J)*GLOAD(M2,I)-GLOAD(M2,J)*GLOAD(M1,I))
          IF(M.EQ.1) THEN
            CSD1=CSD1/2.
            CSD2=CSD2/2.
          ENDIF
          TRH(ICOL,M,1)=(TRH(ICOL,M,1)*(ILOOP-1)+CSD1)/ILOOP
30        TRH(ICOL,M,2)=(TRH(ICOL,M,2)*(ILOOP-1)+CSD2)/ILOOP
20    CONTINUE
      IOUT=IOUT+1
      IF(IOUT.EQ.NLOOP) THEN
        IOUT=0
```

```
      IOUT=0
C  re-order GLOAD vectors on basis of total variance (measured by TRH)
        DO 91 I=1,NEIG
        V(I)=0.0
          DO 91 M=1,NREV*NPMAX+1
          V(I)=V(I)+TRH(I*(I+1)/2,M,1)
91        U(I)=V(I)
        DO 93 II=1,NEIG
        A=0.0
          DO 92 I=1,NEIG
          IF(V(I).GT.A) THEN
            J=I
            A=V(I)
          ENDIF
92        CONTINUE
        IGLOAD(II)=J
93      V(J)=0.0
      WRITE(6,119)
119   FORMAT(/,'RE-ORDERING OF MODES',/,' ORDER MODE# VARIANCE')
      WRITE(6,118)(I,IGLOAD(I),U(IGLOAD(I)),I=1,NEIG)
118   FORMAT(I4,I6,E10.3)
      WRITE(6,101)ILOOP
101   FORMAT(/,' ENSEMBLE MEAN AT LOOP NO.',I3)
C     WRITE(6,105)(I-1,I=1,8),(I,I=1,7)
105   FORMAT(/,' MODE',15X,'VARIANCE AT HARMONICS',32X,'TOTAL',10X,
     1          '% RANDOM VARIANCE', /,3X,8I8,10X,7I8)
      WRITE(6,*)' MODE TOTAL VAR  TOT RAN VAR  %RAN'
      GTOTAL=0.0
      GRAN=0.0
      DO 81 II=1,NVECT
        I=IGLOAD(II)
        TOTAL=0.0
        RAN=0.0
        IC=0
          DO 82 M=1,NREV*NPMAX+1
          V(M)=TRH(I*(I+1)/2,M,1)
          IC=IC+1
          IF(IC.EQ.NREV.OR.M.EQ.1) THEN
            IC=0
          ELSE
            RAN=RAN+V(M)
          ENDIF
82        TOTAL=TOTAL+V(M)
      GTOTAL=GTOTAL+TOTAL
      GRAN=GRAN+RAN
      WRITE(6,107)I,I,TOTAL,RAN,RAN/TOTAL*100.
107   FORMAT(I3,',',I2,2E11.2,F7.1)
81    CONTINUE
      DO 83 JJ=2,NVECT
        J=IGLOAD(JJ)
        DO 83 II=1,JJ-1
        I=IGLOAD(II)
        ICOL=J*(J-1)/2+I
        IF(I.GT.J) ICOL=I*(I-1)/2+J
        TOTAL=0.0
        RAN=0.0
        IC=0
          DO 84 M=1,NREV*NPMAX+1
          V(M)=SQRT(TRH(ICOL,M,1)**2+TRH(ICOL,M,2)**2)
          IC=IC+1
```

```
            IF(IC.EQ.NREV.OR.M.EQ.1) THEN
              IC=0
            ELSE
              RAN=RAN+V(M)
            ENDIF
84          TOTAL=TOTAL+V(M)
        GTOTAL=GTOTAL+TOTAL
        GRAN=GRAN+RAN
        WRITE(6,107)I,J,TOTAL,RAN,RAN/TOTAL*100.
83      CONTINUE
        WRITE(6,108)GTOTAL,GRAN
108     FORMAT(/,'GRAND TOTAL OF VARIANCE =',E9.3,/,
     1            'TOTAL RANDOM VARIANCE    =',E9.3)
      ENDIF
C  write csds onto storage
      REWIND 8
        DO 90 M=1,NL/2
          DO 90 I=1,NSP
90      WRITE(8,106)(TRH(I,M,K),K=1,2)
106     FORMAT(2E12.6)
      RETURN
      END
```

```
C
      SUBROUTINE STUBE(IDS,ICL)
C
C  defines the loop on all streamtubes and calls relevant subroutines.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1                ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
      PI=3.141593
      OMEGA=RPM*0.10472
      ARHOG=ARHO/1728./386.
      KV=2
      GAP=DIA/2.*2.0
      DTHETA=2.*PI/NT
C  zero matrices
      NL=NT*NREV
        DO 50 I=1,NEIG
        DO 50 J=1,NL
50      GLOAD(J,I)=0.0
C  loop on blade nodes; set up blade angle
      DO 10 II=2,NZH
      DR=(R(II+1)-R(II-1))/2.
      DZ=(Z(II+1)-Z(II-1))/2.
      DEL=ATAN(DR/DZ)
      COSD=COS(DEL)
      RR=R(II)/DIA*2.
C  determine airfoil type
      KK=NFOIL+1
1     KK=KK-1
      IF(FHT(KK).GT.ABS(Z(II))) GO TO 1
C  mean windspeed (in/sec)
      VBARZ=VBAR*((Z(II)+HMR)/HMR)**WSE*22./15.*12.
C  loop on lateral location
        DO 10 JJ=1,NT/2
        THETA=(JJ-.5)*DTHETA
C  determine distribution of mean windspeeds in streamtube
        VRW=VBARZ/DIA*2./OMEGA
        INIT=0
        ITURB=0
        PHI=0.0
        ISIGN=+1
        CALL DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
        VDEF=V1RW/VRW
C  generate time series for this streamtube
        CALL VSERIES(II,JJ)
C  turbulent flow included. Loop on revolutions for upstream disk
        ITURB=1
        INIT=1
          DO 20 IREV=1,NREV
C  velocity series index for blade #1
          KV=INT((GAP+R(II)*SIN(THETA)+VBARZ*(THETA+2.*PI*(IREV-1))
     1       /OMEGA)/VBARZ/DELT)
C  load series index for blade #1
          KL=(IREV-1)*NT+JJ
C  total ambient windspeed (non-dimensional)
          VRW=SQRT((VBARZ+VTUBE(KV,1))**2+VTUBE(KV,2)**2)
          PHI=ASIN(VTUBE(KV,2)/VRW)
          VRW=VRW/DIA*2./OMEGA
```

```
          CALL DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
C  contribution to modal loads
          CALL FMODAL(+1,II,KL)
C  blade # 2
          KV=KV+PI/DELT/OMEGA
          IF(KV.GT.NTRAN) WRITE(6,*)' KV > NTRAN'
          KL=KL+NT/2
          VRW=SQRT((VBARZ+VTUBE(KV,1))**2+VTUBE(KV,2)**2)
          PHI=ASIN(VTUBE(KV,2)/VRW)
          VRW=VRW/DIA*2./OMEGA
          CALL DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
          FNODE(1)=-FNODE(1)
          FNODE(2)=-FNODE(2)
          CALL FMODAL(2,II,KL)
20        CONTINUE
C  column loading
        IF(JJ.EQ.NT/4.AND.ICL.EQ.1) THEN
          DO 40 IREV=1,NREV
            DO 40 IT=1,NT
            AIT=IT
            TIME=RPM/60.*(IREV-1+AIT/NT)
            KV=INT((GAP+VBARZ*TIME+R(II)*(1.-1./VDEF))/VBARZ/DELT)
            IF(KV.GT.NTRAN) WRITE(6,*)' KV > NTRAN'
            KL=(IREV-1)*NT+IT
            V=SQRT((VBARZ+VTUBE(KV,1))**2+VTUBE(KV,2)**2)
            PHIC=ASIN(VTUBE(KV,2)/V)
            V=V*VDEF
C  locate neighbouring column nodes
            IC=1
2           IC=IC+1
            IF(ZCOL(IC).LT.Z(II)) GO TO 2
            PRESS=ARHOG*V*V*DZ/2.
            THETAC=2.*PI*IT/NT
40          CALL CMODAL(II,KV,KL,IC,PRESS,THETAC,PHIC)
        ENDIF
C  loop for downstream disk
      INIT=0
      ISIGN=-1
          DO 30 IREV=1,NREV
C  blade #1
          KV=INT((GAP-R(II)*SIN(THETA)*(2./VDEF-1.)
     1       +VBARZ*(2.*PI*IREV-THETA)/OMEGA)/VBARZ/DELT)
          IF(KV.GT.NTRAN) WRITE(6,*)' KV > NTRAN'
          VRW=SQRT((VBARZ+VTUBE(KV,1))**2+VTUBE(KV,2)**2)
          PHI=ASIN(VTUBE(KV,2)/VRW)
          VRW=VRW/DIA*2./OMEGA*VDEF
          KL=IREV*NT-JJ+1
          CALL DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
          CALL FMODAL(1,II,KL)
C  blade # 2
          KV=KV-PI/DELT/OMEGA
          IF(KV.LT.1) WRITE(*,*)' WARNING: KV=',KV
          KL=KL-NT/2
          VRW=SQRT((VBARZ+VTUBE(KV,1))**2+VTUBE(KV,2)**2)
          PHI=ASIN(VTUBE(KV,2)/VRW)
          VRW=VRW/DIA*2./OMEGA*VDEF
          CALL DMST(ISIGN,II,JJ,KK,KV,ITURB,INIT,IDS)
          FNODE(1)=-FNODE(1)
          FNODE(2)=-FNODE(2)
          CALL FMODAL(2,II,KL)
30        CONTINUE
10      CONTINUE
      RETURN
      END
```

```
      END
C
      SUBROUTINE TAB(ALPHR,CL,CD,CDM,INIT,KK)
C
C  Accesses the stored airfoil data and interpolates linearly between
C  Reynolds numbers. Re values are kept constant within a convergence
C  loop.
      COMMON/AIRFOIL/DSET(5,50,11),DSET1(50,2),RE(5,5),AS(5,5),
     1CDMIN(5,5),NRE(5),TC(5),NA(5),ANG(50)
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRN,
     1V1RN,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      IF(INIT.EQ.0) THEN
C if only one Re for this airfoil
        IF(NRE(KK).EQ.1) THEN
          AS1=AS(KK,1)
          CDM=CDMIN(KK,1)
            DO 10 J=1,NA(KK)
            ANG(J)=DSET(KK,J,1)
            DO 10 K=1,2
10          DSET1(J,K)=DSET(KK,J,K+1)
        ELSE
          RE2=RE1
          IF(RE1.LT.RE(KK,1)) RE2=RE(KK,1)
          IF(RE1.GT.RE(KK,NRE(KK))) RE2=RE(KK,NRE(KK))
            DO 1 I=2,NRE(KK)
            IF(RE2.LT.RE(KK,I)) GO TO 2
1           CONTINUE
2         G=(RE2-RE(KK,I-1))/(RE(KK,I)-RE(KK,I-1))
          CDM=CDMIN(KK,I-1)*(1.-G)+G*CDMIN(KK,I)
          AS1=AS(KK,I-1)*(1.-G)+G*AS(KK,I)
            DO 4 J=1,NA(KK)
            ANG(J)=DSET(KK,J,1)
            DO 4 K=1,2
4           DSET1(J,K)=(1.-G)*DSET(KK,J,2*(I-2)+K+1)+DSET(KK,J,2*(I-1)+
     1      K+1)*G
        ENDIF
      ENDIF
      AB=ALPHR*57.295
C  interpolate between angles of attack
      J=0
3     J=J+1
      IF(AB.GT.ANG(J+1)) GO TO 3
      X=(AB-ANG(J))/(ANG(J+1)-ANG(J))
      CL=DSET1(J,1)+X*(DSET1(J+1,1)-DSET1(J,1))
      CD=DSET1(J,2)+X*(DSET1(J+1,2)-DSET1(J,2))+CDM
      RETURN
      END
```

```
C
      SUBROUTINE VSERIES(II,JJ)
C
C  extracts the time series for this streamtube by linear interpolation
C  between the neighbouring locations in the spatial array.
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1              ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI
      COMMON/SPECT/S(256,5),TRH(256,136,2),VTUBE(512,2)
C  determine the lower row no in array and fractional spacing in interval
      ZZ=Z(II)+HT/2
      IROW=0
1     IROW=IROW+1
      ZROW=HT/NHT*IROW
      IF(ZZ.GT.ZROW) GO TO 1
      ZZ=ZZ/HT*NHT-(IROW-1)
C  determine lateral column no. in array
      YY=DIA/2.-R(II)*COS(THETA)
      ICOL=0
2     ICOL=ICOL+1
      YCOL=DIA/NDIA*ICOL
      IF(YY.GT.YCOL) GO TO 2
      YY=YY/DIA*NDIA-(ICOL-1)
C  identify four neighbouring array points
      I1=ICOL+(IROW-1)*(NDIA+1)
      I2=I1+1
      I3=I1+NDIA+1
      I4=I3+1
C  select the closest spatial array point
      IF(ZZ.LT.0.5) THEN
        IF(YY.LT.0.5) THEN
          IND=I1
        ELSE
          IND=I2
        ENDIF
      ELSEIF(YY.LT.0.5) THEN
        IND=I3
      ELSE
        IND=I4
      ENDIF
      IND=IND*(IND-1)/2+1
        DO 10 M=1,NTRAN
C  for longitudinal and lateral directions
          DO 10 IXY=1,2
10        VTUBE(M,IXY)=TRH(M,IND,IXY)*39.37
      RETURN
      END
```

```
C
      SUBROUTINE WRITE1(IPRINT)
C
C  this routine formulates some of the NASTRAN input and writes onto unit 7
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/ROTOR/R(40),Z(40),RPM,CH(5),FHT(5),NFOIL,INDEX(40),DAMP(30)
     1              ,INDEXC(20),ZCOL(20),DCOL(20)
      COMMON/SPECT/S(256,3),TRH(256,136,2),VTUBE(512,2)
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      NF=NDIV*NPMAX+1
      DELF=RPM/60./NDIV
      NSP=NEIG*(NEIG+1)/2
      NRD=NREV/NDIV
C  smooth spectra by bracketing
      IF(NRD.GT.1) THEN
        DO 80 I=1,NSP
          DO 80 M=2,NF
          M1=NRD*(M-2)+2
          SUM1=0.
          SUM2=0.
            DO 90 K=M1,M1+NRD-1
            SUM1=SUM1+TRH(I,K,1)
90          SUM2=SUM2+TRH(I,K,2)
          TRH(I,M,1)=SUM1
          TRH(I,M,2)=SUM2
80      CONTINUE
      ENDIF
C  suppression of unwanted modes
      IF(NVECT.LT.NEIG) CALL HSUP(NEIG,NVECT,IGLOAD)
C  define dummy load
      WRITE(7,100)
100   FORMAT('$',/,'$ DEFINITION OF DUMMY LOAD',/,'$')
        WRITE(7,101)99,99,99,99,2,1,0.0
101     FORMAT('RLOAD1  ',2I8,16X,I8,/,'DAREA   ',3I8,F8.2)
      WRITE(7,102)99,0.0,1.0,100.0,1.0
102   FORMAT('TABLED1 ',I8,56X,'+TABD100',/,'+TABD100',4F8.1,'     ENDT')
C  frequency response range
      KTAB=1000
      WRITE(7,111)
111   FORMAT('$',/,'$ FREQUENCY RESPONSE RANGE',/,'$')
      IF(IPRINT.EQ.3) THEN
        WRITE(7,112)101,0.0,DELF*NDIV,NDIV*(NF-1)
      ELSE
        WRITE(7,112)101,0.0,DELF,NF-1
      ENDIF
112   FORMAT('FREQ1   ',I8,2F8.5,I8)
C  modal (critical) damping
      WRITE(7,113)
113   FORMAT('$',/,'$   MODAL DAMPING',/,'$')
      WRITE(7,114)101,KTAB
114   FORMAT('TABDMP1 ',I8,'     CRIT',48X,'+TAB',I4)
      I1=-3
1     I1=I1+4
      I2=I1+3
```

```
      KTAB=KTAB+1
      IF(I2.LE.NEIG) THEN
        WRITE(7,117)KTAB-1,(EVALUE(L),DAMP(L),L=I1,I2),KTAB
        GO TO 1
      ELSEIF(I2-NEIG.EQ.1) THEN
        WRITE(7,118)KTAB-1,(EVALUE(L),DAMP(L),L=I1,I1+2)
      ELSEIF(I2-NEIG.EQ.2) THEN
        WRITE(7,119)KTAB-1,(EVALUE(L),DAMP(L),L=I1,I1+1)
      ELSEIF(I2-NEIG.EQ.3) THEN
        WRITE(7,120)KTAB-1,EVALUE(I1),DAMP(I1)
      ELSE
        WRITE(7,121)KTAB-1
      ENDIF
117   FORMAT('+TAB',I4,8F8.3,'+TAB',I4)
118   FORMAT('+TAB',I4,6F8.3,'     ENDT')
119   FORMAT('+TAB',I4,4F8.3,'     ENDT')
120   FORMAT('+TAB',I4,2F8.3,'     ENDT')
121   FORMAT('+TAB',I4,'     ENDT')
      CALL WRITE2(NF,NSP,NRD,DELF,KTAB,IPRINT)
      RETURN
      END
```

```
C
      SUBROUTINE WRITE2(NF,NSP,NRD,DELF,KTAB,IPRINT)
C
C  this routine formulates the spectra for NASTRAN input
      COMMON/GEOM/HT,DIA,HMR,NHT,NDIA,NZH,NT,NREV,NEIG,NLOOP,NPMAX,NDIV
     1,NVECT,NCOL
      COMMON/SPECT/S(256,3),TRH(256,136,2),VTUBE(512,2)
      COMMON/EIGEN/EIGV(80,3,22),GLOAD(256,22),EVALUE(22),IGLOAD(22)
      CHARACTER SC(256)
      DIMENSION WORK(256),NC(256)
C  definition of discrete spectral densities
      WRITE(7,103)
103   FORMAT('$',/'$ DEFINITION OF DISCRETE PSDS',/,'$')
      KRAN=1000
        DO 20 II=1,NVECT
        IF(II.EQ.5) WRITE(7,116)
116     FORMAT('ECHOOFF')
        I=IGLOAD(II)
        IC=I*(I+1)/2
        KRAN=KRAN+1
        WRITE(7,104)101,I,I,1.0,KRAN
104     FORMAT('RANDPS  ',3I8,F8.1,8X,I8)
        WRITE(7,105)KRAN,KTAB
105     FORMAT('TABRND1 ',I8,56X,'+TAB',I4)
          DO 30 M=1,NF
30        WORK(M)=TRH(IC,M,1)
C  reformat vector into condensed exponential format (to fit 8-field)
        CALL FORMT(WORK,SC,NC,NF)
          DO 70 J=1,NF/4
          NF1=(J-1)*4+1
          WRITE(7,106)KTAB,(DELF*(L-1),WORK(L),SC(L),NC(L),L=NF1,NF1+3),
     1                KTAB+1
106       FORMAT('+TAB',I4,4(F8.3,F6.4,A1,I1),'+TAB',I4)
70        KTAB=KTAB+1
        WRITE(7,107)KTAB,DELF*(NF-1),WORK(NF),SC(NF),NC(NF)
107     FORMAT('+TAB',I4,F8.3,F6.4,A1,I1,'     ENDT')
20      KTAB=KTAB+1
      WRITE(7,115)
115   FORMAT('ECHOON')
C  total variance of (min) psd
      AMIN=0.0
      I=IGLOAD(NVECT)
      ICOL=I*(I+1)/2
        DO 51 M=1,NF
51      AMIN=AMIN+TRH(ICOL,M,1)
      WRITE(6,*)'AMIN=',AMIN
C  definition of cross spectral densities
      WRITE(7,108)
108   FORMAT('$',/,'$ DEFINITION OF (UPPER TRIANGLE) CROSS SPECTRAL',
     1                '  DENSITIES',/,'$')
        DO 40 JJ=2,NVECT
        J=IGLOAD(JJ)
        IF(JJ.EQ.5) WRITE(7,116)
          DO 40 II=1,JJ-1
          I=IGLOAD(II)
```

```
C  change any lower triangle to upper triangle components
          III=I
          JJJ=J
          IF(I.GT.J)THEN
            III=J
            JJJ=I
          ENDIF
          IC=JJJ*(JJJ-1)/2+III
C  test for total variance > amin
          VAR=0.0
            DO 52 M=1,NF
52          VAR=VAR+SQRT(TRH(IC,M,1)**2+TRH(IC,M,2)**2)
          IF(VAR.GE.AMIN) THEN
C  print out real components ; first +ve then -ve
            DO 62 IS=1,2
            A=(-1.0)**(IS-1)
            VAR=0.0
              DO 50 M=1,NF
              WORK(M)=TRH(IC,M,1)*A
              IF(WORK(M).LT.0.0) WORK(M)=0.0
              VAR=VAR+WORK(M)
50            CONTINUE
            IF(VAR.GE.AMIN/2.) THEN
              CALL FORMT(WORK,SC,NC,NF)
              KRAN=KRAN+1
              WRITE(7,109)101,III,JJJ,A,KRAN
109           FORMAT('RANDPS  ',3I8,F8.1,8X,I8)
              CALL PRINT(WORK,SC,NC,NPMAX,NDIV,KTAB,KRAN,DELF,IPRINT)
            ENDIF
62          CONTINUE
C  print out imaginary components ; +ve and -ve values
            DO 63 IS=1,2
            A=(-1.0)**(IS-1)
            VAR=0.0
              DO 60 M=1,NF
              WORK(M)=TRH(IC,M,2)*A
              IF(WORK(M).LT.0.0) WORK(M)=0.0
              VAR=VAR+WORK(M)
60            CONTINUE
            IF(VAR.GE.AMIN/2.) THEN
              CALL FORMT(WORK,SC,NC,NF)
              KRAN=KRAN+1
              WRITE(7,110)101,III,JJJ,A,KRAN
110           FORMAT('RANDPS  ',3I8,8X,F8.1,I8)
              CALL PRINT(WORK,SC,NC,NPMAX,NDIV,KTAB,KRAN,DELF,IPRINT)
            ENDIF
63          CONTINUE
          ENDIF
40      CONTINUE
      WRITE(7,115)
      RETURN
      END
```

APPENDIX B.1

Basic Input Data File

```
$ TRES.DAT supplies basic data for turbulent response of VAWT
$
$ HT, DIA, HMR, RPM, VBAR, WSE, DELT, ARHO in free format
$
1440.0,991.0,900.0,45.0,45.0,0.16,0.12,0.0728
$
$ C1X, C2X, C1Y, C2Y, ZO, DECAY in free format
$
12.30,192.0,4.000,70.0,0.10,7.500
$
$ NHT,NDIA,NEIG,NT,NREV,NFOIL,NLOOP,NPMAX,NDIV,NVECT in free format
$
3,3,22,16,16,3,18,5,8,20
$
$ INCLUDE DYNAMIC STALL? "YES" OR "NO ", A3 FORMAT
YES
$ INCLUDE COLUMN LOADING? "YES" OR "NO ", A3 FORMAT
YES
$ select option (1,2,or 3) for printing of cross spectra (free format)
1
$ NFOIL(TYPE(I), CH(I), FHT(I)) in format A8,2F10.2
NACA0018    29.0       0.0
NACA0018    29.0     264.0
NACA0018    29.0     432.0
$ eigenvalue numbers and associated critical damping factors, free format
$ default value = 0.01. If no input, enter one dummy line, then end with "$"
5,0.15
6,0.15
12,0.10
13,0.10
$ end
```

APPENDIX B.2

Airfoil Data File

```
NACA0018 DATASET NO 13 FROM NRC (RJT 8 MARCH 1983)
2000000.0        14.0        .005        0.18
   0.              0.0       0.0
   2.             .190      .0002
   4.             .380      .0009
   6.             .567      .0017
   8.             .756      .0029
  10.             .939      .0033
  12.            1.111     .0053
  14.            1.210     .0135
  15.            1.054     .0344
  16.             .958      .0588
  17.             .881      .0837
  18.             .845      .1069
  19.             .809      .1280
  20.             .784      .1446
  25.             .771      .2293
  30.             .827      .3380
  35.             .947      .5374
  40.            1.020     .859
  45.            1.062     1.0492
  50.            1.052     1.209
  60.             .911      1.450
  70.             .696      1.631
  80.             .439      1.740
  90.             .157      1.790
 100.            -.130     1.764
 110.            -.402     1.664
 120.            -.612     1.450
 130.            -.738     1.172
 140.            -.738     .838
 150.            -.626     .506
 160.            -.418     .216
 170.            -.813     .103
 180.              0.0       .020
NACA0018 RE=4E6 DSET13 NRC MARCH 83
4000000.0        15.0       0.005        .18
   0.              0.0       0.0
   2.             .200      0.0
   4.             .400      0.0
   6.             .592      0.0
   8.             .796      0.0
  10.             .994      0.0
  12.            1.193     .0034
  14.            1.364     .0187
  15.            1.400     .0213
  16.            1.133     .1017
  17.             .948      .1396
  18.             .830      .1535
  19.             .792      .1790
  20.             .764      .2019
  25.             .749      .2764
  30.             .798      .3874
  35.             .917      .5808
  40.            1.048     .8261
```

APPENDIX B.3

Eigenvector Data File

```
$TITLE   =PALM SPRINGS 6400 45RPM, NO CORIOLIS, K=3000
$SUBTITLE=
$LABEL   =
$EIGENVECTOR
$REAL OUTPUT
$SUBCASE ID =          1
$EIGENVALUE =   .5992264E+01  MODE =     1
         1       G      0.                  0.                  0.
-CONT-                  0.                  0.                  0.
         2       G      0.                  0.                  0.
-CONT-                 -8.460416E-15        0.                 -1.951300E-03
         3       G      0.                  7.741558E-13        0.
-CONT-                 -7.558834E-15        0.                 -1.961254E-03
         4       G      0.                  1.453285E-12        0.
-CONT-                 -6.498071E-15        0.                 -1.969310E-03
         5       G      0.                  2.026448E-12        0.
-CONT-                 -5.364753E-15        0.                 -1.975923E-03
         6       G      0.                  2.940609E-12        0.
-CONT-                 -3.049068E-15        0.                 -1.981334E-03
         7       G      0.                  3.412840E-12        0.
-CONT-                 -1.300039E-15        0.                 -1.985085E-03
         8       G      0.                  3.494677E-12        0.
-CONT-                  5.448824E-16        0.                 -1.988904E-03
         9       G      0.                  3.078412E-12        0.
-CONT-                  3.292186E-15        0.                 -1.994657E-03
        10       G      0.                  2.683838E-12        0.
-CONT-                  4.874994E-15        0.                 -1.994146E-03
        11       G      0.                  2.128303E-12        0.
-CONT-                  6.631941E-15        0.                 -1.993506E-03
        12       G      0.                  1.394859E-12        0.
-CONT-                  8.561512E-15        0.                 -1.992687E-03
        13       G      0.                  1.222619E-12        0.
-CONT-                  8.580818E-15        0.                 -1.992687E-03
       100       G      0.                 -4.543657E-02        0.
-CONT-                  4.797338E-07        0.                 -1.950997E-03
       101       G      0.                 -1.447585E-01        0.
-CONT-                  9.300124E-06        0.                 -1.951070E-03
       102       G      0.                 -2.434272E-01        0.
-CONT-                  1.965108E-05        0.                 -1.957242E-03
       103       G      0.                 -3.424556E-01        0.
-CONT-                  2.556369E-05        0.                 -1.963388E-03
       104       G      0.                 -4.404916E-01        0.
-CONT-                  2.732972E-05        0.                 -1.970015E-03
       105       G      0.                 -5.362534E-01        0.
-CONT-                  2.560468E-05        0.                 -1.977375E-03
       106       G      0.                 -5.839858E-01        0.
-CONT-                  2.370973E-05        0.                 -1.981197E-03
       107       G      0.                 -6.279056E-01        0.
-CONT-                  2.969094E-05        0.                 -1.982946E-03
       108       G      0.                 -7.162363E-01        0.
-CONT-                  4.613854E-05        0.                 -1.988790E-03
       109       G      0.                 -7.999570E-01        0.
-CONT-                  4.765566E-05        0.                 -2.001440E-03
       110       G      0.                 -8.404062E-01        0.
-CONT-                  4.495988E-05        0.                 -2.009736E-03
```

111	G	0.	-8.738739E-01	0.	56
-CONT-		4.048050E-05	0.	-2.020712E-03	57
112	G	0.	-9.324863E-01	0.	58
-CONT-		2.972419E-05	0.	-2.047984E-03	59
113	G	0.	-9.746347E-01	0.	60
-CONT-		2.007732E-05	0.	-2.076898E-03	61
114	G	0.	-9.969798E-01	0.	62
-CONT-		1.338047E-05	0.	-2.099554E-03	63
115	G	0.	-1.000000E+00	0.	64
-CONT-		1.073739E-05	0.	-2.104685E-03	65
116	G	0.	-9.977098E-01	0.	66
-CONT-		8.256779E-06	0.	-2.104661E-03	67
117	G	0.	-9.768001E-01	0.	68
-CONT-		2.750417E-06	0.	-2.091469E-03	69
118	G	0.	-9.358821E-01	0.	70
-CONT-		-5.535946E-06	0.	-2.068658E-03	71
119	G	0.	-8.782242E-01	0.	72
-CONT-		-1.611908E-05	0.	-2.043396E-03	73
120	G	0.	-8.451187E-01	0.	74
-CONT-		-2.127057E-05	0.	-2.032009E-03	75
121	G	0.	-8.049382E-01	0.	76
-CONT-		-2.577973E-05	0.	-2.021824E-03	77
122	G	0.	-7.215984E-01	0.	78
-CONT-		-2.913368E-05	0.	-2.004337E-03	79
123	G	0.	-6.334825E-01	0.	80
-CONT-		-1.885778E-05	0.	-1.992791E-03	81
124	G	0.	-5.896183E-01	0.	82
-CONT-		-6.114927E-06	0.	-2.000540E-03	83
125	G	0.	-5.418628E-01	0.	84
-CONT-		-7.005402E-06	0.	-1.999666E-03	85
126	G	0.	-4.458659E-01	0.	86
-CONT-		-7.963779E-06	0.	-1.997520E-03	87
127	G	0.	-3.472977E-01	0.	88
-CONT-		-7.446880E-06	0.	-1.995170E-03	89
128	G	0.	-2.473923E-01	0.	90
-CONT-		-4.893651E-06	0.	-1.992478E-03	91
129	G	0.	-1.474615E-01	0.	92
-CONT-		2.060397E-07	0.	-1.989273E-03	93
130	G	0.	-4.639232E-02	0.	94
-CONT-		5.065480E-07	0.	-1.992562E-03	95
200	G	0.	4.543657E-02	0.	96
-CONT-		-4.797338E-07	0.	-1.950997E-03	97
201	G	0.	1.447585E-01	0.	98
-CONT-		-9.300124E-06	0.	-1.951070E-03	99
202	G	0.	2.434272E-01	0.	100
-CONT-		-1.965108E-05	0.	-1.957242E-03	101
203	G	0.	3.424556E-01	0.	102
-CONT-		-2.556369E-05	0.	-1.963388E-03	103
204	G	0.	4.404916E-01	0.	104
-CONT-		-2.732972E-05	0.	-1.970015E-03	105
205	G	0.	5.362534E-01	0.	106
-CONT-		-2.560468E-05	0.	-1.977375E-03	107
206	G	0.	5.839858E-01	0.	108
-CONT-		-2.370973E-05	0.	-1.981197E-03	109
207	G	0.	6.279056E-01	0.	110
-CONT-		-2.969094E-05	0.	-1.982946E-03	111
208	G	0.	7.162363E-01	0.	112
-CONT-		-4.613854E-05	0.	-1.988790E-03	113
209	G	0.	7.999570E-01	0.	114
-CONT-		-4.765566E-05	0.	-2.001440E-03	115

```
       210        G      0.                  8.404062E-01      0.                  116
-CONT-                  -4.495988E-05       0.               -2.009736E-03        117
       211        G      0.                  8.738739E-01      0.                  118
-CONT-                  -4.048050E-05       0.               -2.020712E-03        119
       212        G      0.                  9.324863E-01      0.                  120
-CONT-                  -2.972419E-05       0.               -2.047984E-03        121
       213        G      0.                  9.746347E-01      0.                  122
-CONT-                  -2.007732E-05       0.               -2.076898E-03        123
       214        G      0.                  9.969798E-01      0.                  124
-CONT-                  -1.338047E-05       0.               -2.099554E-03        125
       215        G      0.                  1.000000E+00      0.                  126
-CONT-                  -1.073739E-05       0.               -2.104685E-03        127
       216        G      0.                  9.977098E-01      0.                  128
-CONT-                  -8.256779E-06       0.               -2.104661E-03        129
       217        G      0.                  9.768001E-01      0.                  130
-CONT-                  -2.750417E-06       0.               -2.091469E-03        131
       218        G      0.                  9.358821E-01      0.                  132
-CONT-                   5.535946E-06       0.               -2.068658E-03        133
       219        G      0.                  8.782242E-01      0.                  134
-CONT-                   1.611908E-05       0.               -2.043396E-03        135
       220        G      0.                  8.451187E-01      0.                  136
-CONT-                   2.127057E-05       0.               -2.032009E-03        137
       221        G      0.                  8.049382E-01      0.                  138
-CONT-                   2.577973E-05       0.               -2.021824E-03        139
       222        G      0.                  7.215984E-01      0.                  140
-CONT-                   2.913368E-05       0.               -2.004337E-03        141
       223        G      0.                  6.334825E-01      0.                  142
-CONT-                   1.885778E-05       0.               -1.992791E-03        143
       224        G      0.                  5.896183E-01      0.                  144
-CONT-                   6.114927E-06       0.               -2.000540E-03        145
       225        G      0.                  5.418628E-01      0.                  146
-CONT-                   7.005402E-06       0.               -1.999666E-03        147
       226        G      0.                  4.458659E-01      0.                  148
-CONT-                   7.963779E-06       0.               -1.997520E-03        149
       227        G      0.                  3.472977E-01      0.                  150
-CONT-                   7.446880E-06       0.               -1.995170E-03        151
       228        G      0.                  2.473923E-01      0.                  152
-CONT-                   4.893651E-06       0.               -1.992478E-03        153
       229        G      0.                  1.474615E-01      0.                  154
-CONT-                  -2.060397E-07       0.               -1.989273E-03        155
       230        G      0.                  4.639232E-02      0.                  156
-CONT-                  -5.065480E-07       0.               -1.992562E-03        157
       300        G      0.                 -2.917982E-01      0.                  158
-CONT-                   1.183974E-05       0.               -1.979445E-03        159
       305        G      0.                  4.183987E-12      0.                  160
-CONT-                  -5.364753E-15       0.               -1.975923E-03        161
       310        G      0.                  2.917982E-01      0.                  162
-CONT-                  -1.183974E-05       0.               -1.979445E-03        163
       400        G      0.                 -2.945913E-01      0.                  164
-CONT-                  -3.055512E-06       0.               -1.998526E-03        165
       409        G      0.                  4.619135E-12      0.                  166
-CONT-                   3.292186E-15       0.               -1.994657E-03        167
       410        G      0.                  2.945913E-01      0.                  168
-CONT-                   3.055512E-06       0.               -1.998526E-03        169
      2000        G      0.                  0.                0.                  170
-CONT-                   0.                  0.                0.                  171
$TITLE   =PALM SPRINGS 6400 45RPM, NO CORIOLIS, K=3000                             172
$SUBTITLE=                                                                         173
$LABEL   =                                                                         174
$EIGENVECTOR                                                                       175
```

```
$REAL OUTPUT                                                                    176
$SUBCASE ID =          1                                                        177
$EIGENVALUE =   .6857640E+02  MODE =     2                                      178
        1       G      0.                 0.                 0.                 179
-CONT-                 0.                 0.                 0.                 180
        2       G      0.                 0.                 0.                 181
-CONT-                -7.170108E-04       0.                 9.936337E-15       182
        3       G      0.                 6.723824E-02       0.                 183
-CONT-                -6.708198E-04       0.                 1.030342E-14       184
        4       G      0.                 1.284699E-01       0.                 185
-CONT-                -5.938177E-04       0.                 1.060729E-14       186
        5       G      0.                 1.813622E-01       0.                 187
-CONT-                -4.986636E-04       0.                 1.085006E-14       188
        6       G      0.                 2.669915E-01       0.                 189
-CONT-                -2.864449E-04       0.                 1.092268E-14       190
        7       G      0.                 3.108628E-01       0.                 191
-CONT-                -1.153568E-04       0.                 1.096827E-14       192
        8       G      0.                 3.162276E-01       0.                 193
-CONT-                 6.288997E-05       0.                 1.101756E-14       194
        9       G      0.                 2.756917E-01       0.                 195
-CONT-                 3.064700E-04       0.                 1.110196E-14       196
       10       G      0.                 2.400257E-01       0.                 197
-CONT-                 4.259010E-04       0.                 1.010499E-14       198
       11       G      0.                 1.935103E-01       0.                 199
-CONT-                 5.302815E-04       0.                 8.853785E-15       200
       12       G      0.                 1.382960E-01       0.                 201
-CONT-                 6.042504E-04       0.                 7.255492E-15       202
       13       G      0.                 1.261093E-01       0.                 203
-CONT-                 6.061607E-04       0.                 7.255492E-15       204
      100       G      0.                 1.523087E-02       0.                 205
```

APPENDIX B.4

NASTRAN Bulk Data File

```
$
BEGIN BULK
$
$ SANDIA 17M LOW COST (ROUGH MODEL) TR2BUL
$
$  BLADE 1 NODES
$
GRID          100            45.20          -455.00
GRID          101           136.27          -370.00
GRID          102           219.93          -279.00
GRID          103           288.85          -177.00
GRID          104           330.39           -61.00
GRID          105           336.00              .00
GRID          106           330.39            61.00
GRID          107           288.85           177.00
GRID          108           219.93           279.00
GRID          109           136.27           370.00
GRID          110            45.20           455.00
$
$  BLADE 2 NODES
$
GRID          200           -45.20          -455.00
GRID          201          -136.27          -370.00
GRID          202          -219.93          -279.00
GRID          203          -288.85          -177.00
GRID          204          -330.39           -61.00
GRID          205          -336.00              .00
GRID          206          -330.39            61.00
GRID          207          -288.85           177.00
GRID          208          -219.93           279.00
GRID          209          -136.27           370.00
GRID          210           -45.20           455.00
$
$  BLADE 1 CONNECTIONS
$
CBEAM         100      100        2      100     -1.0
CBEAM         101      101      100      101     -1.0
CBEAM         102      101      101      102     -1.0
CBEAM         103      101      102      103     -1.0
CBEAM         104      101      103      104     -1.0
CBEAM         105      101      104      105     -1.0
CBEAM         106      101      105      106     -1.0
CBEAM         107      101      106      107     -1.0
CBEAM         108      101      107      108     -1.0
CBEAM         109      101      108      109     -1.0
CBEAM         110      101      109      110     -1.0
CBEAM         111      100      110        6     -1.0
$
$ BLADE 2 CONNECTIONS
$
CBEAM         200      100        2      200     -1.0
CBEAM         201      101      200      201     -1.0
CBEAM         202      101      201      202     -1.0
CBEAM         203      101      202      203     -1.0
CBEAM         204      101      203      204     -1.0
CBEAM         205      101      204      205     -1.0
CBEAM         206      101      205      206     -1.0
CBEAM         207      101      206      207     -1.0
CBEAM         208      101      207      208     -1.0
CBEAM         209      101      208      209     -1.0
```

```
CBEAM        210     101     209     210    -1.0
CBEAM        211     100     210       6    -1.0
$
$ COLUMN GRID POINTS
$
GRID           2                          -495.50              123            24.00
GRID           3                          -247.75                0              .00
GRID           4                              .00                0            24.00
GRID           5                           247.75                0              .00
GRID           6                           495.50                0            24.00
GRID           7                           515.50                0            12.00
$
$ COLUMN CONNECTIONS
$
CBEAM          2       2       2       3     1.0
CBEAM          3       3       3       4     1.0
CBEAM          4       4       4       5     1.0
CBEAM          5       5       5       6     1.0
CBEAM          6       6       6       7     1.0
$
$ CONCENTRATED MASSES
$
CONM2          7       7          495.50
$
$ SECTION PROPERTIES - BLADES
$
PBEAM        101      20   13.90    20.3   680.0            80.0        +P101A
+P101A       .00  -10.80     .00   13.20    1.80     .00   -1.80     .00+P101B
+P101B  YESA        1.00
PBEAM        100      20   50.00   500.0 10000.0           600.0
$  PROPERTIES OF COLUMN
PBEAM          2      10   18.00  1356.0  1356.0          2712.0        +P12A
+P12A        .00   12.00     .00  -12.00   12.00     .00  -12.00     .00+P12B
+P12B   YESA        1.00
PBEAM          3      10   18.00  1356.0  1356.0          2712.0        +P13A
+P13A        .00   12.00     .00  -12.00   12.00     .00  -12.00     .00+P13B
+P13B   YESA        1.00
PBEAM          4      10   18.00  1356.0  1356.0          2712.0        +P14A
+P14A        .00   12.00     .00  -12.00   12.00     .00  -12.00     .00+P14B
+P14B   YESA        1.00
PBEAM          5      10   18.00  1356.0  1356.0          2712.0        +P15A
+P15A        .00   12.00     .00  -12.00   12.00     .00  -12.00     .00+P15B
+P15B   YESA        1.00
PBEAM          6      10   18.00  1356.0  1356.0          2712.0        +P16A
+P16A        .00   12.00     .00  -12.00   12.00     .00  -12.00     .00+P16B
+P16B   YESA        1.00
$
$ MATERIAL PROPERTIES
$
MAT1          10.290E+08.115E+08            .283
MAT1          20.106E+08.376E+07            .098
$
$ (PSEUDO) STATIC LOADS: ROTATION, GRAVITY & GUYS
RFORCE        13                     .867      .0      .0     1.0       2
GRAV          12           386.0                    -1.0
FORCE         11       7          30000.                      -1.0
$
PARAM   WTMASS    .00259
$
$ UPPER RESTRAINT
```

```
$
GRID        2000                            515.50          123456
CELAS2      2001  10000.       7       1    2000       1
CELAS2      2002  10000.       7       2    2000       2
$
$ LOWER RESTRAINT
$
GRID           1                           -495.50          123456
CELAS2      1000.500E+08       2       6       1       6
CDAMP2      1001.100E+07       2       6       1       6
$
LOAD         100     1.0     1.0      11     1.0      12     1.0      13
$
EIGC          11HESS    MAX                                                +EIGC1
+EIGC1         .0    10.7      .0    13.2     3.0       1      12
EIGR,21,MGIV,,,30,30,,,+EIGR1
+EIGR1,MASS
$
$ASET1,12,4,6
$ASET1,123,101,103,105,107,109
$ASET1,123,201,203,205,207,209
$
$PARAM,RESDUAL,-1
$PARAM,NEWDYN,-1
$PARAM,SEMAP1,-1
$PARAM,LMODES,22
$PARAM,DDRMM,-1
$PARAM,G,.02
$
$  ROTATING FRAME EFFECTS
$
PARAM   OMEGA      5.445
DMI     SKEW           0       1       1       0               6       6
DMI     SKEW           2       1   -1.00
DMI     SKEW           1       2   +1.00
DMI     SYM            0       6       1       0               6       6
DMI     SYM            1       1    1.00
DMI     SYM            2       2    1.00
DMIG    SOFTNING       0       6       1       0
DMIG    SOFTNING       4       1               4       1  .1E-09
DMIG    CORIOL         0       1       1       0
DMIG    CORIOL         4       1               4       2  .1E-09
DMIG    CORIOL         4       2               4       1  .1E-09
$
ENDDATA
```

APPENDIX C.1

Output File TRES.OUT

```
TRES. CALCULATION OF ROTOR AERODYNAMIC LOADS UNDER TURBULENT WINDS
D.J.MALCOLM, APRIL 1986

ROTOR HEIGHT                =1440.0 INS  = 36.6 M
ROTOR DIAMETER              = 991.0 INS  = 25.2 M
MID-ROTOR HEIGHT            = 900.0 INS  = 22.9 M
ROTOR SPEED                 =  45.0 RPM  =4.713 RAD/S
MID ROTOR WINDSPEED         =  45.0 MPH  = 20.1 M/S
WIND SHEAR EXPONENT         =  .160
AIR DENSITY                 = .0728 LB/FT3
TIME SERIES: DELTA T        =  .120 SECS
# VERT DIV IN WIND ARRAY   =     1
# LAT DIV IN WIND ARRAY    =     1
FROST & TURNER: C1X         = 2.000
FROST & TURNER: C2X         =  80.0
FROST & TURNER: C1Y         = 1.000
FROST & TURNER: C2Y         =  50.0
SURFACE ROUGHNESS           =  .100 M
DECAY COEFFICIENT FOR CSDs= 7.500
NO OF EIGENVECTORS USED     =    10
# EIGENVECTORS IN SOLUTION=    10
NO OF DIVISIONS IN CYCLE    =    16
NO OF ROTOR REVOLUTIONS     =     8
MAX PER-REV MULTIPLE        =     3
OUTPUT: # DIVISIONS/CYCLE =     4
# ENSEMBLE VALUES           =     1
DYNAMIC STALL?                  YES
COLUMN LOADING?                 YES
PRINT OPTION # FOR CSDs     =     1

LENGTH OF WINDSPEED SERIES=   128
LENGTH OF LOAD SERIES       =   128

AIRFOIL TYPE   CHORD(IN)   START-HT(IN)
NACA0018      29.00        .00
NACA0018      29.00     264.00
NACA0018      29.00     432.00

MODE  CRITICAL DAMPING
  5       .01
  6       .01
 11       .01
 12       .01

# OF ELEMENTS PER BLADE    =    32
TOTAL # OF COLUMN ELEMENTS  =    11

MODE  EIGENVALUE
  1     .390
  2    1.318
  3    1.871
  4    2.556
  5    2.825
  6    2.879
  7    3.390
  8    4.039
  9    5.045
 10    5.068

MID-ROTOR LONGITUDINAL TURBULENCE
```

STANDARD DEVIATION = 4.69 MPH
COEFF OF VARIATION = .10

MID-ROTOR LATERAL TURBULENCE
STANDARD DEVIATION = 3.84 MPH
COEFF OF VARIATION = .09

RE-ORDERING OF MODES

ORDER	MODE#	VARIANCE
1	3	.274E+08
2	8	.203E+08
3	1	.597E+07
4	4	.991E+06
5	2	.904E+06
6	6	.350E+06
7	10	.299E+06
8	5	.236E+06
9	9	.193E+06
10	7	.971E+05

ENSEMBLE MEAN AT LOOP NO. 1

MODE	TOTAL VAR	TOT RAN VAR	%RAN
3, 3	.27E+08	.13E+06	.5
8, 8	.20E+08	.93E+05	.5
1, 1	.60E+07	.63E+05	1.1
4, 4	.99E+06	.33E+05	3.4
2, 2	.90E+06	.66E+05	7.3
6, 6	.35E+06	.26E+06	73.3
10,10	.30E+06	.94E+04	3.1
5, 5	.24E+06	.15E+06	65.2
9, 9	.19E+06	.11E+05	5.9
7, 7	.97E+05	.19E+05	19.6
3, 8	.24E+08	.94E+05	.4
3, 1	.27E+06	.54E+05	20.3
8, 1	.30E+06	.51E+05	17.0
3, 4	.48E+07	.47E+05	1.0
8, 4	.40E+07	.38E+05	1.0
1, 4	.86E+05	.31E+05	36.1
3, 2	.34E+07	.78E+05	2.3
8, 2	.27E+07	.53E+05	1.9
1, 2	.14E+06	.40E+05	28.7
4, 2	.86E+06	.38E+05	4.5
3, 6	.35E+06	.11E+06	31.3
8, 6	.31E+06	.10E+06	33.2
1, 6	.50E+06	.11E+06	21.4
4, 6	.12E+06	.64E+05	55.0
2, 6	.12E+06	.73E+05	59.6
3,10	.19E+06	.24E+05	12.6
8,10	.17E+06	.19E+05	11.3
1,10	.13E+07	.21E+05	1.6
4,10	.58E+05	.14E+05	23.6
2,10	.74E+05	.17E+05	23.2
6,10	.13E+06	.40E+05	31.5
3, 5	.13E+07	.12E+06	9.4
8, 5	.10E+07	.95E+05	9.1
1, 5	.20E+06	.69E+05	34.6
4, 5	.32E+06	.57E+05	18.1
2, 5	.32E+06	.72E+05	22.7
6, 5	.17E+06	.13E+06	76.1
10, 5	.68E+05	.30E+05	44.3
3, 9	.11E+06	.29E+05	26.1
8, 9	.10E+06	.23E+05	22.8
1, 9	.10E+07	.24E+05	2.3
4, 9	.39E+05	.15E+05	38.7
2, 9	.55E+05	.21E+05	38.7
6, 9	.13E+06	.44E+05	34.3
10, 9	.24E+06	.91E+04	3.9
5, 9	.64E+05	.32E+05	50.3
3, 7	.14E+07	.36E+05	2.6
8, 7	.12E+07	.29E+05	2.5
1, 7	.49E+05	.21E+05	43.1
4, 7	.29E+06	.21E+05	7.1
2, 7	.26E+06	.30E+05	11.3
6, 7	.60E+05	.45E+05	75.8
10, 7	.24E+05	.89E+04	36.7
5, 7	.11E+06	.40E+05	35.1
9, 7	.19E+05	.10E+05	54.9

GRAND TOTAL OF VARIANCE = .109E+09
TOTAL RANDOM VARIANCE = .297E+07

APPENDIX C.2

Output File TRES1.OUT

```
$
$ DE-ACTIVATE UNWANTED MODES
$
DMI     HSUP            0       2       1       0                   22       1
DMI     HSUP            1      11     1.0      21     1.0
$
$ DEFINITION OF DUMMY LOAD
$
RLOAD1         99      99                      99
DAREA          99       2       1     .00
TABLED1        99                                                          +TABD100
+TABD100       .0     1.0   100.0     1.0    ENDT
$
$ FREQUENCY RESPONSE RANGE
$
FREQ1         101  .00000  .09375      40
$
$   MODAL DAMPING
$
TABDMP1       101    CRIT                                                   +TAB1000
+TAB1000     .390    .010   1.318    .010   1.871    .010   2.556    .010+TAB1001
+TAB1001    2.825    .150   2.879    .150   3.390    .010   4.039    .010+TAB1002
+TAB1002    5.045    .010   5.068    .010   5.425    .100   5.434    .100+TAB1003
+TAB1003    5.513    .010   6.261    .010   6.443    .010   7.285    .010+TAB1004
+TAB1004    7.419    .010   7.615    .010   8.434    .010   9.621    .010+TAB1005
+TAB1005    9.970    .010  10.382    .010    ENDT
$
$ DEFINITION OF DISCRETE PSDS
$
RANDPS        101       3       3     1.0            1001
TABRND1      1001                                                          +TAB1006
+TAB1006     .000 .1751+4    .094 .1070+5    .188 .1280+5    .281 .1333+5+TAB1007
+TAB1007     .375 .2096+5    .469 .1886+5    .563 .5292+5    .656 .1608+6+TAB1008
+TAB1008     .750 .2619+8    .844 .2942+6    .938 .6012+5   1.031 .4351+5+TAB1009
+TAB1009    1.125 .1178+5   1.219 .8827+4   1.313 .6401+4   1.406 .8216+4+TAB1010
+TAB1010    1.500 .4918+4   1.594 .8193+4   1.688 .7636+4   1.781 .5691+4+TAB1011
+TAB1011    1.875 .5120+4   1.969 .1146+5   2.063 .9996+4   2.156 .3159+5+TAB1012
+TAB1012    2.250 .8787+6   2.344 .8261+5   2.438 .4505+5   2.531 .2203+5+TAB1013
+TAB1013    2.625 .1269+5   2.719 .9194+4   2.813 .7274+4   2.906 .3732+4+TAB1014
+TAB1014    3.000 .4793+4   3.094 .3288+4   3.188 .5011+4   3.281 .4306+4+TAB1015
+TAB1015    3.375 .3744+4   3.469 .1181+5   3.563 .4213+4   3.656 .6606+4+TAB1016
+TAB1016    3.750 .3430+5    ENDT
RANDPS        101       8       8     1.0            1002
TABRND1      1002                                                          +TAB1017
+TAB1017     .000 .2828+4    .094 .8613+4    .188 .5817+4    .281 .8352+4+TAB1018
+TAB1018     .375 .9205+4    .469 .2513+5    .563 .3830+5    .656 .6836+5+TAB1019
+TAB1019     .750 .1704+8    .844 .1174+6    .938 .4565+5   1.031 .2898+5+TAB1020
+TAB1020    1.125 .8429+4   1.219 .8683+4   1.313 .7854+4   1.406 .1204+5+TAB1021
+TAB1021    1.500 .6791+4   1.594 .5720+4   1.688 .7123+4   1.781 .5017+4+TAB1022
+TAB1022    1.875 .5749+4   1.969 .1420+5   2.063 .1219+5   2.156 .2252+5+TAB1023
+TAB1023    2.250 .4238+6   2.344 .8432+5   2.438 .4071+5   2.531 .1999+5+TAB1024
+TAB1024    2.625 .1927+5   2.719 .9650+4   2.813 .7899+4   2.906 .4699+4+TAB1025
+TAB1025    3.000 .5621+4   3.094 .3838+4   3.188 .4738+4   3.281 .7497+4+TAB1026
+TAB1026    3.375 .7788+4   3.469 .8669+4   3.563 .7344+4   3.656 .1036+5+TAB1027
+TAB1027    3.750 .2669+5    ENDT
RANDPS        101       1       1     1.0            1003
TABRND1      1003                                                          +TAB1028
+TAB1028     .000 .3598+7    .094 .3636+5    .188 .2142+5    .281 .1327+5+TAB1029
+TAB1029     .375 .5082+4    .469 .2762+4    .563 .3214+4    .656 .4225+4+TAB1030
+TAB1030     .750 .3616+4    .844 .3399+4    .938 .3115+4   1.031 .3184+4+TAB1031
```

```
+TAB1031   1.125 .3587+4   1.219 .1550+5   1.313 .1405+5   1.406 .2734+5+TAB1032
+TAB1032   1.500 .1098+7   1.594 .7385+5   1.688 .3624+5   1.781 .1877+5+TAB1033
+TAB1033   1.875 .9137+4   1.969 .4512+4   2.063 .4227+4   2.156 .2167+4+TAB1034
+TAB1034   2.250 .2416+4   2.344 .2227+4   2.438 .2174+4   2.531 .3319+4+TAB1035
+TAB1035   2.625 .4282+4   2.719 .3750+4   2.813 .6832+4   2.906 .1134+5+TAB1036
+TAB1036   3.000 .1372+6   3.094 .5369+5   3.188 .2836+5   3.281 .2274+5+TAB1037
+TAB1037   3.375 .1072+5   3.469 .6166+4   3.563 .4680+4   3.656 .3610+4+TAB1038
+TAB1038   3.750 .2399+4    ENDT
```

additional auto spectral density tables

```
$
$ DEFINITION OF (UPPER TRIANGLE) CROSS SPECTRAL DENSITIES
$
RANDPS      101       3       8     1.0            1021
TABRND1    1021                                                      +TAB1226
+TAB1226    .000 .1129+4    .094 .4951+4    .188 .3307+4    .281 .3552+4+TAB1227
+TAB1227    .375 .7904+4    .469 .1253+5    .563 .2962+5    .656 .8183+5+TAB1228
+TAB1228    .750 .2105+8    .844 .1621+6    .938 .3550+5   1.031 .1958+5+TAB1229
+TAB1229   1.125 .2694+4   1.219 .3628+4   1.313 .2576+4   1.406 .5491+4+TAB1230
+TAB1230   1.500 .2577+4   1.594 .2432+4   1.688 .3665+4   1.781 .1968+4+TAB1231
+TAB1231   1.875 .1104+4   1.969 .8490+4   2.063 .5385+4   2.156 .1783+5+TAB1232
+TAB1232   2.250 .6019+6   2.344 .7525+5   2.438 .3611+5   2.531 .1538+5+TAB1233
+TAB1233   2.625 .1169+5   2.719 .5815+4   2.813 .4220+4   2.906 .1903+4+TAB1234
+TAB1234   3.000 .2473+4   3.094 .1021+4   3.188 .1594+4   3.281 .1794+4+TAB1235
+TAB1235   3.375 .2385+4   3.469 .4662+4   3.563 .3114+4   3.656 .4147+4+TAB1236
+TAB1236   3.750 .2480+5    ENDT
RANDPS      101       3       8               1.0    1022
TABRND1    1022                                                      +TAB1237
+TAB1237    .000 .0000+0    .094 .0000+0    .188 .0000+0    .281 .0000+0+TAB1238
+TAB1238    .375 .3216+4    .469 .0000+0    .563 .5008+4    .656 .0000+0+TAB1239
+TAB1239    .750 .1094+7    .844 .0000+0    .938 .0000+0   1.031 .1874+4+TAB1240
+TAB1240   1.125 .4337+4   1.219 .0000+0   1.313 .5700+3   1.406 .0000+0+TAB1241
+TAB1241   1.500 .2297+2   1.594 .2590+3   1.688 .9317+3   1.781 .1319+3+TAB1242
+TAB1242   1.875 .2510+3   1.969 .2144+4   2.063 .0000+0   2.156 .0000+0+TAB1243
+TAB1243   2.250 .9390+4   2.344 .0000+0   2.438 .0000+0   2.531 .8896+3+TAB1244
+TAB1244   2.625 .0000+0   2.719 .0000+0   2.813 .2434+3   2.906 .0000+0+TAB1245
+TAB1245   3.000 .0000+0   3.094 .1650+3   3.188 .8525+2   3.281 .1437+3+TAB1246
+TAB1246   3.375 .5033+3   3.469 .0000+0   3.563 .0000+0   3.656 .0000+0+TAB1247
+TAB1247   3.750 .0000+0    ENDT
RANDPS      101       1       3    -1.0            1023
TABRND1    1023                                                      +TAB1248
+TAB1248    .000 .2449+5    .094 .0000+0    .188 .2514+4    .281 .0000+0+TAB1249
+TAB1249    .375 .9570+3    .469 .3287+3    .563 .4152+3    .656 .0000+0+TAB1250
+TAB1250    .750 .5896+5    .844 .4616+4    .938 .3484+3   1.031 .0000+0+TAB1251
+TAB1251   1.125 .0000+0   1.219 .2595+4   1.313 .0000+0   1.406 .0000+0+TAB1252
+TAB1252   1.500 .1637+4   1.594 .0000+0   1.688 .1411+4   1.781 .0000+0+TAB1253
+TAB1253   1.875 .0000+0   1.969 .0000+0   2.063 .5681+3   2.156 .0000+0+TAB1254
+TAB1254   2.250 .1771+5   2.344 .5187+2   2.438 .0000+0   2.531 .0000+0+TAB1255
+TAB1255   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .7789+3+TAB1256
+TAB1256   3.000 .0000+0   3.094 .0000+0   3.188 .0000+0   3.281 .1171+4+TAB1257
+TAB1257   3.375 .0000+0   3.469 .1411+4   3.563 .2584+3   3.656 .5998+3+TAB1258
+TAB1258   3.750 .7163+3    ENDT
RANDPS      101       1       3              -1.0    1024
TABRND1    1024                                                      +TAB1259
+TAB1259    .000 .0000+0    .094 .3942+4    .188 .3573+4    .281 .2201+4+TAB1260
```

```
+TAB1260    .375 .3029+3    .469 .1545+4    .563 .2270+4    .656 .3188+4+TAB1261
+TAB1261    .750 .1001+6    .844 .0000+0    .938 .0000+0   1.031 .0000+0+TAB1262
+TAB1262   1.125 .0000+0   1.219 .0000+0   1.313 .0000+0   1.406 .0000+0+TAB1263
+TAB1263   1.500 .0000+0   1.594 .9644+4   1.688 .2951+4   1.781 .2825+4+TAB1264
+TAB1264   1.875 .2640+3   1.969 .2067+4   2.063 .1122+4   2.156 .1736+4+TAB1265
+TAB1265   2.250 .2878+4   2.344 .0000+0   2.438 .0000+0   2.531 .0000+0+TAB1266
+TAB1266   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .6437+2+TAB1267
+TAB1267   3.000 .0000+0   3.094 .1682+4   3.188 .2337+4   3.281 .9154+3+TAB1268
+TAB1268   3.375 .2316+4   3.469 .8329+3   3.563 .0000+0   3.656 .4887+3+TAB1269
+TAB1269   3.750 .0000+0    ENDT
RANDPS       101       1       8    -1.0            1025
TABRND1     1025                                                      +TAB1270
+TAB1270    .000 .8265+5    .094 .0000+0    .188 .0000+0    .281 .0000+0+TAB1271
+TAB1271    .375 .1199+3    .469 .8523+3    .563 .0000+0    .656 .0000+0+TAB1272
+TAB1272    .750 .4362+5    .844 .0000+0    .938 .8886+3   1.031 .0000+0+TAB1273
+TAB1273   1.125 .3420+3   1.219 .4495+3   1.313 .0000+0   1.406 .0000+0+TAB1274
+TAB1274   1.500 .8250+4   1.594 .3093+4   1.688 .3107+3   1.781 .0000+0+TAB1275
+TAB1275   1.875 .0000+0   1.969 .3891+3   2.063 .1084+4   2.156 .8748+3+TAB1276
+TAB1276   2.250 .1355+5   2.344 .0000+0   2.438 .0000+0   2.531 .0000+0+TAB1277
+TAB1277   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .0000+0+TAB1278
+TAB1278   3.000 .1864+4   3.094 .0000+0   3.188 .3894+3   3.281 .1238+4+TAB1279
+TAB1279   3.375 .4039+3   3.469 .4708+3   3.563 .0000+0   3.656 .4867+3+TAB1280
+TAB1280   3.750 .5802+3    ENDT
RANDPS       101       1       8            -1.0    1026
TABRND1     1026                                                      +TAB1281
+TAB1281    .000 .0000+0    .094 .3835+4    .188 .2626+4    .281 .2053+4+TAB1282
+TAB1282    .375 .1025+4    .469 .1004+4    .563 .3563+4    .656 .2849+4+TAB1283
+TAB1283    .750 .8243+5    .844 .0000+0    .938 .0000+0   1.031 .0000+0+TAB1284
+TAB1284   1.125 .0000+0   1.219 .0000+0   1.313 .0000+0   1.406 .0000+0+TAB1285
+TAB1285   1.500 .0000+0   1.594 .4599+2   1.688 .2737+1   1.781 .1801+3+TAB1286
+TAB1286   1.875 .8463+3   1.969 .2580+4   2.063 .1983+4   2.156 .1600+4+TAB1287
+TAB1287   2.250 .1290+4   2.344 .0000+0   2.438 .2878+3   2.531 .4026+3+TAB1288
+TAB1288   2.625 .0000+0   2.719 .0000+0   2.813 .1819+3   2.906 .1624+4+TAB1289
+TAB1289   3.000 .0000+0   3.094 .0000+0   3.188 .0000+0   3.281 .0000+0+TAB1290
+TAB1290   3.375 .3119+4   3.469 .1142+4   3.563 .0000+0   3.656 .6299+3+TAB1291
+TAB1291   3.750 .1023+3    ENDT
RANDPS       101       3      22     1.0            1027
TABRND1     1027                                                      +TAB1292
+TAB1292    .000 .1590+3    .094 .2364+4    .188 .1421+4    .281 .2298+4+TAB1293
+TAB1293    .375 .4054+4    .469 .5113+4    .563 .1119+5    .656 .2674+5+TAB1294
+TAB1294    .750 .6671+7    .844 .6125+5    .938 .1380+5   1.031 .1336+5+TAB1295
+TAB1295   1.125 .3827+4   1.219 .2673+4   1.313 .2741+4   1.406 .1716+4+TAB1296
+TAB1296   1.500 .1204+4   1.594 .2390+4   1.688 .2383+4   1.781 .1337+4+TAB1297
+TAB1297   1.875 .1202+4   1.969 .3967+4   2.063 .2461+4   2.156 .6824+4+TAB1298
+TAB1298   2.250 .2755+6   2.344 .3153+5   2.438 .1233+5   2.531 .7713+4+TAB1299
+TAB1299   2.625 .6086+4   2.719 .2723+4   2.813 .1094+4   2.906 .1726+4+TAB1300
+TAB1300   3.000 .1064+4   3.094 .1092+4   3.188 .2086+4   3.281 .1135+4+TAB1301
+TAB1301   3.375 .7668+3   3.469 .3333+4   3.563 .1343+4   3.656 .2090+4+TAB1302
+TAB1302   3.750 .8881+4    ENDT
```

additional cross spectral density tables

APPENDIX D.1

NASTRAN Solution 64

```
/JOB
DAF,P3,T500.
/USER
/CHARGE
PURGE,SOL64/NA.
DEFINE,SOL64.
PURGE,INP1/NA.
DEFINE,INP1.
BEGIN,,NAST,EXEC=N.
NASTRAN(,SOL64)220000
SKIP,OVER.
EXIT.
ENDIF,OVER.
SUMMARY,O=SOL64.
DAYFILE,SOL64.
COMMENT.BEGIN,,PRINT1,SOL64.
/EOR
NASTRAN FILES=(INP1)
ID TEST64, MODAL
TIME 5
SOL 64
ALTER 1
DBMGR //0
ALTER 315
DBFETCH   /ZKJJ,ZKGG1,,,/MODEL/0/1 $
ADD       ZKJJ,ZKGG1/ZKGGD/(1.,0.)/(-1.,0.) $
$DBSTORE  ZKGGD//MODEL/0 $
OUTPUT1   //-1/1 $
OUTPUT1   ZKGGD//0/1 $
ALTER 321
DBMGR     //2////5 $
ENDALTER
CEND
ECHO=UNSORT
TITLE=PALM SPRINGS 6400 45RPM
SET 7=13,115
SET 8=2,100,101,106,107,115,124,125,130,131
SET 9=2,101,107
LOAD=100
SUBCASE 1
SUBCASE 2
DISPL=7
FORCE=8
STRESS=9
```

APPENDIX D.2

NASTRAN Solution 3

```
/JOB
DAF,P2,T500.
/USER
/CHARGE
PURGE,SOL03/NA.
DEFINE,SOL03.
PURGE,PSVECT/NA.
DEFINE,PSVECT.
ATTACH,INP1.
BEGIN,,NAST,EXEC=N.
NASTRAN(,SOL03,PSVECT)220000
COMMENT.NASPLOT.
SKIP,OVER.
EXIT.
ENDIF,OVER.
SUMMARY,0=SOL03.
DAYFILE,SOL03.
COMMENT.BEGIN,,PRINT1,SOL03.
/EOR
NASTRAN FILES=(INP1)
ID TEST64, MODAL
TIME 5
SOL 3
ALTER 78
MATMOD     SYM,SIL,,,,/SYMG,/5        $PLACE BASIC SYM 6*6 IN G*G MATRIX
MPYAD      MGG,SYMG,/KGSYM//-1      $MPLY MGG BY -SYMG
PARAMR     //C,N,MPY/V,N,OMEGASQ/V,Y,OMEGA/V,Y,OMEGA  $OMEGASQ=OMEGA2
PARAMR     //C,N,COMPLEX//V,N,OMEGASQ/0.0/V,N,COMEGASQ  $COMEGASQ=OMEGASQ,0.0
ADD        KGSYM,K2GG/KSOFT/COMEGASQ  $KSOFT=KGSYM*W) +K2GG
MODTRL     KSOFT////6/ $
EQUIV      KSOFT,K2GG/ALWAYS
INPUTT1   /,,,,/-1/1   $
INPUTT1   /HZKGGD,,,,/0/1  $
$PARAML    K2PP//PRES////V,N,NKTPP  $
$EQUIV     HZKGGD,K2PP/NKTPP  $
$COND      NOADD2,NKTPP  $
ADD       K2GG,HZKGGD/ZK2GG/  $
EQUIV     ZK2GG,K2GG/ALWAYS
$LABEL     NOADD2
ENDALTER
CEND
ECHO=UNSORT
TITLE=PALM SPRINGS 6400 45RPM, NO CORIOLIS, K=3000
METHOD=21
K2GG=SOFTNING
SET 7=4,7,103,105,107,203,205,207
DISP(SORT1,,PUNCH)=ALL
$DISP=7
$OUTPUT(PLOT)
$PLOTTER NAST
$SET 1=ALL
$AXES X,Y,Z
$MAXIMUM DEFORMATION=100
$VIEW 0.,0.,0.
$PLOT MODAL DEFORMATION,RANGE 0.3,10.0,SET 1,ORIGIN 2
$VIEW 90.,0.,0.
$PLOT MODAL DEFORMATION,RANGE 0.3,10.0,SET 1,ORIGIN 3
$
$
BEGIN BULK
```

APPENDIX D.3

NASTRAN Solution 30

```
/JOB
DJM,P2,T2000.
/USER
/CHARGE
RETURN,OUTPUT.
PURGE,SOL30E/NA.
DEFINE,OUTPUT=SOL30E.
PURGE,OTP49/NA.
COMMENT.DEFINE,TAPE49=OTP49.
ATTACH,INP1=INP1PS.
BEGIN,,NAST,EXEC=N.
NASTRAN.350000
SKIP,OVER.
EXIT.
ENDIF,OVER.
SUMMARY.
DAYFILE.
/EOR
NASTRAN FILES=(INP1)
ID VAWT,TR
TIME 100
SOL 30
$DIAG 8
ALTER 78
MATMOD     SYM,SIL,,,,/SYMG,/5        $PLACE BASIC SYM 6*6 IN G*G MATRIX
MPYAD      MGG,SYMG,/KGSYM//-1     $MPLY MGG BY -SYMG
PARAMR     //C,N,MPY/V,N,OMEGASQ/V,Y,OMEGA/V,Y,OMEGA  $OMEGASQ=OMEGA2
PARAMR     //C,N,COMPLEX//V,N,OMEGASQ/0.0/V,N,COMEGASQ  $COMEGASQ=OMEGASQ,0.0
ADD        KGSYM,K2GG/KSOFT/COMEGASQ  $KSOFT=KGSYM*WJ +K2GG
MODTRL     KSOFT////6/ $
EQUIV      KSOFT,K2GG/ALWAYS
INPUTT1   /,,,,/-1/1   $
INPUTT1   /HZKGGD,,,,/0/1  $
ADD       K2GG,HZKGGD/ZK2GG/  $
EQUIV     ZK2GG,K2GG/ALWAYS
ALTER 451
MATMOD     SKEW,SIL,,,,/SKEWG,/5       $PLACE BASIC SKEW 6*6 IN G*G MATRIX
MPYAD      MGG,SKEWG,/MGSKEW       $MPLY MGG BY SKEWG
PARAMR     //C,N,MPY/V,N,OMEGA2/V,Y,OMEGA/2.0   $OMEGA2=2*OMEGA
PARAMR     //C,N,COMPLEX//V,N,OMEGA2/0.0/V,N,COMEGA2 $COMEGA2=(OMEGA2,0.0)
ADD        MGSKEW,B2PP/CORIOLIS/COMEGA2  $CORIOLIS=COMEGA2*MGSKEW+K2PP
EQUIV      CORIOLIS,B2PP/ALWAYS    $
$ ALTER FOR PH-REVISION
ALTER 483
$ PRINT FREQUENCIES OF THE SELECTED MODES AS MATRIX FHMOD .
$ NOTE THAT KHH ETC. MAY NOT NECESSARILY BE DIAGONAL.
GKAM      USETD,PHIA,MI,LAMA,DIT,,,,CASEXX/MUHH,BUHH,KUHH,PHIDUH/
          NOUE/C,Y,LMODES=0/C,Y,LFREQ=0.0/C,Y,HFREQ=1.E+30/
          -1/-1/-1/V,N,NUH1/V,N,NUH2 $
ADD       KUHH,MUHH/OMEGSQ///2 $
DIAGONAL  OMEGSQ/OMEG/COLUMN/0.5 $
ADD       OMEG,/FHMOD/0.159155 $
MATPRN    FHMOD// $
PURGE     MUHH,BUHH,KUHH,PHIDUH/ALWAYS $
$ RE-DEFINE MATRIX PH.
PARAML    OLST//TRAILER/1/V,N,NFQ $
PRTPARM   ///C,N,NFQ $
PARAML    PH//TRAILER/1/V,N,NCPH $
PARAML    PH//TRAILER/2/V,N,NMOD $
PARAM     //DIV/V,N,NCASE/NCPH/NFQ $
```

```
PRTPARM   ///C,N,NCASE $ NCASE NOT USED ANYWHERE.
MATGEN    ,/PUB/4/NMOD/NCPH/0/NFQ/NCPH/1/NFQ/NMOD $
ADD       PUB,/PUBDUP/ $
ADD       PUB,PUBDUP/PUC///2 $  REPLACE COL. NO. WITH UNITY.
$ SECOND-LEVEL SEPARATION WITH DMI-HSUP DE-ACTIVATES SPECIFIED
$ MODAL CONTRIBUTIONS. IT COMPLEMENTS LMODES,LFREQ AND HFREQ.
$ AND, IT OBVIATES NEED TO CHANGE SUBCASES AND RANDPS.
JUMP      LSHUT $
DBFETCH   /HSUP,,,,/ $
LABEL     LSHUT $
PARAML    HSUP//PRES////V,N,HFLAG $
EQUIV     PUC,PUC1/HFLAG $
COND      LHS1,HFLAG $
MATGEN    ,/HONE/4/1/NMOD/1/NMOD/NMOD/1/1/1 $
ADD       HONE,HSUP/HSEL//(-1.,0.) $
$ PRINT FREQUENCIES AFTER SECOND-LEVEL SEPARATION VIA HSUP.
PARTN     FHMOD,,HSEL/FDROP,FKEEP,,/1 $
MATPRN    FKEEP,FDROP// $
MATMOD    HSEL,,,,,/HSELD,/28 $
MPYAD     PUC,HSELD,/PUC1/ $
LABEL     LHS1 $
TRNSP     PUC1/PHNEW/ $
MODTRL    PHNEW/////3 $ CHANGE TO COMPLEX.
EQUIV     PHNEW,PH/ALWAYS $
$MATPRN    PH// $
ALTER 484
COND      LHS2,HFLAG $
MPYAD     HSELD,UHV,/UHVNEW/ $
EQUIV     UHVNEW,UHV/ALWAYS $
LABEL     LHS2 $
$ ALTER FOR ROUTING FREQ. RESP. TO TAPE49.
ALTER 495
PARAM     //STSR/V,N,OPU/2 $
PARAM     //STSR/C,Y,TPU=49/-2 $
ALTER 496
PARAM     //STSR/OPU/-2 $
ALTER 554
PARAM     //STSR/V,N,OPU/2 $
PARAM     //STSR/C,Y,TPU=49/-2 $
ALTER 555,555
ALTER 555
PARAM     //STSR/OPU/-2 $
$ ALTER FOR PRINTING MODAL PSD-OUTPUT.
$ALTER 561
$EQUIV     OUDV2,OUGV2/ALWAYS $
$JUMP      LUDV2 $
$TABPT     OUDV2// $
$LABEL     LUDV2 $
CEND
TITLE = PS 6400 /1440.,991.0,900.0/45.0,45.0,0.16/YES,YES/.02,.01,.01/
SUBTITLE=/.12,3,3/40.,300.,12.,192/0.10,7.50/.32,.28/22,20/16,16/5,8,18/
ECHO = UNSORT
METHOD = 21
SDAMP = 101
FREQ=101
DLOAD=99  $ DUMMY LOAD
RANDOM=101
K2GG=SOFTNING
B2PP=CORIOL
OUTPUT
```

```
$SDISP(SORT2,PHASE) = ALL
SET 1=13,106,115
SET 2=7,101,108,115,124,130,1000,2001,2002,300
SET 3=7,101,108,124,130
DISP(SORT2,PHASE) = 1
ELFO(SORT2,PHASE) = 2
ELSTRESS(SORT2,PHASE) = 3
SUBCASE 1
SUBCASE 2
SUBCASE 3
SUBCASE 4
SUBCASE 5
SUBCASE 6
SUBCASE 7
SUBCASE 8
SUBCASE 9
SUBCASE 10
SUBCASE 11
SUBCASE 12
SUBCASE 13
SUBCASE 14
SUBCASE 15
SUBCASE 16
SUBCASE 17
SUBCASE 18
SUBCASE 19
SUBCASE 20
SUBCASE 21
SUBCASE 22
$SUBCASE 23
$SUBCASE 24
$SUBCASE 25
OUTPUT(XYOUT)
$ XGRID = YES
$ YGRID = YES
$ CURV = 1
XTITLE = FREQUENCY (HERTZ)
YTIT = PSD OF X DISP AT 13,106,115
XYPRINT DISP PSDF / 13(T1),115(T1)
 YTITLE = PSD OF M1,M2 IN ELEMENT 7
XYPRINT ELFO PSDF / 7(4),7(5)
 YTITLE = PSD OF M1,M2 IN ELEMENT 101
XYPRINT ELFO PSDF / 101(4),101(5)
 YTITLE = PSD OF M1,M2 IN ELEMENT 108
XYPRINT ELFO PSDF / 108(4),108(5)
 YTITLE = PSD OF M1,M2 IN ELEMENT 124
XYPRINT ELFO PSDF / 124(4),124(5)
 YTITLE = PSD OF M1,M2 IN ELEMENT 130
XYPRINT ELFO PSDF / 130(4),130(5)
 YTITLE = PSD OF M1,M2 IN ELEMENT 300
XYPRINT ELFO PSDF / 300(4),300(5)
 YTITLE = PSD OF FORCE IN ELEMENTS 1000
XYPRINT ELFO PSDF / 1000(2)
 YTITLE = PSD OF FORCE IN ELEMENT 2001,2002
XYPRINT ELFO PSDF / 2001(2)
 YTIT = PSD OF STRESS IN ELEMENT 7 AT C,E
XYPRINT STRESS PSDF / 7(4),7(6)
YTIT = PSD OF STRESS IN ELEMENT 101 AT C,E
XYPRINT STRESS PSDF / 101(4),101(6)
YTIT = PSD OF STRESS IN ELEMENT 108 AT C,E
```

```
XYPRINT STRESS PSDF / 108(4),108(6)
YTIT = PSD OF STRESS IN ELEMENT 124 AT C,E
XYPRINT STRESS PSDF / 124(4),124(6)
YTIT = PSD OF STRESS IN ELEMENT 130 AT C,E
XYPRINT STRESS PSDF / 130(4),130(6)
$
BEGIN BULK
```

standard Bulk Data lines here

```
$
$PARAM,RESDUAL,-1
$PARAM,NEWDYN,-1
$PARAM,SEMAP1,-1
PARAM,LMODES,22
$PARAM,DDRMM,-1
PARAM,G,.04
$
$  ROTATING FRAME EFFECTS
$
PARAM   OMEGA      4.712
DMI     SKEW           0       1       1       0               6       6
DMI     SKEW           2       1   -1.00
DMI     SKEW           1       2   +1.00
DMI     SYM            0       6       1       0               6       6
DMI     SYM            1       1    1.00
DMI     SYM            2       2    1.00
DMIG    SOFTNING       0       6       1       0
DMIG    SOFTNING       4       1               4       1  .1E-09
DMIG    CORIOL         0       1       1       0
DMIG    CORIOL         4       1               4       2  .1E-09
DMIG    CORIOL         4       2               4       1  .1E-09
$
$ DE-ACTIVATE UNWANTED MODES
$
DMI     HSUP           0       2       1       0              22       1
DMI     HSUP           1      11     1.0      21     1.0
$
$ DEFINITION OF DUMMY LOAD
$
RLOAD1         99      99                      99
DAREA          99       2       1     .00
TABLED1        99                                                      +TABD100
+TABD100       .0     1.0   100.0     1.0    ENDT
$
$ FREQUENCY RESPONSE RANGE
$
FREQ1         101   .00000  .09375      40
$
$   MODAL DAMPING
$
TABDMP1       101    CRIT                                              +TAB1000
+TAB1000     .390    .010   1.318    .010   1.871    .010   2.556    .010+TAB1001
+TAB1001    2.825    .010   2.879    .010   3.390    .010   4.039    .010+TAB1002
+TAB1002    5.045    .010   5.068    .010   5.425    .010   5.434    .010+TAB1003
+TAB1003    5.513    .010   6.261    .010   6.443    .010   7.285    .010+TAB1004
+TAB1004    7.419    .010   7.615    .010   8.434    .010   9.621    .010+TAB1005
+TAB1005    9.970    .010  10.382    .010    ENDT
```

```
$
$ DEFINITION OF DISCRETE PSDS
$
RANDPS      101       3       3     1.0            1001
TABRND1    1001                                                        +TAB1006
+TAB1006    .000 .1751+4    .094 .1070+5    .188 .1280+5    .281 .1333+5+TAB1007
+TAB1007    .375 .2096+5    .469 .1886+5    .563 .5292+5    .656 .1608+6+TAB1008
+TAB1008    .750 .2619+8    .844 .2942+6    .938 .6012+5   1.031 .4351+5+TAB1009
+TAB1009   1.125 .1178+5   1.219 .8827+4   1.313 .6401+4   1.406 .8216+4+TAB1010
+TAB1010   1.500 .4918+4   1.594 .8193+4   1.688 .7636+4   1.781 .5691+4+TAB1011
+TAB1011   1.875 .5120+4   1.969 .1146+5   2.063 .9996+4   2.156 .3159+5+TAB1012
+TAB1012   2.250 .8787+6   2.344 .8261+5   2.438 .4505+5   2.531 .2203+5+TAB1013
+TAB1013   2.625 .1269+5   2.719 .9194+4   2.813 .7274+4   2.906 .3732+4+TAB1014
+TAB1014   3.000 .4793+4   3.094 .3288+4   3.188 .5011+4   3.281 .4306+4+TAB1015
+TAB1015   3.375 .3744+4   3.469 .1181+5   3.563 .4213+4   3.656 .6606+4+TAB1016
+TAB1016   3.750 .3430+5    ENDT
RANDPS      101       8       8     1.0            1002
TABRND1    1002                                                        +TAB1017
+TAB1017    .000 .2828+4    .094 .8613+4    .188 .5817+4    .281 .8352+4+TAB1018
+TAB1018    .375 .9205+4    .469 .2513+5    .563 .3830+5    .656 .6836+5+TAB1019
+TAB1019    .750 .1704+8    .844 .1174+6    .938 .4565+5   1.031 .2898+5+TAB1020
+TAB1020   1.125 .8429+4   1.219 .8683+4   1.313 .7854+4   1.406 .1204+5+TAB1021
+TAB1021   1.500 .6791+4   1.594 .5720+4   1.688 .7123+4   1.781 .5017+4+TAB1022
+TAB1022   1.875 .5749+4   1.969 .1420+5   2.063 .1219+5   2.156 .2252+5+TAB1023
+TAB1023   2.250 .4238+6   2.344 .8432+5   2.438 .4071+5   2.531 .1999+5+TAB1024
+TAB1024   2.625 .1927+5   2.719 .9650+4   2.813 .7899+4   2.906 .4699+4+TAB1025
+TAB1025   3.000 .5621+4   3.094 .3838+4   3.188 .4738+4   3.281 .7497+4+TAB1026
+TAB1026   3.375 .7788+4   3.469 .8669+4   3.563 .7344+4   3.656 .1036+5+TAB1027
+TAB1027   3.750 .2669+5    ENDT
$
$ DEFINITION OF (UPPER TRIANGLE) CROSS SPECTRAL DENSITIES
$
RANDPS      101       3       8     1.0            1021
TABRND1    1021                                                        +TAB1226
+TAB1226    .000 .1129+4    .094 .4951+4    .188 .3307+4    .281 .3552+4+TAB1227
+TAB1227    .375 .7904+4    .469 .1253+5    .563 .2962+5    .656 .8183+5+TAB1228
+TAB1228    .750 .2105+8    .844 .1621+6    .938 .3550+5   1.031 .1958+5+TAB1229
+TAB1229   1.125 .2694+4   1.219 .3628+4   1.313 .2576+4   1.406 .5491+4+TAB1230
+TAB1230   1.500 .2577+4   1.594 .2432+4   1.688 .3665+4   1.781 .1968+4+TAB1231
+TAB1231   1.875 .1104+4   1.969 .8490+4   2.063 .5385+4   2.156 .1783+5+TAB1232
+TAB1232   2.250 .6019+6   2.344 .7525+5   2.438 .3611+5   2.531 .1538+5+TAB1233
+TAB1233   2.625 .1169+5   2.719 .5815+4   2.813 .4220+4   2.906 .1903+4+TAB1234
+TAB1234   3.000 .2473+4   3.094 .1021+4   3.188 .1594+4   3.281 .1794+4+TAB1235
+TAB1235   3.375 .2385+4   3.469 .4662+4   3.563 .3114+4   3.656 .4147+4+TAB1236
+TAB1236   3.750 .2480+5    ENDT
RANDPS      101       3       8               1.0    1022
TABRND1    1022                                                        +TAB1237
+TAB1237    .000 .0000+0    .094 .0000+0    .188 .0000+0    .281 .0000+0+TAB1238
+TAB1238    .375 .3216+4    .469 .0000+0    .563 .5008+4    .656 .0000+0+TAB1239
+TAB1239    .750 .1094+7    .844 .0000+0    .938 .0000+0   1.031 .1874+4+TAB1240
+TAB1240   1.125 .4337+4   1.219 .0000+0   1.313 .5700+3   1.406 .0000+0+TAB1241
+TAB1241   1.500 .2297+2   1.594 .2590+3   1.688 .9317+3   1.781 .1319+3+TAB1242
+TAB1242   1.875 .2510+3   1.969 .2144+4   2.063 .0000+0   2.156 .0000+0+TAB1243
+TAB1243   2.250 .9390+4   2.344 .0000+0   2.438 .0000+0   2.531 .8896+3+TAB1244
+TAB1244   2.625 .0000+0   2.719 .0000+0   2.813 .2434+3   2.906 .0000+0+TAB1245
+TAB1245   3.000 .0000+0   3.094 .1650+3   3.188 .8525+2   3.281 .1437+3+TAB1246
+TAB1246   3.375 .5033+3   3.469 .0000+0   3.563 .0000+0   3.656 .0000+0+TAB1247
+TAB1247   3.750 .0000+0    ENDT
RANDPS      101       1       3    -1.0            1023
TABRND1    1023                                                        +TAB1248
```

```
+TAB1248    .000 .2449+5    .094 .0000+0    .188 .2514+4    .281 .0000+0+TAB1249
+TAB1249    .375 .9570+3    .469 .3287+3    .563 .4152+3    .656 .0000+0+TAB1250
+TAB1250    .750 .5896+5    .844 .4616+4    .938 .3484+3   1.031 .0000+0+TAB1251
+TAB1251   1.125 .0000+0   1.219 .2595+4   1.313 .0000+0   1.406 .0000+0+TAB1252
+TAB1252   1.500 .1637+4   1.594 .0000+0   1.688 .1411+4   1.781 .0000+0+TAB1253
+TAB1253   1.875 .0000+0   1.969 .0000+0   2.063 .5681+3   2.156 .0000+0+TAB1254
+TAB1254   2.250 .1771+5   2.344 .5187+2   2.438 .0000+0   2.531 .0000+0+TAB1255
+TAB1255   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .7789+3+TAB1256
+TAB1256   3.000 .0000+0   3.094 .0000+0   3.188 .0000+0   3.281 .1171+4+TAB1257
+TAB1257   3.375 .0000+0   3.469 .1411+4   3.563 .2584+3   3.656 .5998+3+TAB1258
+TAB1258   3.750 .7163+3    ENDT
RANDPS       101       1       3            -1.0    1024
TABRND1     1024                                                   +TAB1259
+TAB1259    .000 .0000+0    .094 .3942+4    .188 .3573+4    .281 .2201+4+TAB1260
+TAB1260    .375 .3029+3    .469 .1545+4    .563 .2270+4    .656 .3188+4+TAB1261
+TAB1261    .750 .1001+6    .844 .0000+0    .938 .0000+0   1.031 .0000+0+TAB1262
+TAB1262   1.125 .0000+0   1.219 .0000+0   1.313 .0000+0   1.406 .0000+0+TAB1263
+TAB1263   1.500 .0000+0   1.594 .9644+4   1.688 .2951+4   1.781 .2825+4+TAB1264
+TAB1264   1.875 .2640+3   1.969 .2067+4   2.063 .1122+4   2.156 .1736+4+TAB1265
+TAB1265   2.250 .2878+4   2.344 .0000+0   2.438 .0000+0   2.531 .0000+0+TAB1266
+TAB1266   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .6437+2+TAB1267
+TAB1267   3.000 .0000+0   3.094 .1682+4   3.188 .2337+4   3.281 .9154+3+TAB1268
+TAB1268   3.375 .2316+4   3.469 .8329+3   3.563 .0000+0   3.656 .4887+3+TAB1269
+TAB1269   3.750 .0000+0    ENDT
RANDPS       101       1       8    -1.0            1025
TABRND1     1025                                                   +TAB1270
+TAB1270    .000 .8265+5    .094 .0000+0    .188 .0000+0    .281 .0000+0+TAB1271
+TAB1271    .375 .1199+3    .469 .8523+3    .563 .0000+0    .656 .0000+0+TAB1272
+TAB1272    .750 .4362+5    .844 .0000+0    .938 .8886+3   1.031 .0000+0+TAB1273
+TAB1273   1.125 .3420+3   1.219 .4495+3   1.313 .0000+0   1.406 .0000+0+TAB1274
+TAB1274   1.500 .8250+4   1.594 .3093+4   1.688 .3107+3   1.781 .0000+0+TAB1275
+TAB1275   1.875 .0000+0   1.969 .3891+3   2.063 .1084+4   2.156 .8748+3+TAB1276
+TAB1276   2.250 .1355+5   2.344 .0000+0   2.438 .0000+0   2.531 .0000+0+TAB1277
+TAB1277   2.625 .0000+0   2.719 .0000+0   2.813 .0000+0   2.906 .0000+0+TAB1278
+TAB1278   3.000 .1864+4   3.094 .0000+0   3.188 .3894+3   3.281 .1238+4+TAB1279
+TAB1279   3.375 .4039+3   3.469 .4708+3   3.563 .0000+0   3.656 .4867+3+TAB1280
+TAB1280   3.750 .5802+3    ENDT
RANDPS       101       1       8            -1.0    1026
TABRND1     1026                                                   +TAB1281
+TAB1281    .000 .0000+0    .094 .3835+4    .188 .2626+4    .281 .2053+4+TAB1282
+TAB1282    .375 .1025+4    .469 .1004+4    .563 .3563+4    .656 .2849+4+TAB1283
+TAB1283    .750 .8243+5    .844 .0000+0    .938 .0000+0   1.031 .0000+0+TAB1284
+TAB1284   1.125 .0000+0   1.219 .0000+0   1.313 .0000+0   1.406 .0000+0+TAB1285
+TAB1285   1.500 .0000+0   1.594 .4599+2   1.688 .2737+1   1.781 .1801+3+TAB1286
+TAB1286   1.875 .8463+3   1.969 .2580+4   2.063 .1983+4   2.156 .1600+4+TAB1287
+TAB1287   2.250 .1290+4   2.344 .0000+0   2.438 .2878+3   2.531 .4026+3+TAB1288
+TAB1288   2.625 .0000+0   2.719 .0000+0   2.813 .1819+3   2.906 .1624+4+TAB1289
+TAB1289   3.000 .0000+0   3.094 .0000+0   3.188 .0000+0   3.281 .0000+0+TAB1290
+TAB1290   3.375 .3119+4   3.469 .1142+4   3.563 .0000+0   3.656 .6299+3+TAB1291
+TAB1291   3.750 .1023+3    ENDT
ECHOON
ENDDATA
```

APPENDIX E

Report by Control Data Canada Ltd.

1.0 INTRODUCTION

Random response analysis in MSC/NASTRAN (1) presupposes that the spectral densities of excitation are input in terms of the physical degrees of freedom (DOFs) of the structure. However, as outlined in Reference 2, certain practical reasons associated with the analysis of Vertical Axis Wind Turbines make it desirable to develop a procedure that would permit the PSD-input to be referred to normal-mode co-ordinates rather than physical DOF's. The present Report sets forth such a procedure. The basic goal is accomplished by incorporating certain DMAP ALTERs in SOL-30 and SOL-71 of MSC/NASTRAN (Version 64A).

2.0 OVERVIEW OF PROCEDURE

The RANDOM module in MSC/NASTRAN functions as a post-processor to Harmonic Response Analysis. It operates on Table Data-Blocks as input and output rather than on Matrix Data-Blocks. This restricts the DMAP-programmer's freedom somewhat, inasmuch as Tables are less amenable to manipulation than Matrices. The present work recognizes this inherent restriction and fashions a data-input structure that imitates that of the standard approach.

The modal technique for frequency-domain analysis of dynamic response is available in both SOL-30 and SOL-71. SOL-30 is a rigid-format; it uses NPTP for storage and restart and precludes the use of superelements. SOL-71 provides for superelements and employs Data-Base files for storage. For the purpose of the present Report, it is assumed for convenience that the whole structure constitutes, in SOL-71, a single superelement, i.e., the residual structure. The user is free to isolate eigensolution in a checkpoint run using SOL-3 or SOL-63 as required.

3.0 THEORETICAL BACKGROUND

Let us introduce the following matrix-notations:

$S^P_{gg}(\omega)$: PSD-Input w.r.t. physical DOFs

$u_g(\omega)$: Physical DOFs

$S^P_{cc}(\omega)$: PSD-Input w.r.t. modal coordinates

Z_{gh} : Modal Matrix of 'h' modes

Y_{gc} : Physical-to-Modal Load Transformation Matrix

h : Number of modes used for response calculation

c : Number of Modal Subcases used for definition of PSD-Input

(Ordinarily, $c = h$ and $Y = Z$.)

$H_{hc}(\omega)$: Modal Harmonic-Response to Unit-Amplitude Modal Harmonic-Input

$S^u_{hh}(\omega)$: Modal PSD-Output

$S^u_{gg}(\omega)$: PSD-Output of physical DOFs

$R^e(\omega)$: Physical Response Variables (e.g., Displacement, Stress)

B_{eg} : Matrix relating $R^e(\omega)$ to $u_g(\omega)$

$S_{ee}(\omega)$: PSD-Output of Physical Response Variables

ω : Circular Frequency of Excitation

'T' : Superscript denoting matrix transpose

'*' : Superscript denoting matrix conjugate-transpose

We can write down the following equations:

$$S^P_{cc}(\omega) = Y^T_{gc} \quad S^P_{gg}(\omega) \quad Y_{gc} \tag{E1}$$

$$S^u_{hh}(\omega) = H_{hc}(\omega) \quad S^P_{cc}(\omega) \quad H^*_{hc}(\omega) \tag{E2}$$

$$S^u_{gg}(\omega) = Z_{gh} \quad S^u_{hh}(\omega) \quad Z^T_{gh} \tag{E3}$$

$$R^e(\omega) = B_{eg} \quad u_g(\omega)$$

$$S_{ee}(\omega) = B_{eg} \quad S^u_{gg}(\omega) \quad B^T_{eg}$$

Thus,

$$S_{ee}(\omega) = G_{ec}(\omega) \quad S^P_{cc}(\omega) \quad G^*_{ec}(\omega) \tag{E4}$$

where,

$$G_{ec}(\omega) = B_{eg} \quad Z_{gh} \quad H_{hc}(\omega) \tag{E5}$$

The user indicates the presence of 'c' SUBCASEs and inputs $S^P_{cc}(\omega)$. The program (with ALTERs) sets up 'c' unit-load vectors and determines $H_{hc}(\omega)$ and $G_{ec}(\omega)$. It then computes the diagonal terms of $S^u_{hh}(\omega)$ and $S_{ee}(\omega)$ and integrals like mean-square and auto-correlation.

For the purpose of verification, the user may draw upon Equation (E1) and perform a standard analysis with $S^P_{gg}(\omega)$ as the PSD-Input.

4.0 DESCRIPTION OF ALTER-PACKETS

ALTER-Packet S30PHF (or S71PHF) is mandatory for the present purpose of implementing modal PSD-input. It redefines the PH-load matrix as a unit-load matrix. The ALTER prints, under the heading FHMOD, the natural frequencies of the 'h' modes selected via the LMODES/LFREQ/HFREQ parameters. It also provides the user with an <u>option</u> for second-level selection/suppression of modes. The user exercises second-level suppression by entering a DMI column matrix named HSUP having 'h' rows. The load-and-response contribution of any of the 'h' modes is <u>deactivated</u> by assigning a value of 1.0 to the corresponding term of HSUP. An important additional benefit derived from HSUP is that there is no need to modify the SUBCASE and RANDPS specifications. For instance, the user may extract 25 modes via the EIGR card. He then selects h=20 modes for response analysis, via the LMODES/LFREQ/HFREQ parameters. He specifies 20 SUBCASEs in Case Control and defines a 20 x 20 matrix function $S^{P}_{cc}(\ )$ on RANDPS cards. If, in a given run of a parametric study, modes 5 to 8 and 17 to 20 are to be suppressed, the user simply enters a DMI column matrix HSUP having 20 rows, with rows 5 to 8 and 17 to 20 assigned a value of unity each. The natural frequencies of the modes retained by HSUP are printed as FKEEP and the ones suppressed are identified as FDROP. The number of response frequencies is printed as NFQ and the number of Subcases as NCASE.

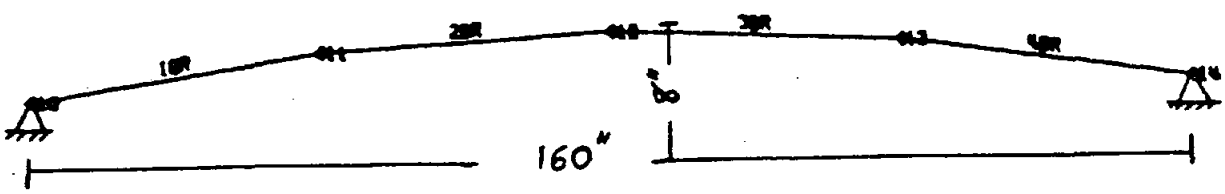
ALTER-Packet S30PRT/S71PRT is an optional utility. It helps route harmonic-response output to TAPE49, so that the standard output file displays only the random-response results.

In passing, it is emphasized that output of random response is available in NASTRAN only as XYOUT. Cross-PSDs and cross-correlations of response are not computed. It happens that, except for some items like SPCFORCE, an item may be requested as PSD-XYOUT, even in the absence of a corresponding request for harmonic-OUTPUT. Though the NASTRAN documentation does not state it, it is found that PSD-XYOUT of model SDISP-responses falls in a special category. First, SOL-30 needs ALTER-Packet S30SDP for outputting modal response-PSD, whereas SOL-71 needs no ALTER. Secondly, modal

PSD-XYOUT is requested via the term DISP rather than SDISP. Thirdly, modal PSD-XYOUT should not be requested in the same deck as one containing a request for XYOUT of physical DISP/VELO/ACCEL, so as to avoid erroneous interpretation of the request.

5.0 ILLUSTRATIVE ANALYSIS

A simple parabolic arch lying in the XY-plane is taken as the structure to be analyzed (Figure 1). It is pinned to ground at both ends and modelled via five grid-points and four BAR elements. SDAMP modal damping is assumed. The response analysis considers the first three modes, the associated natural frequencies being 11.7 Hz., 24.7 Hz. and 66.9 Hz. The arch is subjected to modal PSD-input that is derived from a pair of concentrated transverse random forces at grid-points 11 and 12.



$A = 0.785$ in.^{2}

$I_1 = 0.049$ in.^{4}

$I_2 = 0.049$ in.^{4}

$J = 0.098$ in.^{4}

$E = 10. \times 10^6$ psi

$\upsilon = 0.3$

$\zeta = 2.6 \times 10^{-4}$ lb - sec^2/in.^{4}

Figure 1: Shallow Arch Example

5.1 Input Explanation

The Executive Control calls on SOL-71, the mandatory ALTER-Packet S71PHF and the optional Packet S71PRT.

In the Case Control, the SEALL = ALL card satisfies the superelement request. The METHOD card selects an EIGR card for MGIV eigensolution for up to 10 modes. There are, however, fewer than 10 modes in the model and only three are selected via LFREQ-HFREQ for response analysis. The FREQ card specifies six frequencies at which the response would be computed, although it is necessary to consider more frequencies in a realistic case.

There is one, and only one, DLOAD card above the Subcase level. It sets up a dummy physical harmonic-load via RLOAD1, DAREA and TABLED1 cards. The only function of these cards is to ensure correct matrix-sizes and smooth program flow. As such, the magnitudes on these cards are immaterial.

The RANDOM card applies the desired random loading via the RANDPS-TABRND1 cards. These cards embody the actual full modal PSD-input, on the strict basis that the program-generated modal harmonic loads are unit loads.

OUTPUT requests for harmonic response may be entered above or within the Subcases, the former being the more likely option. The harmonic OUTPUT goes to TAPE49 when the ALTER-packet S71PRT (or S30PRT) is present. This would reduce clutter in the standard output file.

In accordance with the three modes selected via LFREQ-HFREQ, three SUBCASEs are identified in Case Control, i.e., we set c = h.

With six frequencies, three modes and three subcases, the PH-matrix is of size 3 x 18 and is as follows:

$$
\begin{array}{c}
\\
\text{Mode 1} \\
\text{Mode 2} \\
\text{Mode 3} \\
\\
\end{array}
\begin{array}{c}
\text{Subcase 1} \\
\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
f_1 \; f_2 \; f_3 \; f_4 \; f_5 \; f_6
\end{array}
\begin{array}{c}
\text{Subcase 2} \\
\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{array}
\begin{array}{c}
\text{Subcase 3} \\
\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}
\end{array}
$$

The OUTPUT (XYOUT) block of Case Control requests the calculation, printing and plotting of random response. (Harmonic response also may be plotted here.) The 'SEPLOT 0' card caters to superelement considerations.

The DMI-HSUP Bulk-Data cards are optional. They serve to deactivate the contribution of the second mode to loading and response, though the SUBCASE-RANDPS input embraces the first three modes.

Though not illustrated, a checkpoint-restart process is feasible. A recommended strategy would be to perform eigensolution in a checkpoint run and execute every run of response-analysis as a restart.

Since the output features of the ALTER'ed Solution are no different from those of the standard approach, they are not presented as part of this Report. It is, however, pointed out that a warning message SWM-3002 may be issued by SOL-71 as it attempts to determine PSD-XYOUT for nonexistent modal IDs when a DISP PSD-request is present. This is due to a quirk in the basic Solution Sequence and is NOT engendered by the ALTER's introduced in this work.

6.0 CONCLUSION

The ALTER-Packets developed herein have been successfully tested. They provide the user with the capability to input the spectral densities of random excitation in terms of modal coordinates as opposed to physical DOFs. Both SOL-30 and SOL-71 have thus been enhanced. The ALTERs also

yield incidental benefits in the form of second-level mode-suppression, modal PSD-XYOUT and routing of harmonic OUTPUT to TAPE49. The DMAP-flexibility of MSC/NASTRAN is the basis of this fruitful effort.

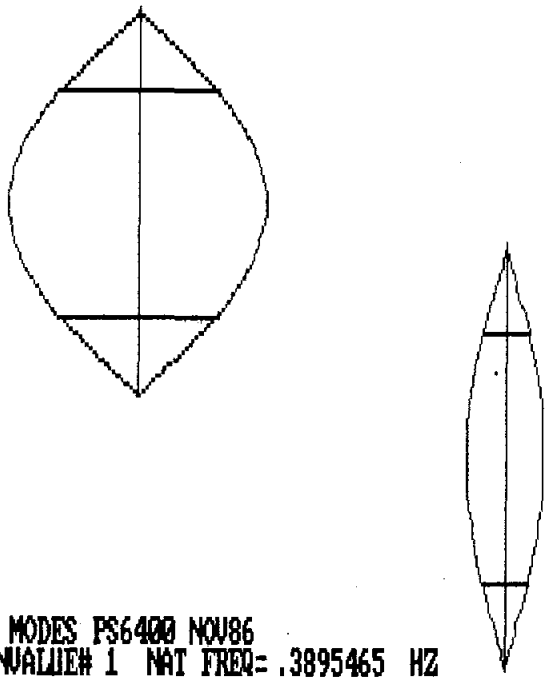
REFERENCES

1. MSC/NASTRAN User's Manual, MSR-39, July 1984, The MacNeal-Schwendler Corporation.

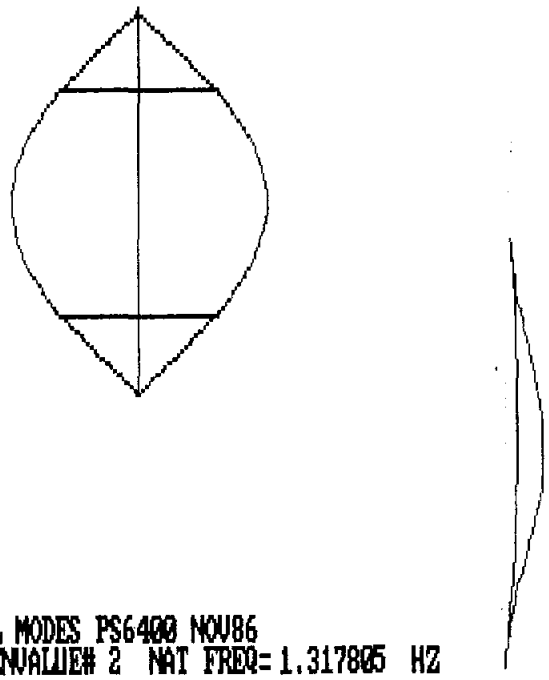
2. INDAL Technologies Inc., P.O. No. P813251, supplemented by D. J. Malcolm's Notes.

APPENDIX F.1

Real Modes of Indal 6400 Used in Modal Formulation



REAL MODES PS6400 NOV86
EIGENVALUE# 1 NAT FREQ= .3895465 HZ



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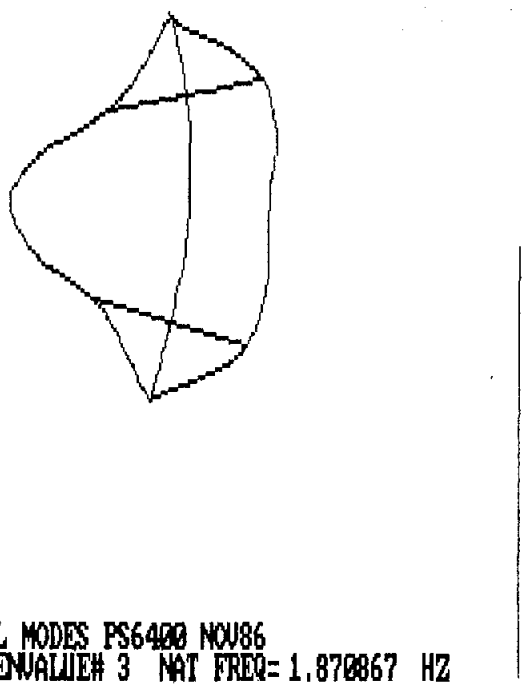

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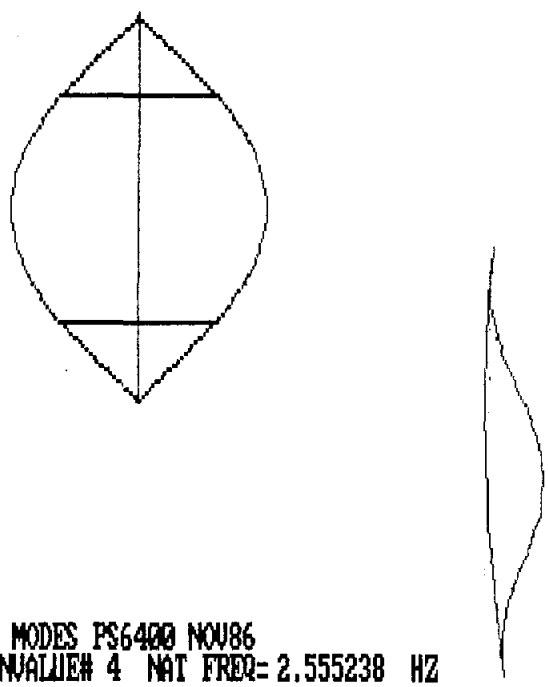

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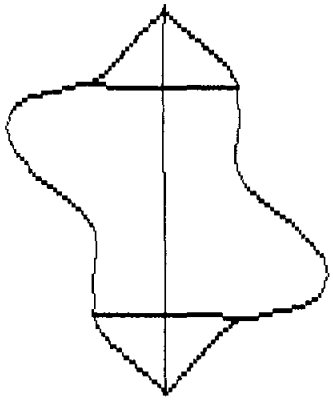

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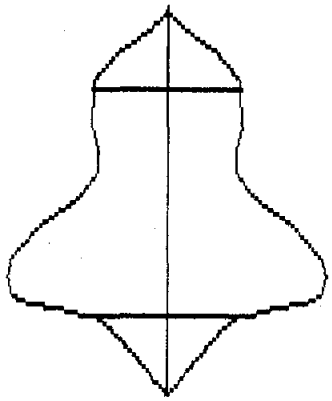

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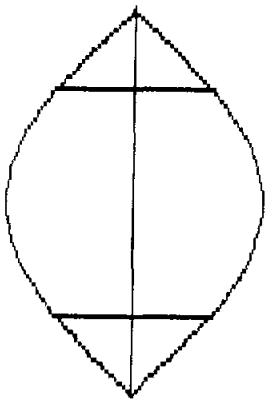
EIGENVALUE# 6 NAT FREQ= 2.878586 HZ



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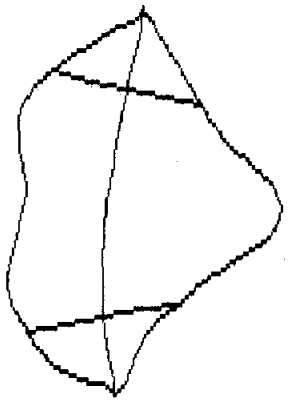

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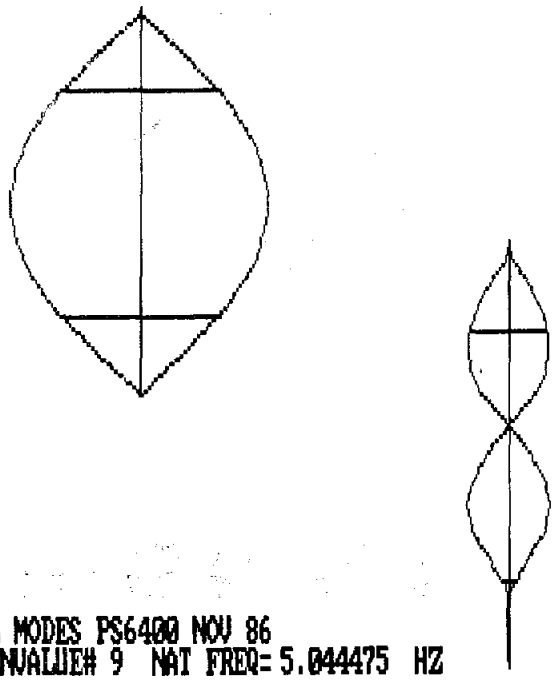

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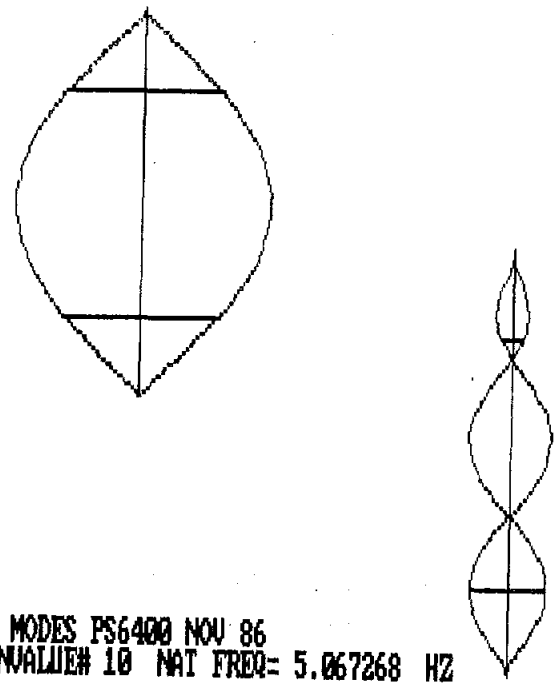

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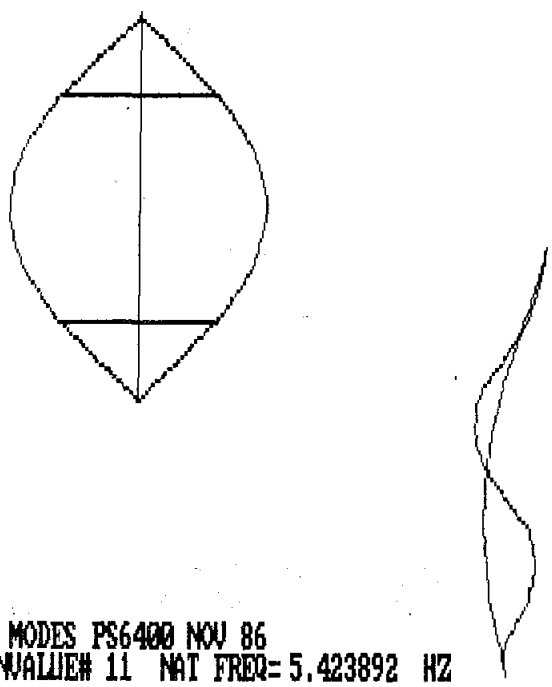

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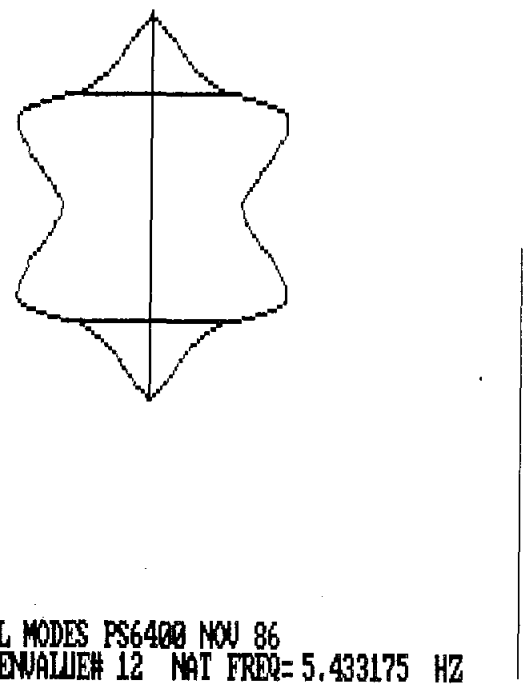

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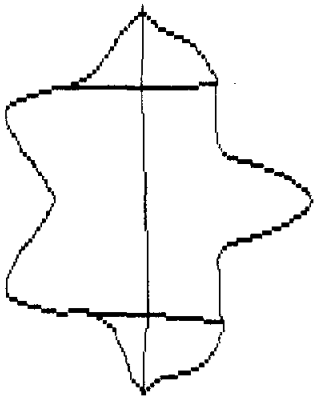

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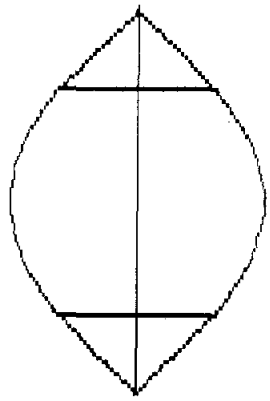

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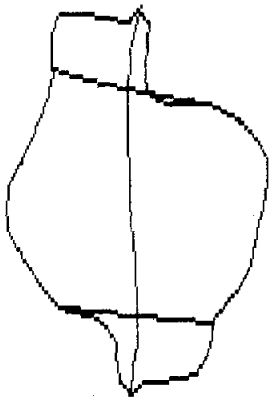

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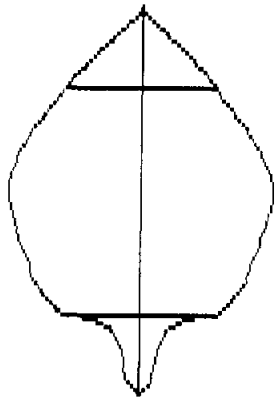

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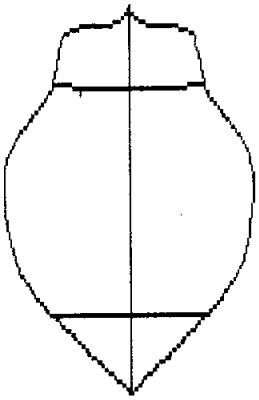

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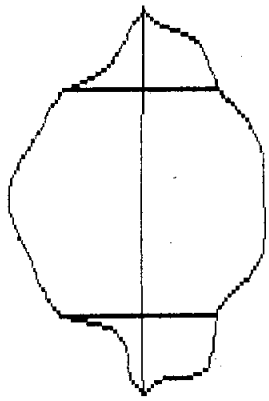

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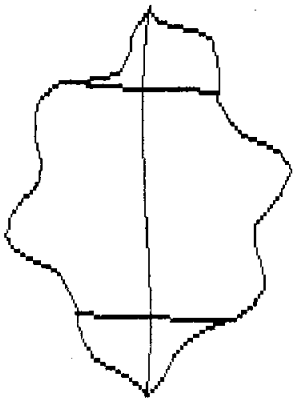

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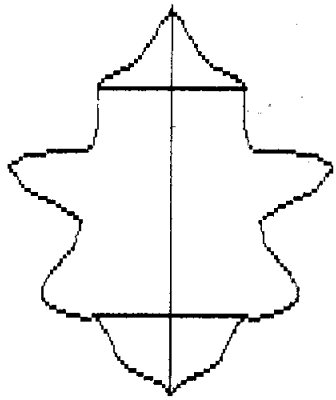

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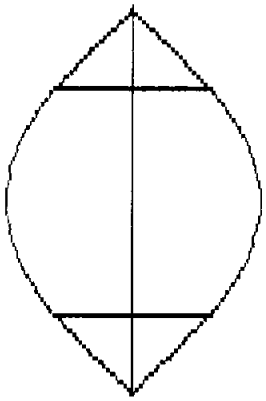

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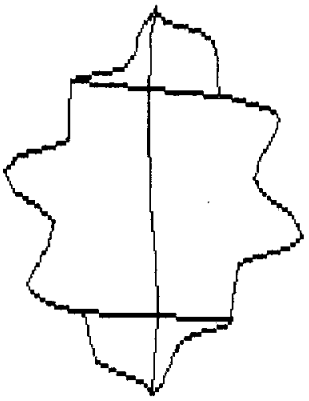

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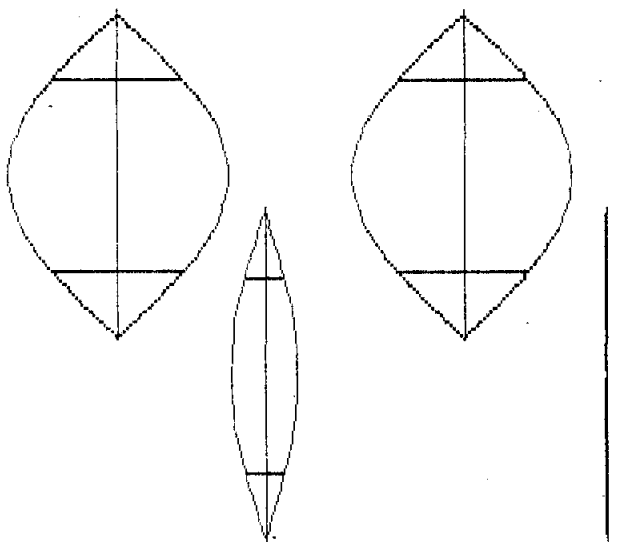
APPENDIX F.2

Complex Modes of Indal 6400 (SCE1) Operating at 45 RPM



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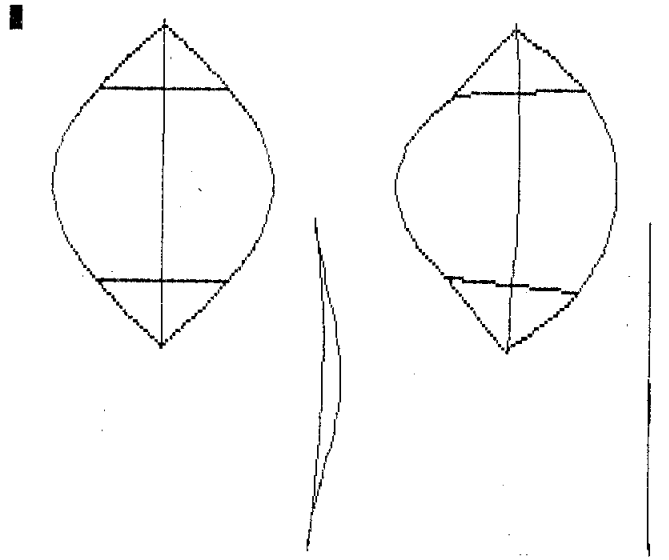

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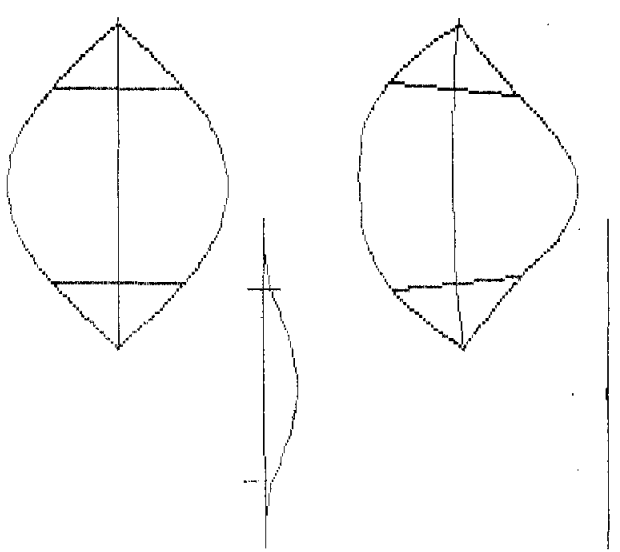

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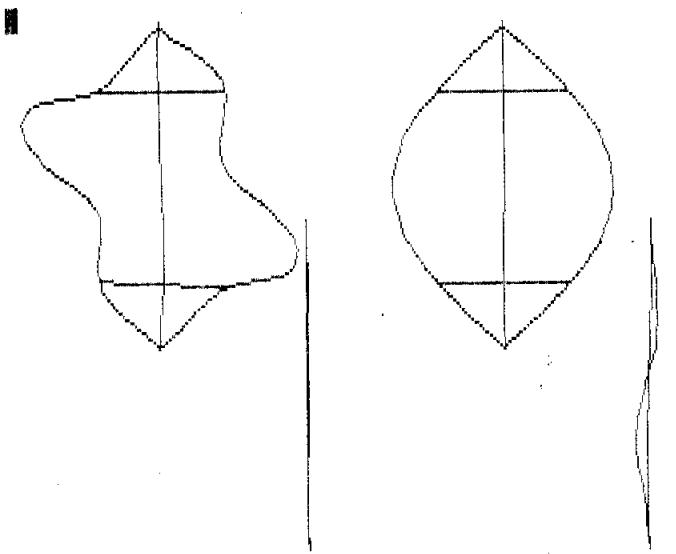

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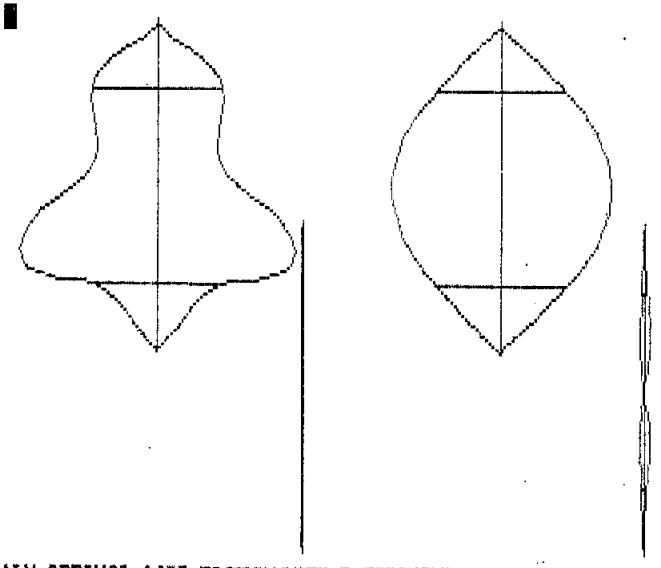
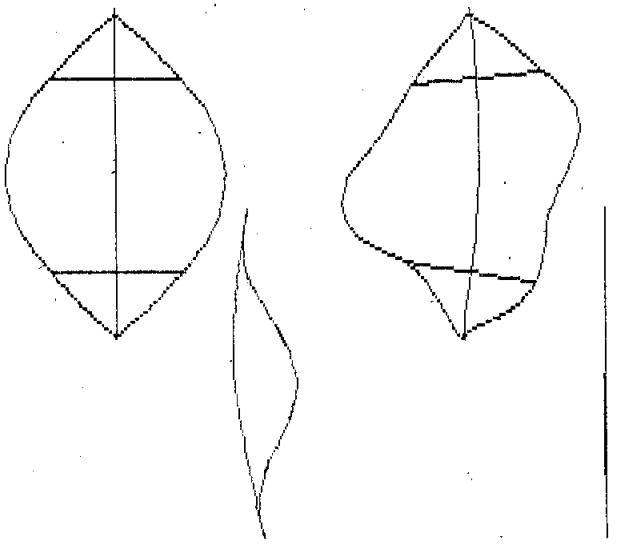
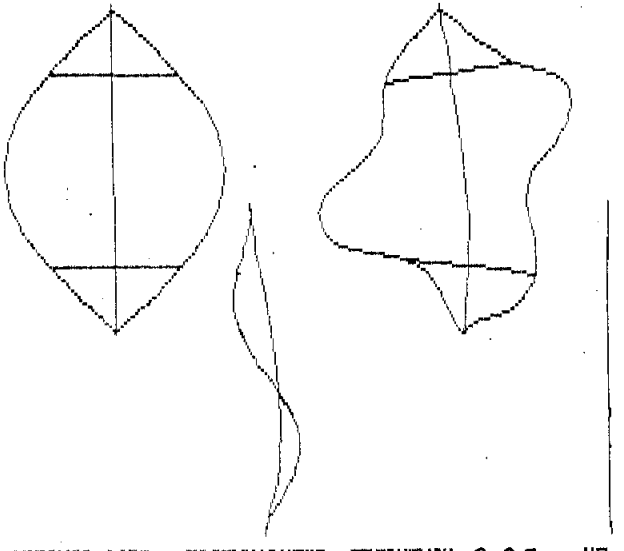


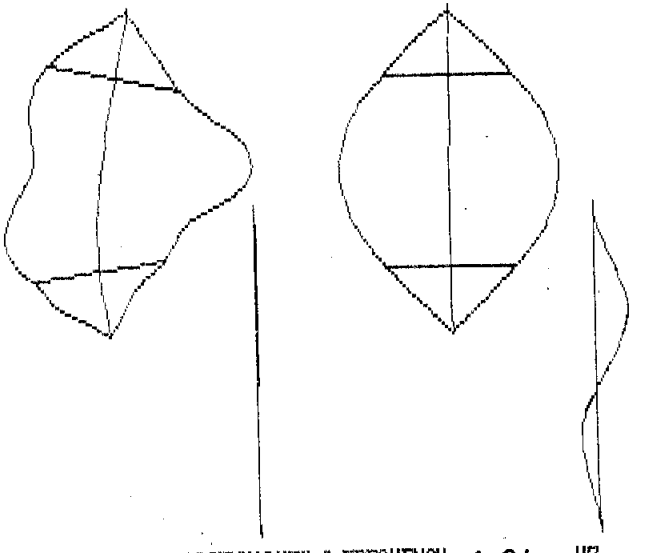
PALM SPRINGS 6400 EIGENVALUE# 5 FREQUENCY 2.81 HZ



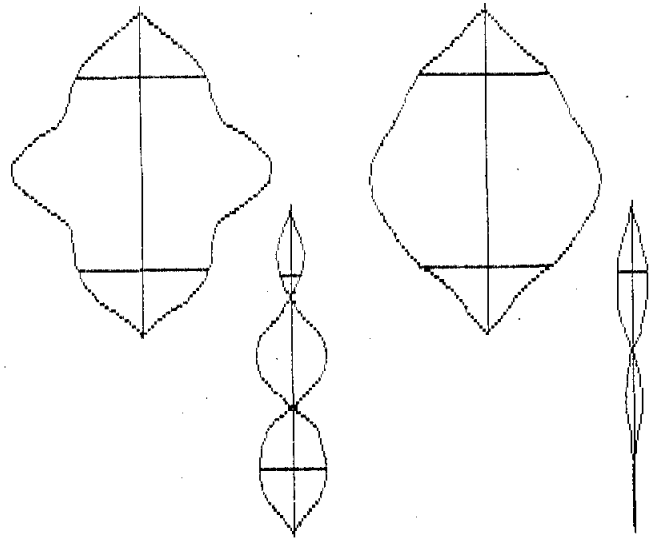
PALM SPRINGS 6400 EIGENVALUE# 6 FREQUENCY 2.99 HZ



PALM SPRINGS 6400 - EIGENVALUE#7 FREQUENCY 3.35 HZ



PALMSPRINGS 6400 - EIGENVALUE# 8 FREQUENCY 4.21 HZ



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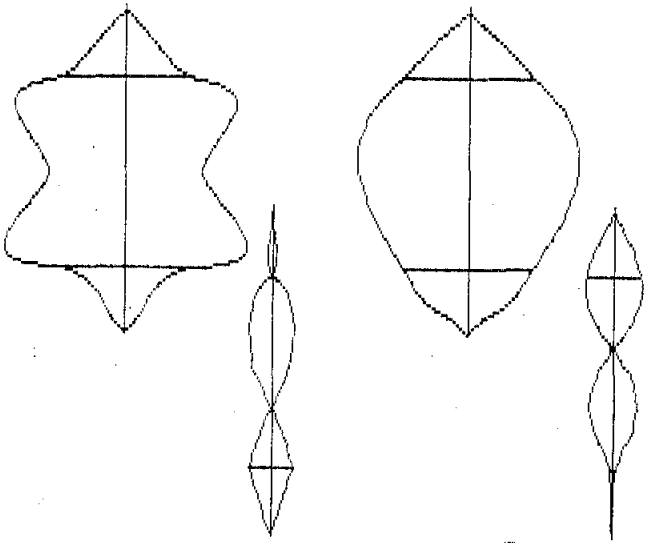

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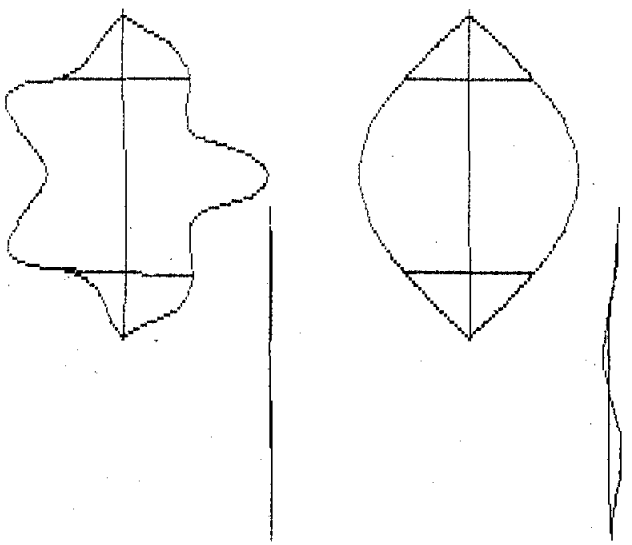

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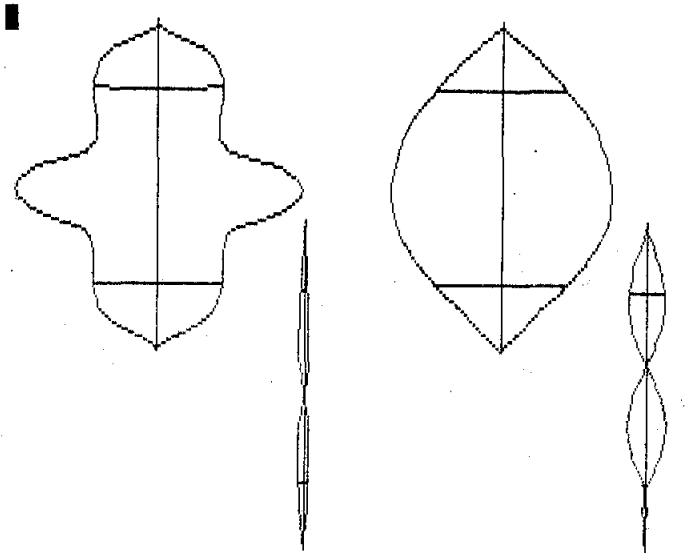

PALM SPRINGS 6400 - EIGENVALUE# 12 FREQUENCY 5.50 HZ

DISTRIBUTION:
Amarillo College
Amarillo, TX 79100
Attn: E. Gilmore

American Wind Energy Association
1017 King Street
Alexandria, VA 22314

Dr. A. S. Barker
Trinity Western
7600 Glover Road
Langley, BC
CANADA V3A 4R9

Battelle-Pacific Northwest
Laboratory
P.O. Box 999
Richland, WA 99352
Attn: L. Wendell

Dr. George Bergeles
Dept. of Mechanical Engineering
National Technical University
42, Patission Street
Athens, GREECE

Canadian Standards Association
178 Rexdale Blvd.
Rexdale, Ontario, M9W 1R3
CANADA
Attn: T. Watson

Monique Carpentier
Energy, Mines and Resources
National Research Council
of Canada
Montreal Road
Ottawa, Ontario
CANADA K1A OR6

Professor V. A. L. Chasteau
School of Engineering
University of Auckland
Private Bag
Auckland, NEW ZEALAND

Colorado State University
Dept. of Civil Engineering
Fort Collins, CO 80521
Attn: R. N. Meroney

Otto de Vries
National Aerospace Laboratory
Anthony Fokkerweg 2
Amsterdam 1017
THE NETHERLANDS

DOE/ALO/ETWMD
Albuquerque, NM 87115
Attn: G. P. Tennyson

DOE/ALO
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NGD
Albuquerque, NM 87115
Attn: Capt. J. L. Hanson, USAF

DOE Headquarters (5)
Wind/Oceans Technologies Division
1000 Independence Avenue
Washington, DC 20585
Attn: L. J. Rogers
P. R. Goldman

J. B. Dragt
Nederlands Energy Research
Foundation
(E.C.N.)
Physics Department
Westerduinweg 3 Petten (nh)
THE NETHERLANDS

Alcir de Faro Orlando
Pontificia Universidade Catolica-
PUC/Rj
Mechanical Engineering Department
R. Marques de S. Vicente 225
Rio de Janeiro, BRAZIL

FloWind Corporation (2)
1183 Quarry Lane
Pleasanton, CA 94566
Attn: L. Schienbein
B. Im

A. D. Garrad
Garrad Hasson
10 Northampton Square
London EC1M 5PA
UNITED KINGDOM

H. Gerardin
Mechanical Engineering Department
Faculty of Sciences and Engineering
Universite Laval-Quebec, G1K 7P4
CANADA

R. T. Griffiths
University College of Swansea
Dept. of Mechanical Engineering
Singleton Park
Swansea, SA2 8PP
UNITED KINGDOM

Indal Technologies, Inc. (10)
3570 Hawkestone Road
Mississauga, Ontario
CANADA L5C 2V8
Attn: D. Malcolm
C. Wood

Institut de Recherche d'Hydro-Quebec
1800, Montee Ste-Julie
Varennes, Quebec, JOL 2P.O.
CANADA
Attn: Bernard Masse

K. Jackson
West Wind Industries
P.O. Box 1705
Davis, CA 95617

R. E. Kelland
The College of Trades and Technology
P.O. Box 1693
Prince Philip Drive
St. John's, Newfoundland, A1C 5P7
CANADA

Olle Ljungstrom
FFA, The Aeronautical Research Institute
Box 11021
S-16111 Bromma, SWEDEN

Robert Lynette
R. Lynette & Assoc., Inc.
15042 NE 40th Street
Suite 206
Redmond, WA 98052

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
Attn: Professor N. D. Ham
W. L. Harris, Aero/Astro Dept.

G. M. McNerney
US Wind Power
160 Wheeler Road
Burlington, MA 01803

Michigan State University
Division of Engineering Research
East Lansing, MI 48825
Attn: O. Krauss

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Edinburgh, EH10 5DT
ENGLAND

Ohio State University
Aeronautical and Astronautical Dept.
2070 Neil Avenue
Columbus, OH 43210
Attn: Professor G. Gregorek

Oklahoma State University
Mechanical Engineering Dept.
Stillwater, OK 76074
Attn: D. K. McLaughlin

Oregon State University
Mechanical Engineering Dept.
Corvallis, OR 97331
Attn: R. E. Wilson

Ion Paraschivoiu
Department of Mechanical Engineering
Ecole Polytecnique
CP 6079
Succursale A
Montreal H3C 3A7
CANADA

RANN, Inc.
260 Sheridan Ave., Suite 414
Palo Alto, CA 94306
Attn: A. J. Eggers, Jr.

Dr. R. Ganesh Rajagopalan,
Asst. Prof.
Aerospace Engineering Department
Iowa State University
404 Town Engineering Bldg.
Ames, IA 50011

Mr. Bent Rasmussen
Overgade 14
DK-7000 Fredericia
Denmark

R. G. Richards
Atlantic Wind Test Site
P.O. Box 189
Tignish P.E.I., COB 2BO
CANADA

Riso National Laboratory
Postbox 49
DK-4000 Roskilde
DENMARK
Attn: Peter Hauge Madsen

Dr. Ing. Hans Ruscheweyh
Institut fur Leichbau
Technische Hochschule Aachen
Wullnerstrasse 7
FEDERAL REPUBLIC OF GERMANY

Beatrice de Saint Louvent
Establissement d'Etudes et de
Recherches
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77 Rue de Serves
92106 Boulogne-Billancourt Cedex
FRANCE

Gwen Schreiner
Librarian
National Atomic Museum
Albuquerque, NM 87185

Arnan Seginer
Professor of Aerodynamics
Technion-Israel Institute of
Technology
Aeronautical Engineering Dept.
Haifa
ISRAEL

David Sharpe
Dept. of Aeronautical Engineering
Queen Mary College
Mile End Road
London, E1 4NS
UNITED KINGDOM

Kent Smith
Instituto Technologico Costa Rico
Apartado 159 Cartago
COSTA RICA

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Attn: R. W. Thresher

Bent Sorenson
Roskilde University Center
Energy Group, Bldg. 17.2
IMFUFA
P.O. Box 260
DK-400 Roskilde
DENMARK

Peter South
ADECON
32 Rivalda Road
Weston, Ontario, M9M 2M3
CANADA

G. Stacey
The University of Reading
Department of Engineering
Whiteknights, Reading, RG6 2AY
ENGLAND

Stanford University
Dept. of Aeronautics and
Astronautics Mechanical Engineering
Stanford, CA 94305
Attn: Holt Ashley

Dr. Derek Taylor
Alternative Energy Group
Walton Hall
Open University
Milton Keynes, MK7 6AA
UNITED KINGDOM

R. J. Templin
Low Speed Aerodynamics Laboratory
NRC-National Aeronautical
Establishment
Montreal Road
Ottawa, Ontario, K1A 0R6
CANADA

Texas Tech University
Mechanical Engineering Dept.
P.O. Box 4289
Lubbock, TX 79409
Attn: J. W. Oler

K. J. Touryan
Moriah Research
6200 Plateau Dr.
Englewood, CO 80111

Tulane University
Dept. of Mechanical Engineering
New Orleans, LA 70018
Attn: R. G. Watts

University of Colorado
Dept. of Aerospace Engineering
Sciences
Boulder, CO 80309
Attn: J. D. Fock, Jr.

University of Massachusetts
Mechanical and Aerospace
Engineering Dept.
Amherst, MA 01003
Attn: Dr. D. E. Cromack

University of Oklahoma
Aero Engineering Department
Norman, OK 73069
Attn: K. Bergey

University of Sherbrooke
Faculty of Applied Science
Sherbrooke, Quebec, J1K 2R1
CANADA
Attn: A. Laneville
P. Vittecoq

USDA, Agricultural Research Service
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Center
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Attn: Dr. R. N. Clark

W. A. Vachon
W. A. Vachon & Associates
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St. Pietersniewstraat 41
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Morgantown, WV 26505
Attn: R. Walters

Wichita State University
Aero Engineering Department (2)
Wichita, KS 67208
Attn: M. Snyder
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