8524

CONTRACTOR REPORT

RS-8232-2/069847
C.1

SAND89—7042
Unlimited Release
UC—261

Vertical Axis Wind Turbine Turbulent Response Model

8232-2//069847
00000001 -

Indal Technologies, Inc.
3570 Hawkestone Road
Mississauga, Ontario
L5C 2V8

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed January 1990

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from
National Technical Information Service
US Department of Commerce
5285 Port Royal Rd
Springfield, VA 22161

NTIS price codes
Printed copy: A05
Microfiche copy: A01

Distribution
Category
UC-261

SAND89-7042
Unlimited Release
Printed January 1990

VERTICAL AXIS WIND TURBINE TURBULENT RESPONSE MODEL

Part 2:

Response of Sandia National Laboratories' 34-Meter VAWT with Aeroelastic Effects

Indal Technologies, Inc.
3570 Hawkestone Road
Mississauga, Ontario L5C 2V8
Canada

Sandia Contract: 32-3044

ABSTRACT

The dynamic response of Sandia National Laboratories' 34-m Darrieus rotor wind turbine at Bushland, Texas, is presented. The formulation used a double-multiple streamtube aerodynamic model with a turbulent airflow and included the effects of linear aeroelastic forces. The structural analysis used established procedures with the program MSC/NASTRAN. The effects of aeroelastic forces on the damping of natural modes agree well with previous results at operating rotor speeds, but show some discrepancies at very high rotor speeds. A number of alternative expressions for the spectrum of turbulent wind were investigated. The modal loading represented by each does not differ significantly; a more significant difference is caused by imposing a full lateral coherence of the turbulent flow. Spectra of the predicted stresses at various locations show that without aeroelastic forces, very severe resonance is likely to occur at certain natural frequencies. Inclusion of aeroelastic effects greatly attenuates this stochastic response, especially in modes involving in-plane blade bending.

TABLE OF CONTENTS

		PAGE
	SUMMARY	i
	TABLE OF CONTENTS	ii
	LIST OF FIGURES	iv
	LIST OF TABLES	iv
1.0	INTRODUCTION	1
	1.1 Background	1
	1.2 Objectives	2
	1.3 Statement of Work	2
2.0	ATMOSPHERIC TURBULENCE	5
	2.1 Simulation of Turbulent Flow	5
	2.2 Modifications in Version 4 (TRES4)	7
3.0	AEROELASTIC EFFECTS	10
	3.1 Mathematical Modelling	10
	3.2 Program AEROB5	16
	3.3 Damping of Natural Modes	17
4.0	STRUCTURAL RESPONSE	21
	4.1 Operation at 37.5 rpm	21
	4.2 Operation at 28 rpm	38
	4.3 Axial Effects	38
5.0	ALTERNATIVE TURBULENCE SPECTRA	48
	5.1 Different Spectra of Atmospheric Turbulence	48
	5.2 Comparison of Modal Loads	

TABLE OF CONTENTS (cont'd)

		PAGE
6.0	CONCLUSIONS	62
7.0	REFERENCES	64
	APPENDICES	
	A. FORTRAN Program TRES4	
	A.1 Flowchart	
	A.2 Listing	
	A.3 Input File	
	B. FORTRAN Program AEROB5	
	B.1 Documentation	
	B.2 Listing	
	B.3 Input File	
	C. NASTRAN Bulk Data for SNL-34	
	D. Modes of Vibration of Stationary Rotor	

LIST OF FIGURES

		PAGE
1.	Local and Global Axes of Airfoil Element	11
2.	Finite element Model of SNL 34-m	22
3.	Blade Stress Spectra, 37.5 rpm	23
4.	Location of Strain Gauges on SNL 34-m	35
5.	Blade Stress Spectra, 28 rpm	40
6.	Comparison of Turbulence Spectra	51
7.	Comparison of Modal Load #3 from Alternative Spectra	51
8.	Modal Loads #1 thru 8; V = 25 and 45 mph	52

LIST OF TABLES

1.	Parameters Used in Load Simulation	6
2.	Natural Frequencies and Damping of SNL34 at 37.5 rpm	19
3.	Natural Frequencies and Damping of SNL34 at 90 rpm	20
4.	Total and Stochastic Variance of Modal Loads. V = 25 mph	58
5.	Total and Stochastic Variance of Modal Loads. V = 45 mph	59
6.	Variance of Modal Loads. 25 mph. Correlated vs. Uncorrelated.	60
7.	Variance of Modal Loads. 45 mph. Correlated vs. Uncorrelated.	61

1.0 INTRODUCTION

1.1 Background

The aerodynamic loading and hence the structural response of a Darrieus rotor is essentially cyclic at multiples of the rotor speed. However, it has been found experimentally that at some locations there can be response at frequencies which are not harmonics of the rotor speed; these responses are a product of the non-steady or turbulent flow through the rotor.

A procedure to model and to incorporate the effects of turbulent flow was recently completed by Indal Technologies on behalf of Sandia National Laboratories (1, 2). Application of this procedure to the Indal 6400 rotor indicated that a turbulence intensity of 10% could result in considerable increases in the rms of some cyclic stresses at locations influenced by in-plane blade bending; this result is in close agreement with experimental data and has encouraged the further use of this analysis procedure.

Inclusion of stochastic effects has also focused attention on the importance of aerodynamic damping. This damping is a result of interaction between the airflow and the structural motion and has been studied by a number of previous investigators (3, 4, 5, 6, 7, 8, 9). These previous reports have been largely concerned with the prediction of flutter instabilities but references 3 and 9 did also examine the effect of aeroelastic forces on the frequency response of a rotor under uniform flow.

The erection and operation at Bushland, Texas, of the 34-m Test Bed Darrieus rotor wind turbine by Sandia National Laboratories and the United States Department of Agriculture is an important project. It will allow testing of the specially designed airfoils, tapering of the blade chord, and confirmation of aerodynamic and structural dynamic theories. Sandia National Laboratories were, therefore, interested in obtaining predictions of structural response which included the effects of both turbulent flow and aeroelastic damping.

1.2 Objectives

The original objectives of the project were to investigate the effect of turbulence on both the Indal 6400 Darrieus rotor and the SNL 34-m rotor. However, it became clear that priority should be given to studying the SNL 34-m Test Bed and to include both atmospheric turbulence and aeroelastic damping.

Other objectives were to study the effect of including certain additional terms in the aeroelastic formulation and to study the effect of using alternative expressions for the spectrum of atmospheric turbulence.

1.3 Statement of Work

The Statement of Work to be found in the contract document is shown below.

9. Using a Sandia-supplied NASTRAN bulk-data deck for the SNL 34-m VAWT test bed and the code developed in B-1 and B-7, above, study the response of that

machine to a turbulent flow with mean wind speeds of 30 and 45 mph and turbulence intensities of 10% and 30%. Draw conclusions concerning the effect of turbulence on the fatigue life of that machine.

10. Incorporate the Sandia-developed aeroelastic effects in the modelling of the Indal 6400 rotor. Study the impact of these effects on the rotor natural frequencies and damping for both deterministic and stochastic wind loading.

11. Study the use of alternative or modified turbulence spectra in the code developed in B-1 and B-7, above, to investigate the dependence of the structural response on the spectra. For each spectrum, examine the modal loading at windspeeds of 30 and 45 mph and turbulence intensities of 10% and 30%. Determine the structural response characteristics as necessary to examine the effect of any difference in modal loading.

12. If the studies performed in B-10, and B-11 reveal significant effects due to aeroelastic effects and/or different turbulence spectra, repeat the study performed in B-9, above, utilizing the results of B-10 and B-11.

13. Reformulate the aeroelastic damping effects work of Don Lobitz and Tom Ashwill and examine the rotating frame and inertial term contributions to aeroelastic damping.

14. Determine the impact of these effects on the previously-computed response of the SNL 34-m Test Bed.

In June, 1988, a preliminary report, reference (10), was issued on this project. That report did not include the modelling of aeroelastic forces, but did contain much data that will not be repeated in this final report. Occasional references will, therefore, be made to the preliminary report.

2.0 ATMOSPHERIC TURBULENCE

2.1 Simulation of Turbulent Flow

A full description of the preparation of the aerodynamic loads under turbulent flow may be found elsewhere (1, 2, 13) and will not be repeated here. However, a summary and the values of some pertinent parameters is appropriate.

The double multiple streamtube (DMST) model was used with modifications for Reynolds number and dynamic stall effects. The aerodynamic loading on the two blades as it passed through each of the upwind and downwind discs was calculated for a number of rotor revolutions. This involved generating vectors of both longitudinal and lateral velocity perturbations for each streamtube. These vectors were obtained by interpolation between a properly correlated set of turbulence vectors associated with a spatial array of points (1, 14). As each aerodynamic loading in the time series for each blade was generated, it was decomposed into components of the first (approximately) twenty modes of the stationary rotor. When completed, these time domain modal loads were transformed to the frequency domain and written as auto- and cross-spectral densities for input to a NASTRAN analysis. The important parameter values used throughout the present work are given in Table 1.

The basic spectrum of turbulence, known as a Kaimal spectrum for stable atmospheres, was used as in (15) and has the form

$$S(f) = \sigma^2 \frac{Z}{V} \frac{C1}{1 + C2\left(\frac{fZ}{V}\right)^{5/3}}$$

where S is the power spectral density, f is the frequency (Hz), σ^2 is the variance of the process, Z is a reference height (m), V is a reference wind velocity (m/s), and C1 and C2 are constants with the following values:

	C1	C2
longitudinal velocity	11.8	192
lateral velocity	4.0	70

TABLE 1

PARAMETERS USED IN LOAD SIMULATION

rotor speed	= 37.5 rpm
mean windspeed	= 45 mph
column loading included	yes
structural damping	= 2%
modal damping: 1st & 2nd flatwise	= 2%
all others	= 0%
18 of first 20 modes used	
spatial array (vertical x lateral grid of points) = 7 x 5	
coherence coefficient (Ref. 3)	= 7.5
lateral motion included	yes
wind shear exponent	= 0.16
time step	= 0.24s
rotor revolutions	= 16
ensemble no.	= 30
turbulence spectrum: kaimal (stable), specified variance	

2.2 Modifications in Version 4 (TRES4)

The documentation for the original FORTRAN program used to simulate the turbulent flow and the subsequent stochastic blade loads is to be found in reference (2). That program, TRES, has undergone several modifications and the present version is TRES4, a listing of which is included as Appendix A of this report. Full documentation of TRES4 will not be given here because of its basic similarity to TRES, but major changes and additions are listed below.

1. Suppressed eigenvectors. Whereas the original program could suppress those eigenvectors which were associated with the lowest variance of loads, TRES4 allows selection of eigenvectors to be suppressed and to be absent in the load file. NSUP is the number of vectors to be suppressed and are recorded in the vector ISUP.

2. The formula used for the spectrum of atmospheric turbulence can be selected by number in the input file. This number corresponds to one of a number of expressions to be found in the new function routine TSPECT.

3. The level at which modal cross spectra are ignored can now be controlled from the input file through the parameter VMIN. This fraction is applied to the lowest variance of the modal load auto-spectra and all cross spectra which have variances less than that value are excluded.

4. The parameter CMIN controls the exclusion of individual terms in the cross spectra. This feature helps to control the size of the input file to NASTRAN.

5. NSOFT is an input parameter used to smooth the time series vectors of windspeed perturbations (see subroutine SOFTEN).

6. Reduced set of blade modes. In order to separate the structural requirements of the finite element model of the blade from the (usually less demanding) requirements of the aerodynamic model, a subset of the blade nodes has been introduced. This subset of length NZSET is stored in the vector IZSET and is read, in subroutine READ2, from a card which has been inserted into the NASTRAN bulk data (see Appendix C).

7. The calculation of the spectra of turbulence (subroutine SIJ) and the decomposition of the matrix of turbulence spectra into triangular form (subroutine DECOMP) are both processes that do not have to be repeated for each member of the ensemble. The routines DECOMP and SMOOTH, have, therefore, been modified to store the triangular matrix of vectors in a file TRES.TMP and to recover it at the start of each ensemble loop.

8. It was found that recalculation of the interference factor at each time step for each streamtube of the DMST model was not necessary. The present program, therefore, calculates the interference factor, or VIRW, for the uniform flow case and uses the same factor for all subsequent time steps of that streamtube. This affects subroutines STUBE and DMST.

9. For computing reasons it is not possible to have one spatial vector of windspeed fluctuations for each streamtube of the DMST model. The original program therefore associated the closest spatial vector to each streamtube. The present version of the program calculates a vector by linear interpolation between vectors associated with the four neighbouring spatial points (see subroutine VSERIES). The disadvantage of this is that interpolation between uncorrelated vectors can result in loss of rms of the variable. To correct this subroutine SOFTEN adds white noise to the vector, as suggested in reference (11), so that the variance of the vector is equal to the average of the variances of the neighbouring points.

10. The storage of the current auto- and cross-spectral densities at the end of each ensemble loop has been reformatted. The auto-spectra are written onto file first followed by the cross-spectra. A direct access binary format of storage was selected.

11. The organization of the writing of the output has been changed because of other changes and to simplify the logic. The new relationships of the subroutines are shown in the flowchart in Appendix A.

3.0 AEROELASTIC EFFECTS

3.1 Mathematical Modelling

The formulation of the aeroelastic effects was based on the report by Lobitz and Ashwill (3) which in turn is based on classical rigid body unsteady aerodynamics (12); the same approach was also taken in previous work (4, 5, 6). The present separate formulation was carried out for two reasons: to include rotating frame and elastic centre offset terms which had been previously omitted (because they were assumed to be negligible), and to provide an independent check of the unexpectedly high aeroelastic damping predicted by Lobitz and Ashwill (3).

Figure 1 shows a typical VAWT airfoil blade and a set of local axes. The lift and moment due to a set of displacements and displacement derivatives is (12)

$$L = a_0 \rho V^2 b \left\{ -\frac{C\dot{u}}{V} - C\theta_z - \left[C(1-2a)+1\right]\frac{b\dot{\theta}_z}{2V} - \frac{b\ddot{u}}{2V^2} + \frac{ab^2}{2V^2}\ddot{\theta}_z \right\}$$

$$M = a_0 \rho V^2 b \left\{ d_1\left[\frac{C\dot{u}}{V} + C\theta_z + C(1-2a)\frac{b\dot{\theta}_z}{2V}\right] + \frac{d_2 b\dot{\theta}}{2V} + \frac{ab^2\ddot{u}}{2V^2} - \left(\frac{1}{8}-a^2\right)\frac{b^3\ddot{\theta}_z}{2V^2} \right\} \qquad (1)$$

where

a_0 = coefficient of lift (per radian)

ρ = air density

V = relative air speed

b = 1/2 blade chord

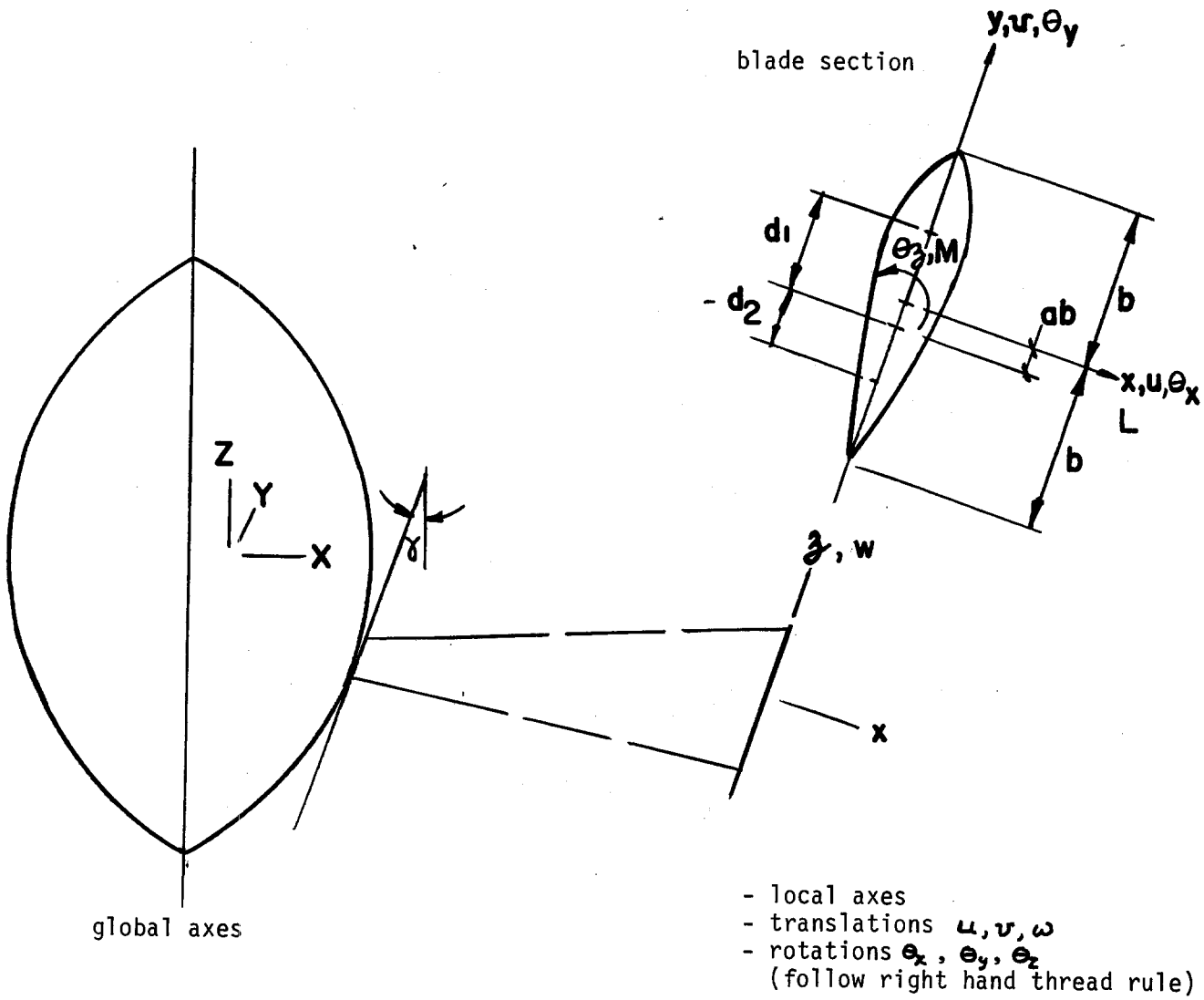


FIGURE I, LOCAL AND GLOBAL AXES

a = locates the centre of twist (see Figure 1)

d_1 = distance by which the forward centre of pressure is forward of the centre of twist

d_2 = distance by which the rear centre of pressure is forward of the centre of twist

C = Theodorsen function

u = lateral translation of airfoil (see Figure 1)

θ_z = rotation of airfoil (see Figure 1)

The signs used in Equation (1) are not identical to previous work but are consistent with directions indicated in Figure 1. The Theodorsen function defines the phase lag under non—steady conditions and may be written (7)

$$C(k) = \left[1 - \frac{0.165k^2}{k^2+.0455^2} - \frac{.335k^2}{k^2+.3^2}\right] - i\left[\frac{.165 * .0455k}{k^2+.0455^2} + \frac{.335 * .3k}{k^2+.3}\right]$$

where $k = \omega b/V$ is the reduced frequency and ω is the frequency of oscillation (rad/sec). For the SNL 34-m VAWT the phase angle implied by C(k) is about 13° at the mid-rotor and greater nearer the roots. However, other terms can combine to make the phase of the Theodorsen function significant.

In the presence of an ambient windspeed, the airspeed seen by the airfoil is not constant but has periodic terms which, if included, would invalidate the linear eigenvalue procedure normally used. A more complex Floquet analysis as done in reference (9) would be required instead. In this work the airspeed is regarded as constant.

The equations (1) are not in a form suitable for immediate use. The local element coordinates to which they refer must be expressed in the global coordinates used by the finite element program. In addition, the equations must refer to the axes and displacements in the rotating frame which is used in the structural analysis.

The transformation between local axes (lower case letters) and global axes (upper case letters) is

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = [R] \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} \tag{2}$$

where, with reference to Figure 1

$$[R] = \begin{bmatrix} \cos\gamma & 0 & -\sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} .$$

A position vector (or any vector of displacements or rotations) which has components R_i in the rotating frame can be written

$$\bar{R} = R_i \bar{e}_i$$

where repeated indices indicate summation. The time derivatives are

$$\begin{aligned} \dot{\bar{R}} &= \dot{R}_i \bar{e}_i + R_i \bar{\Omega} \times \bar{e}_i \\ \ddot{\bar{R}} &= \ddot{R}_i \bar{e}_i + 2\dot{R}_i \bar{\Omega} \times \bar{e}_i + R_i \bar{\Omega} \times (\bar{\Omega} \times \bar{e}_i) \end{aligned} \tag{3}$$

where $\bar{\Omega}$ is the rotation vector.

Using equations (2) and (3) the local fixed-frame displacements (subscript f) can be written as

$$\begin{aligned} \dot{u}_f &= \dot{u}_r - \Omega v_r \cos\gamma \\ \ddot{u}_f &= \ddot{u}_r - 2\Omega \dot{v}_r \cos\gamma - \Omega^2 \cos\gamma (u_r \cos\gamma + w_r \sin\gamma) \\ \dot{\theta}_{zf} &= \dot{\theta}_{zr} - \Omega \theta_y \cos\gamma \\ \ddot{\theta}_{zf} &= \ddot{\theta}_{zr} - 2\Omega \dot{\theta}_{yr} \sin\gamma - \Omega^2 \cos\gamma (\theta_{xr} \cos\gamma + \theta_{zr} \sin\gamma) \end{aligned} \tag{4}$$

where a subscript r refers to the rotating frame.

Equations (4) can then be substituted into equation (1) resulting in expressions of considerably greater length. The final equations express forces as linear functions of displacements or of their first or second time derivatives. When moved to the left hand side of the equation of motion these terms can be regrouped, therefore, as contributions to the stiffness damping and mass matrices of the system. They represent the coupling between the airflow and the response of the rotor.

The finite element formulation followed a course similar to that used in (3) and involved integration along the beam elements assuming linear shape functions. The following 6 x 6 stiffness (K), damping (B) and mass (M) matrices were obtained relating the six degrees of freedom at each end of a beam.

$$K = -a_0 \rho V^2 b \frac{\ell}{3} \begin{bmatrix} \frac{b\ell^2 c^2}{2V^2}, & \frac{C\ell c}{V}, & \frac{b\ell^2 cs}{2V^2}, & -\frac{ab^2\ell^2 cs}{2V^2}, & \frac{b\ell(C(1-2a)+1)s}{2V}, & -C-\frac{ab^2\ell^2 s^2}{2V^2} \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ -\frac{ab^2c^2}{2V^2}, & -\frac{d_1 C\ell c}{V}, & \frac{ab^2\ell^2 sc}{2V^2}, & -(a^2+\frac{1}{8})\frac{b^3\ell^2 sc}{2V^2}, & -\frac{b\ell s}{2V}(C(1-2a)d_1+d_2), & Cd_1-(a^2+\frac{1}{8})\frac{b^3\ell^2 s^2}{2V^2} \end{bmatrix}$$

$$B = -a_0 \rho V^2 b \frac{\ell}{3} \begin{bmatrix} -\frac{C}{V}, & \frac{b\ell c}{V^2}, & 0, & 0, & \frac{ab^2\ell s}{V^2}, & -\frac{b}{2V}(C(1-2a)+1) \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ \frac{d_1 C}{V}, & -\frac{ab^2\ell c}{V^2}, & 0, & 0, & -(a^2+\frac{1}{8})\frac{b^3\ell s}{V^2}, & \frac{b}{2V}(C(1-2a)d_1+d_2) \end{bmatrix}$$

$$M = -a_0 \rho V^2 b \frac{\ell}{3} \begin{bmatrix} \frac{-b}{2V^2}, & 0, & 0, & 0, & 0, & \frac{ab^2}{2V^2} \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ 0 & & & & & 0 \\ \frac{ab^2}{2V^2}, & 0, & 0, & 0, & 0, & (a^2+\frac{1}{8})\frac{b^3}{2V^2} \end{bmatrix}$$

where $s = \sin\gamma$, $c = \cos\gamma$. The full 12 x 12 element matrices are made up in the form shown below.

$$K_{12\times12} = \left[\begin{array}{c|c} K & K/2 \\ \hline K/2 & K \end{array}\right]$$

The above matrices differ from those presented in (4) by considering the rotation vector, $\bar{\theta}$, to be influenced by rotating frame effects (just as the displacement vector is), and by neglecting terms that combined the airfoil drag with the angle of attack.

3.2 Program AEROB5

A FORTRAN program was written to calculate the additional matrix elements for the blades of a Darrieus rotor and to format them as NASTRAN DMIG cards (Direct Matrix Input) . It was decided not to use the similar program used by D. Lobitz for several reasons: Lobitz's program combined DMIG cards for aeroelastic terms with terms describing rotating frame effects whereas the latter are incorporated by DMAP programming at Indal; Lobitz's program did not include rotating frame and other terms in the aeroelastic formulation; a more thoroughly documented program was required.

An overall flowchart, a listing and some documentation of the program AEROB5 are included as Appendix B to this report.

The output from AEROB5 can become excessively long especially if the blade is made up of many elements and

if rotating frame terms are included. To reduce the size of output, the program has two features: one is the definition of a reduced set of blade nodes (the ZSET), and the specification of a minimum magnitude of terms to be included in the output.

3.3 Damping of Natural Modes

The addition of non-Hermitian terms to the damping matrix of the structure results in mathematically complex values of eigenvalues. The imaginary part of the eigenvalue indicates the frequency of free vibrations and the real part indicates the degree and type of damping of free motion; a negative real part corresponds to positive damping whereas a positive real part implies flutter instability.

Eigenvalues and modes of the SNL 34-m rotor were extracted for a number of cases in order to check values against previous results and to investigate the sensitivity to new parameters. These results are summarized in Table 2 (37.5 rpm) and Table 3 (90 rpm).

Table 2 shows that at operating speed the agreement with results reported by Lobitz and Ashwill (3) is good. In addition the influence of the rotating frame terms and the mid-chord/elastic centre offset is shown to be small.

The results obtained at 90 rpm are compared with corresponding results by Lobitz and Ashwill in Table 3. These sets of results are very different. Earlier results indicated that at 90 rpm the fundamental flatwise modes are lightly or negatively damped. Present results

suggest that damping of these fundamental modes is high (in the region of 40% structural, or 20% critical damping) and that it is the second torsional mode that becomes unstable. The reason for this discrepancy at 90 rpm is not yet apparent but the close agreement at 37.5 rpm was considered to justify application of the aeroelastic terms to the frequency response of the operating rotor.

TABLE 2. Natural Frequencies and Damping of SNL34 at 37.5 rpm

Mode	nat. frequencies present report no aero Hz	nat. frequencies present report with aero Hz	structural damping coefficients Lobitz (7) w=4 Hz no rot a = o	present report w=4 Hz no rot a = o	present report w=4 Hz with rot a = o	present report w=4 Hz with rot a = -.2
1P	0.215	.222	0	-0.012	0.003	0.003
1FA	1.418	1.386	0.186	0.173	0.178	0.179
1FS	1.428	1.391	0.185	0.181	0.186	0.186
1B	1.544	1.537	0.005	0.009	0.012	0.012
1TI	2.041	2.038	0.005	0.022	0.024	0.024
2FS	2.666	2.628	0.103	0.107	0.110	0.110
2FA	2.745	2.711	0.124	0.070	0.067	0.067
1TO	3.025	3.022	0	0.005	0.005	0.005
2TI	3.599	3.595	0.010	0.002	0.002	0.002
2PR	3.697	3.682	0.010	-0.004	-0.005	-0.005
3FA	4.067	4.054	0.062	0.034	0.035	0.035
3P	4.189	4.190		-0.008	-0.009	-0.010

NOTE:

1. The work by Lobitz and Ashwill refers to the "preliminary" finite element model of the rotor. The work by Indal used the "11.87" or "as-built" model. The correspondence of the higher modes between the two sets may not be exact.

2. The "no rot." and "with rot." refers to terms in the aeroelastic forces that depend on the rotating reference frame.

3. The variable "a" measures the distance between the mid-chord and the centre of twist (as a fraction of the half chord).

4. All analyses neglected the inertia terms associated with the aeroelastic forces. These were estimated to be negligible.

5. The above results were obtained without any structural damping. In practice an overall structural damping coefficient of up to 0.04 would be appropriate.

6. To translate the structural damping coefficients into equivalent critical damping ratios, damping values should be divided by 2.0.

TABLE 3. Natural Frequencies and Damping of SNL 34-m at 90 rpm

Mode	nat. freq. with aero present report	structural damping coefficient Lobitz (3)	structural damping coefficient present report
1P	0.209	0.012	0.016
1B	0.676	-0.014	0.031
1FS	2.190	0.091	0.400
1FA	2.220	0.116	0.356
1TI	2.225	-0.012	0.005
2TI	2.452	0.014	0.062
1TO	3.798	0.005	0.011
2FS	3.872	-0.014	0.257
2FA	4.492	0.160	0.167
2P	4.702	0.109	-0.036
3P	5.111	-	-0.021
2B	5.381	-	0.004

NOTE:

1. Both analyses neglected apparent mass, rotational terms and elastic centre offset in the aeroelastic formulation.

2. The Lobitz (3) analysis referred to the "preliminary" configuration whereas the present report used the "as built" configuration.

4.0 STRUCTURAL RESPONSE

4.1 Operation at 37.5 rpm

The structural analysis procedure described in Section 2 for calculating the response to turbulent flow was applied to the SNL 34-m rotor. The finite element model is shown in Figure 2 and a listing is included as Appendix C. Eight cases were analyzed for operation at 37.5 rpm: turbulence intensities at 10% and 30%, mean windspeeds of 25 mph and 45 mph, and both with and without aeroelastic forces. These eight were augmented with deterministic (uniform flow) analyses at the same two windspeeds. The values selected for the various parameters are listed in Table 1.

Stresses were obtained as power spectral densities at points which were defined to be identical to the locations of strain gauges attached to the blades and central column. Some of these results are included as Figures 3.1 3.6 a, b, c, d, e, referring to locations A, H, I, N, Q and T respectively. Results are presented for both the "outer surface" and the "trailing edge" which are locations defined on SNL's drawing AY-558729 (see Figure 4). It should be noted that neither location is exactly on a neutral axis and there will appear to be some cross-coupling between in-plane and out-of-plane bending.

All of the results in Figures 3.1 thru 3.6 show the amplitude spectra of stresses with a resolution of eight divisions between harmonic frequencies (this translates to a resolution of 0.0781 Hz). Such a resolution is more coarse than would normally be used in a data acquisition system.

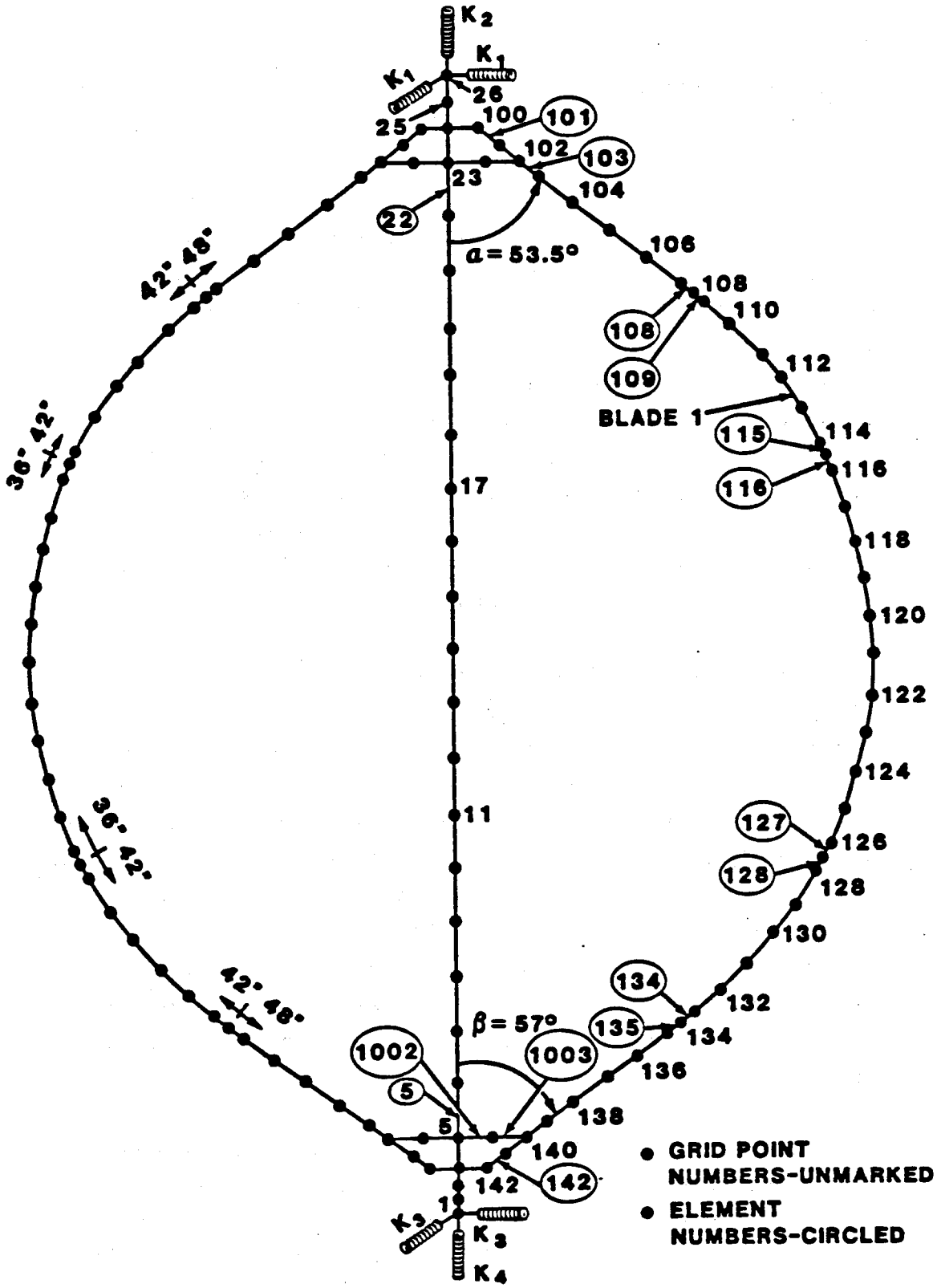
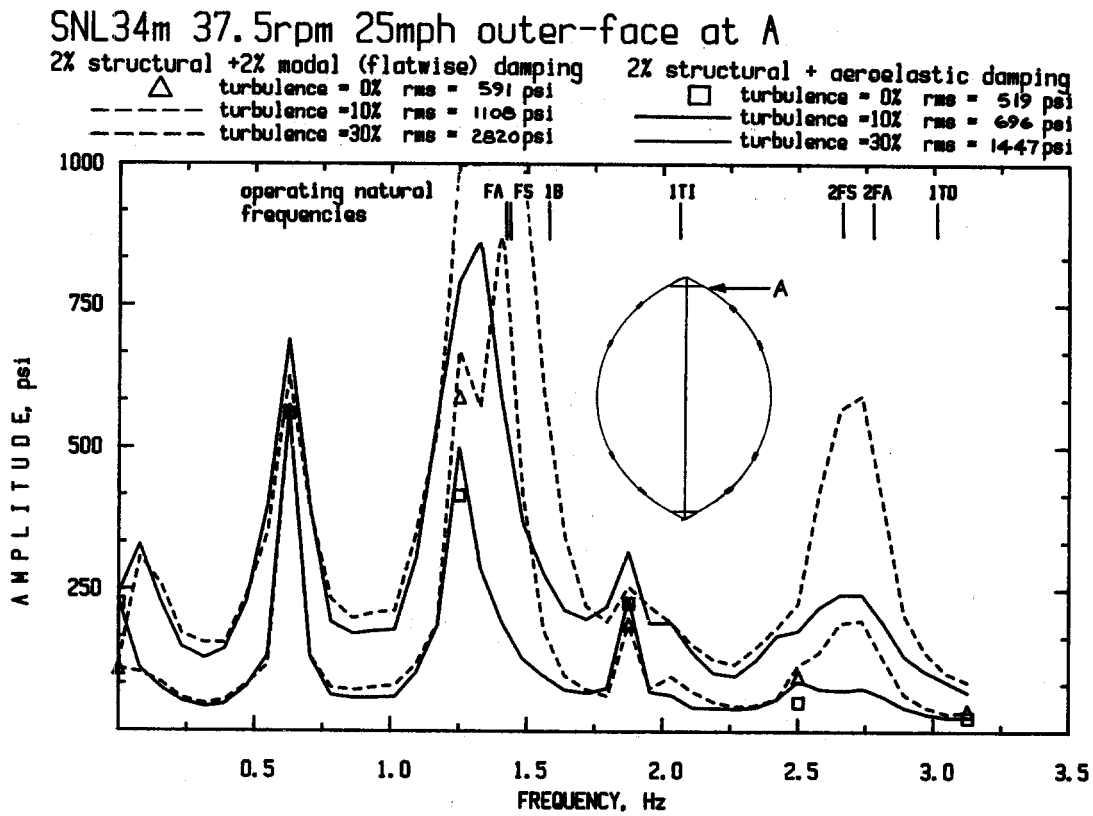


Figure 2. Finite Element Grid for 34-m Test Bed



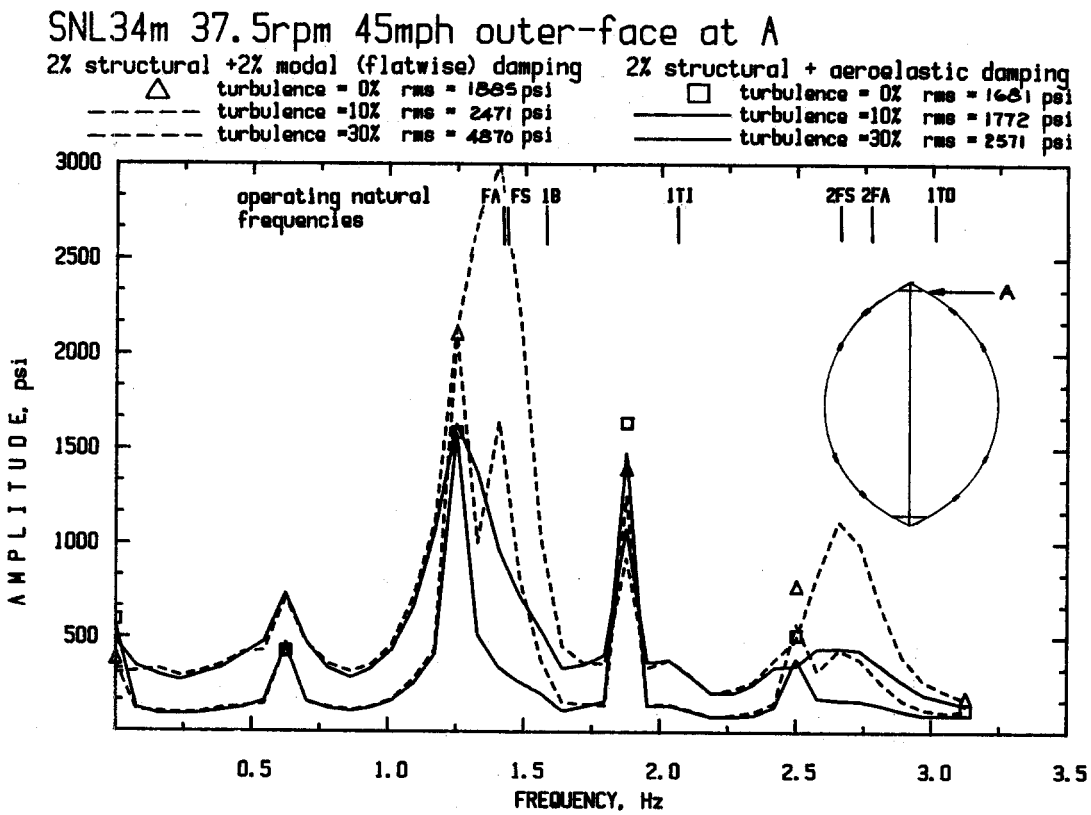
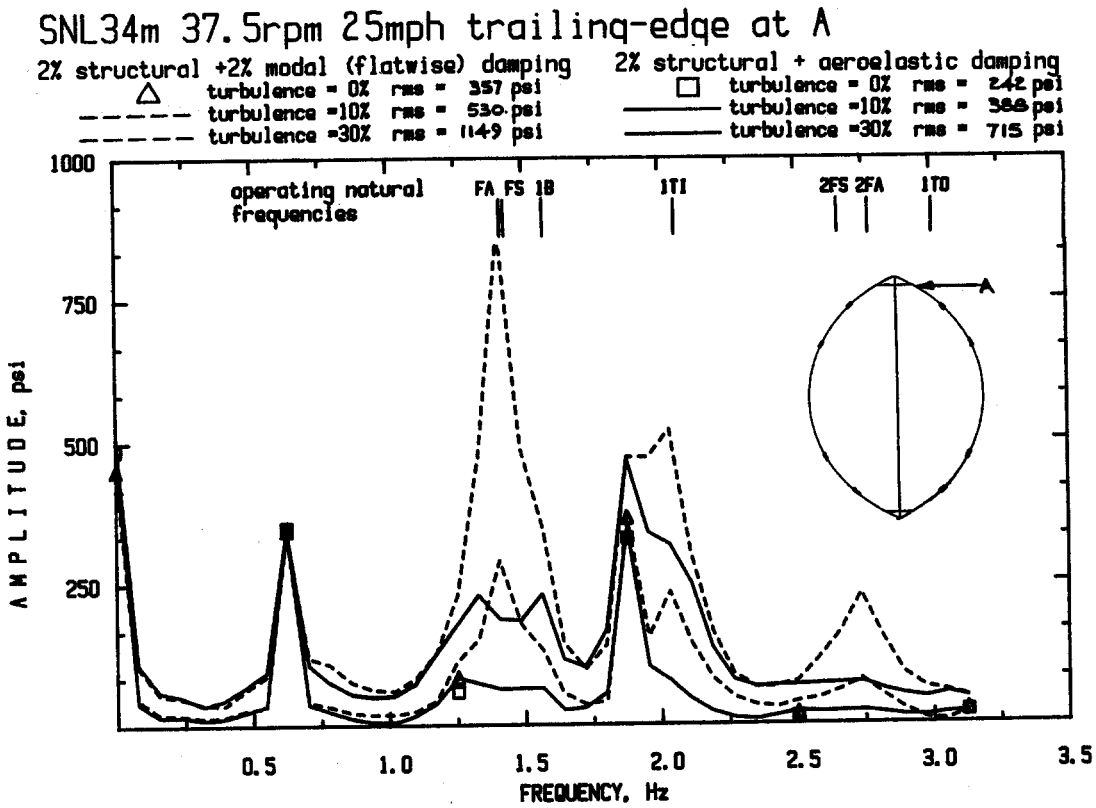


Figure 3.1 a. Spectra of Stress Response at Outer Face at A. 37.5 rpm



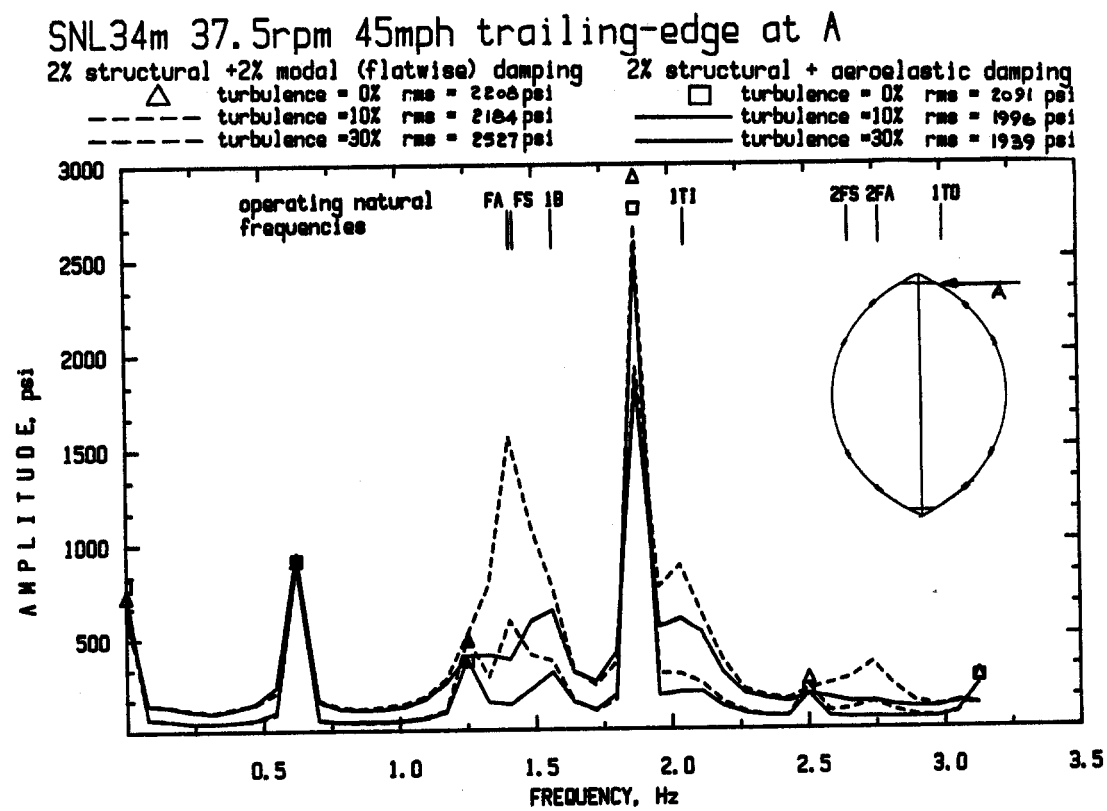
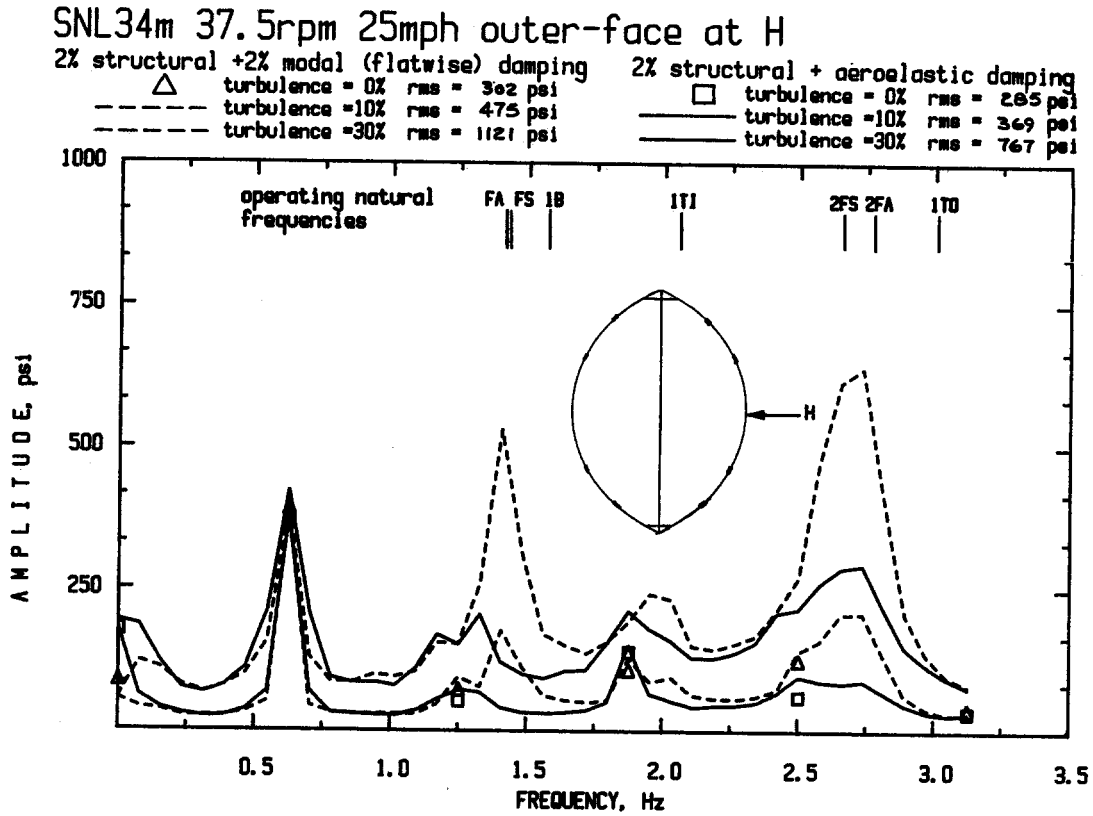


Figure 3.1 b. Spectra of Stress Response at Trailing Edge at A. 37.5 rpm



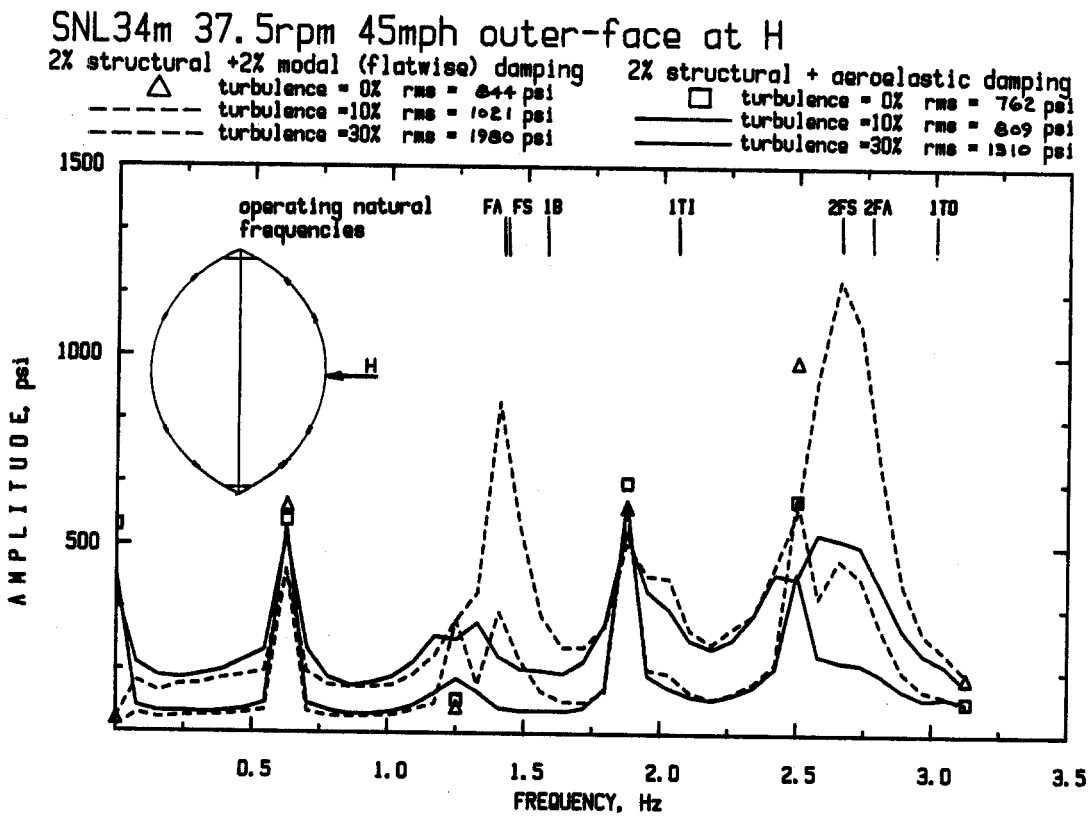
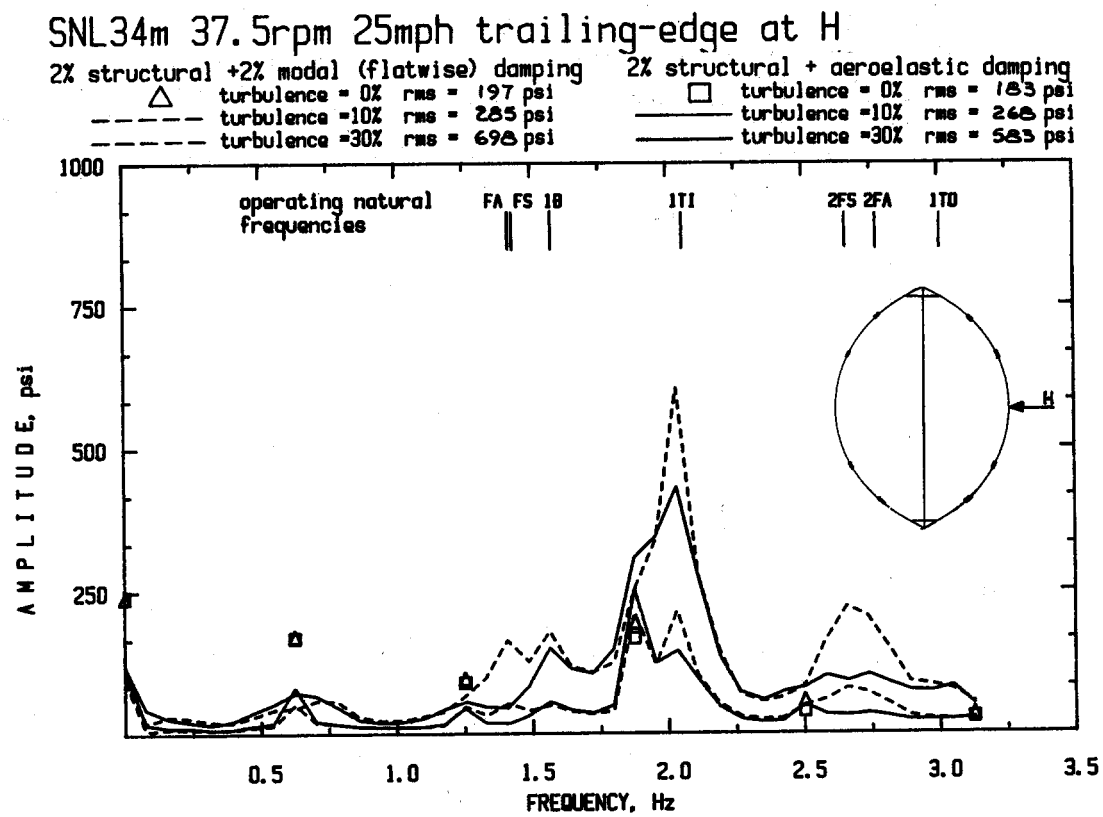


Figure 3.2 a. Spectra of Stress Response at Outer Face at H. 37.5 rpm



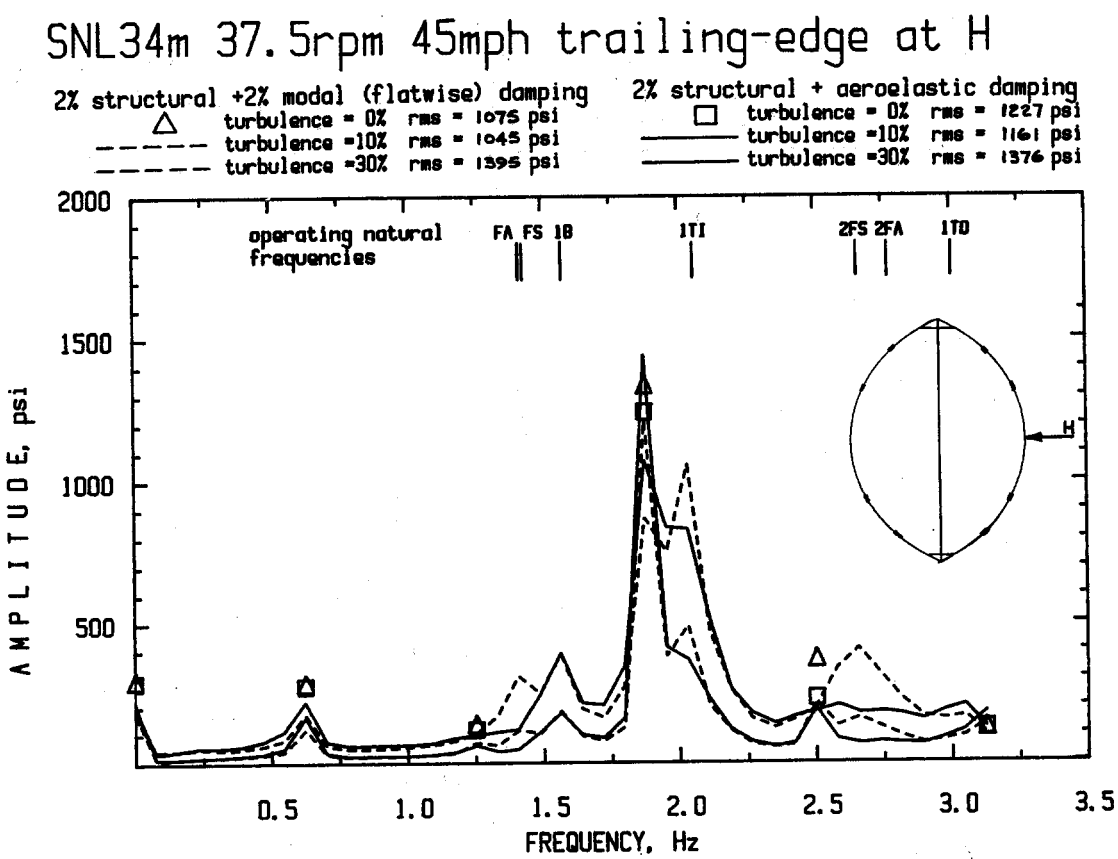
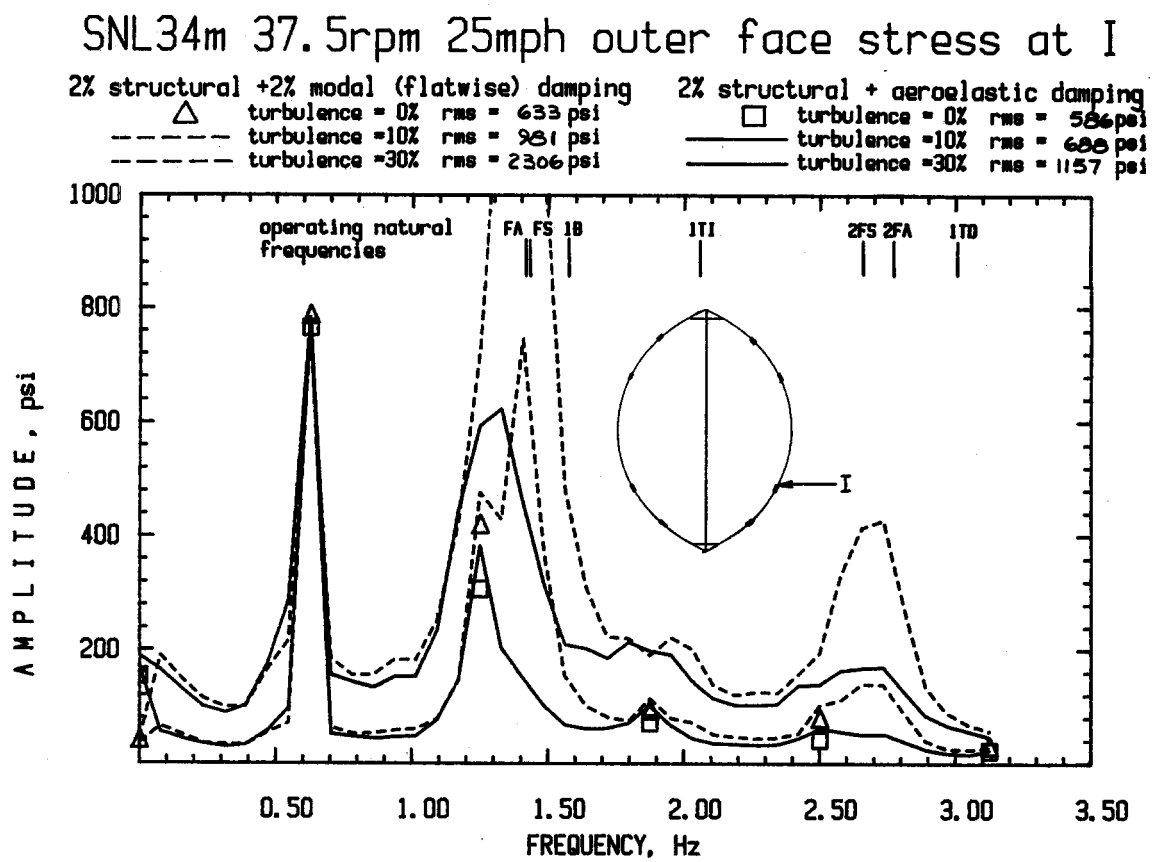


Figure 3.2 b. Spectra of Stress Response at Trailing Edge at H. 37.5 rpm



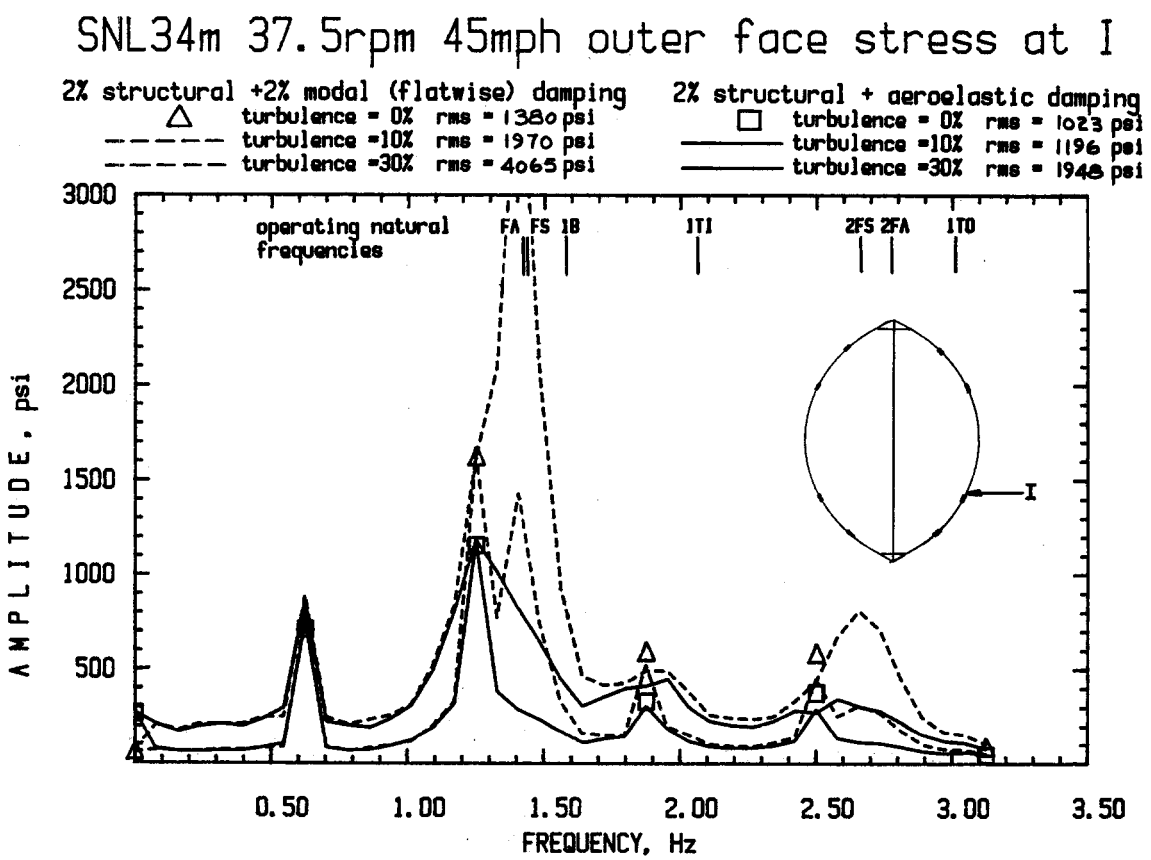
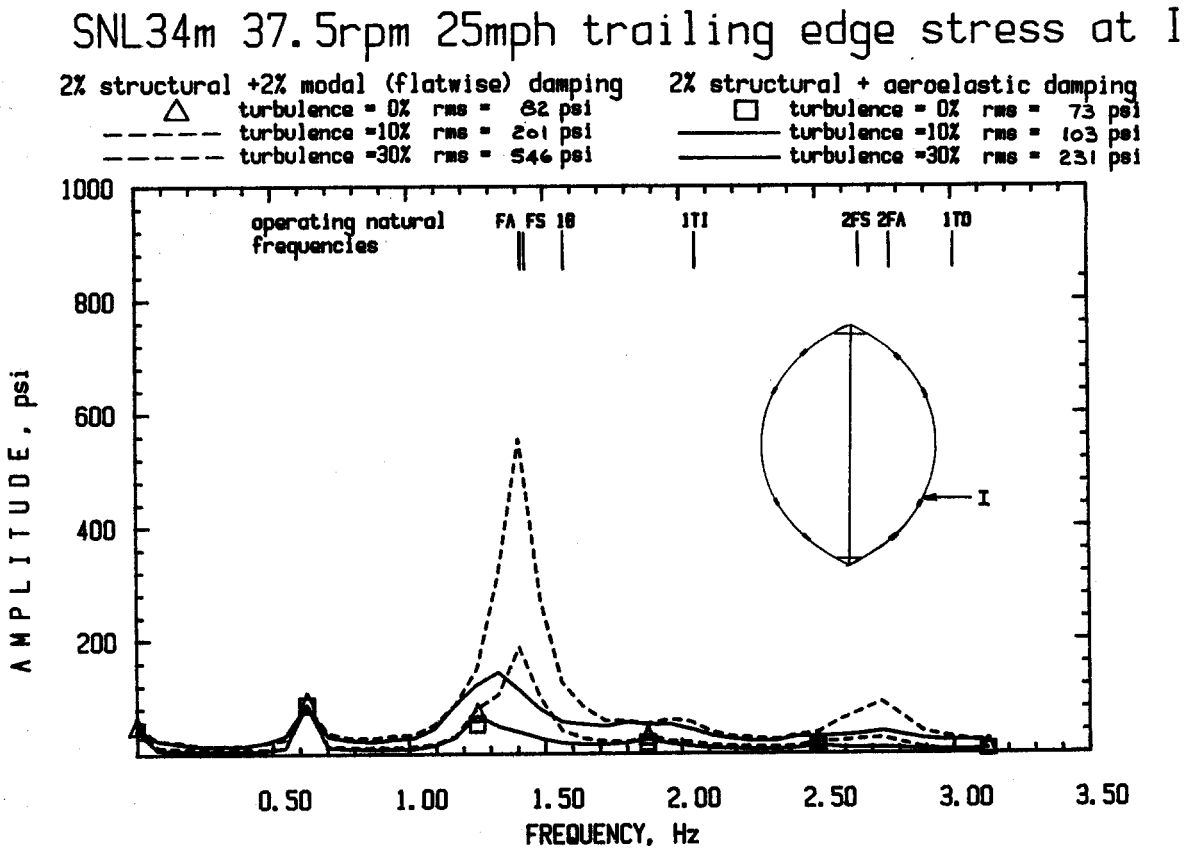


Figure 3.3 b. Spectra of Stress Response at Trailing Edge at I. 37.5 rpm



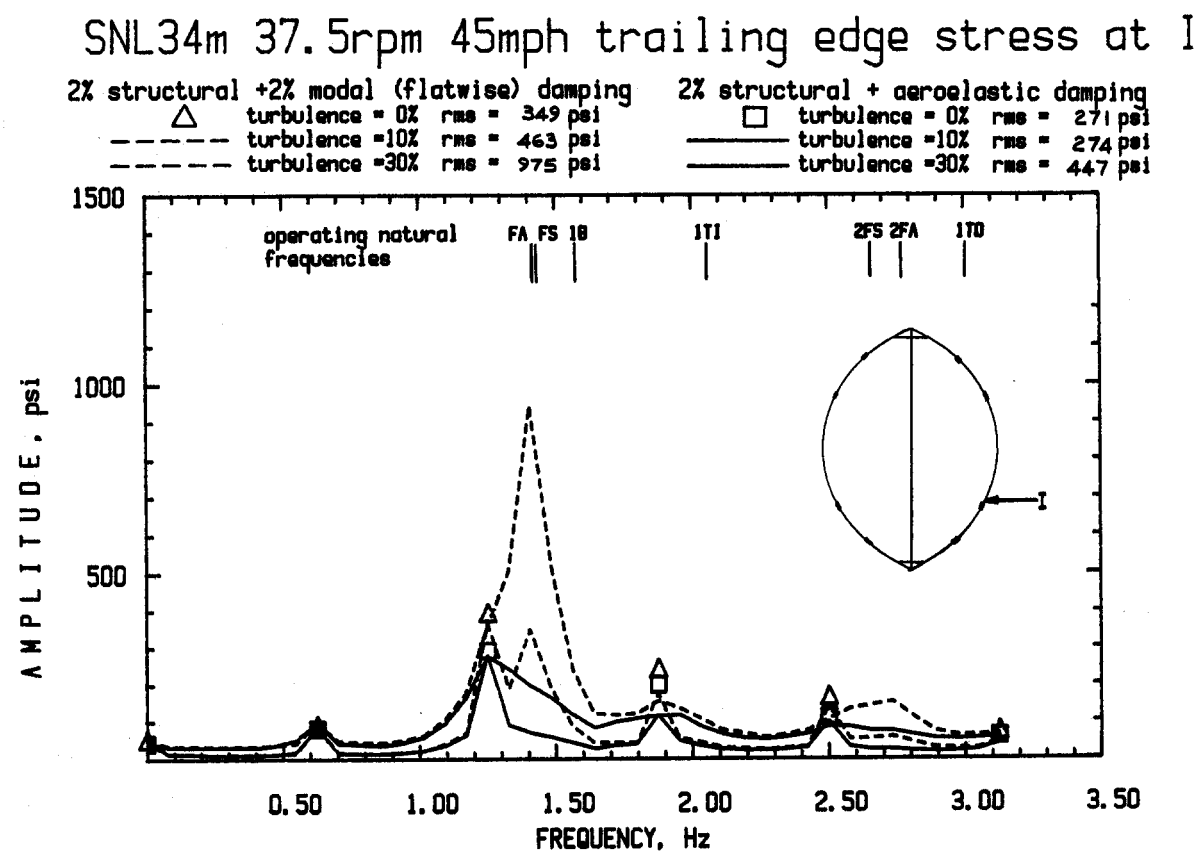
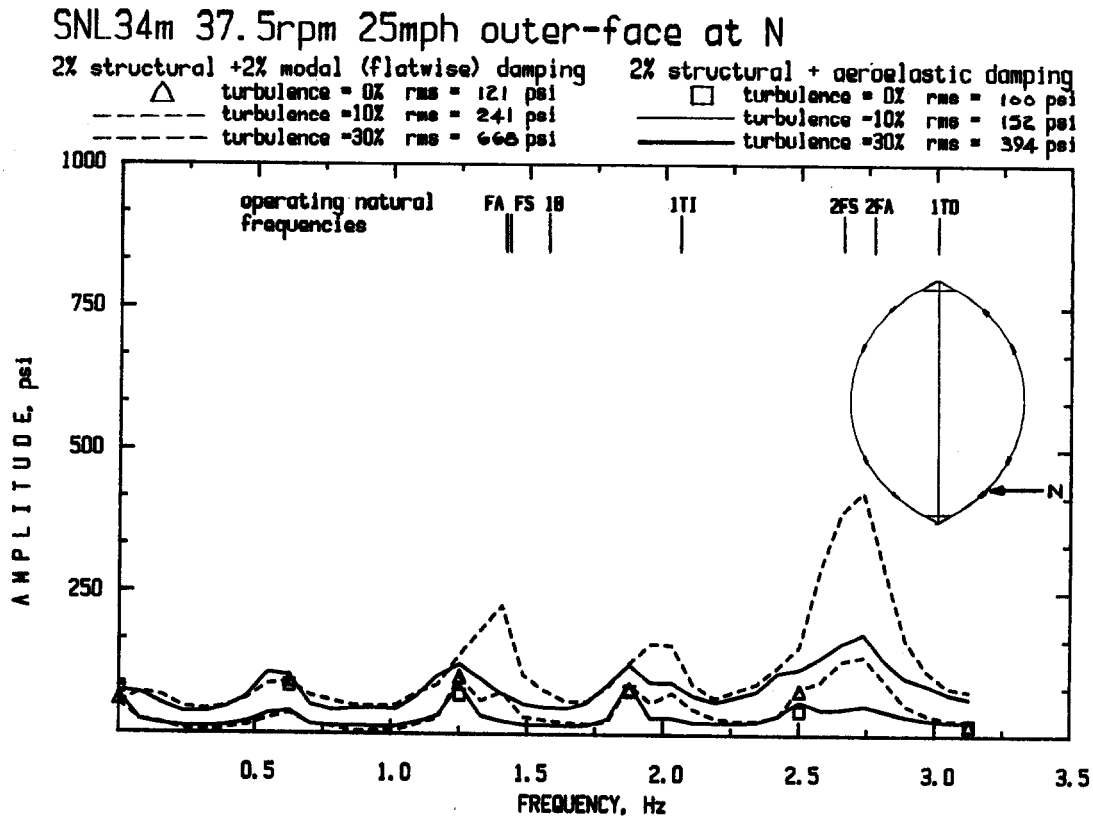


Figure 3.3 a. Spectra of Stress Response at Outer Face at I. 37.5 rpm



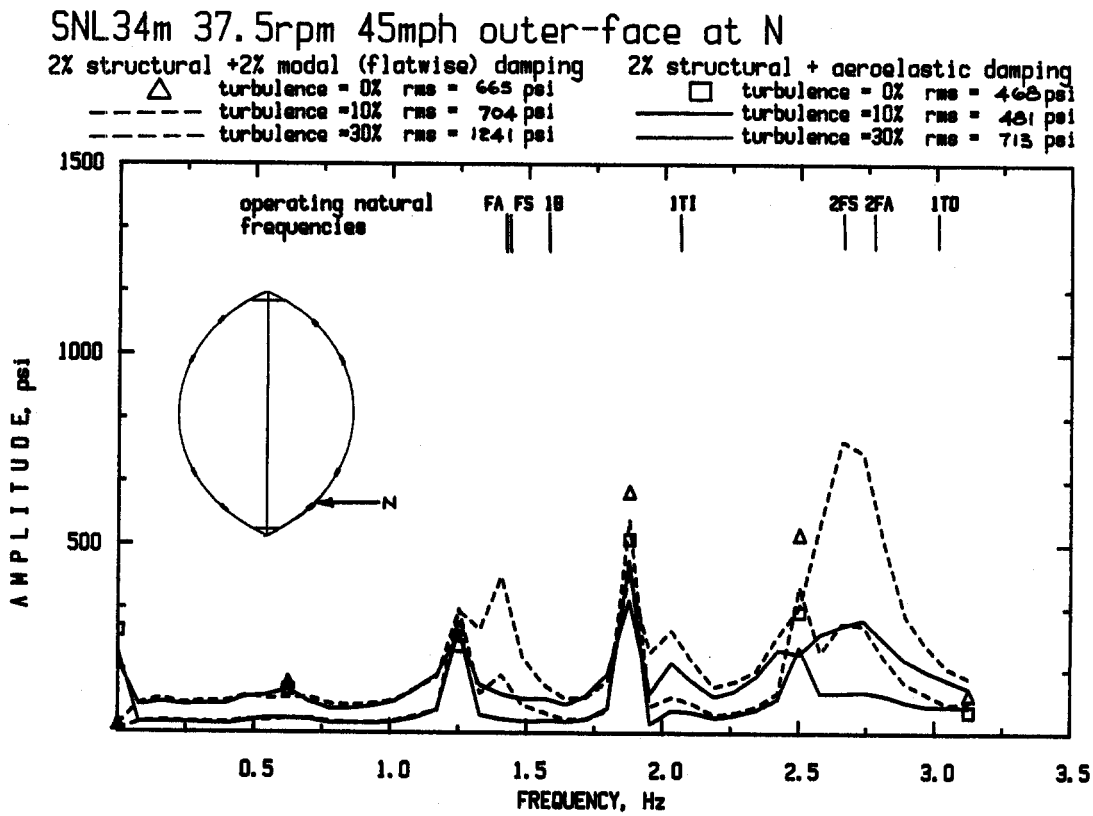
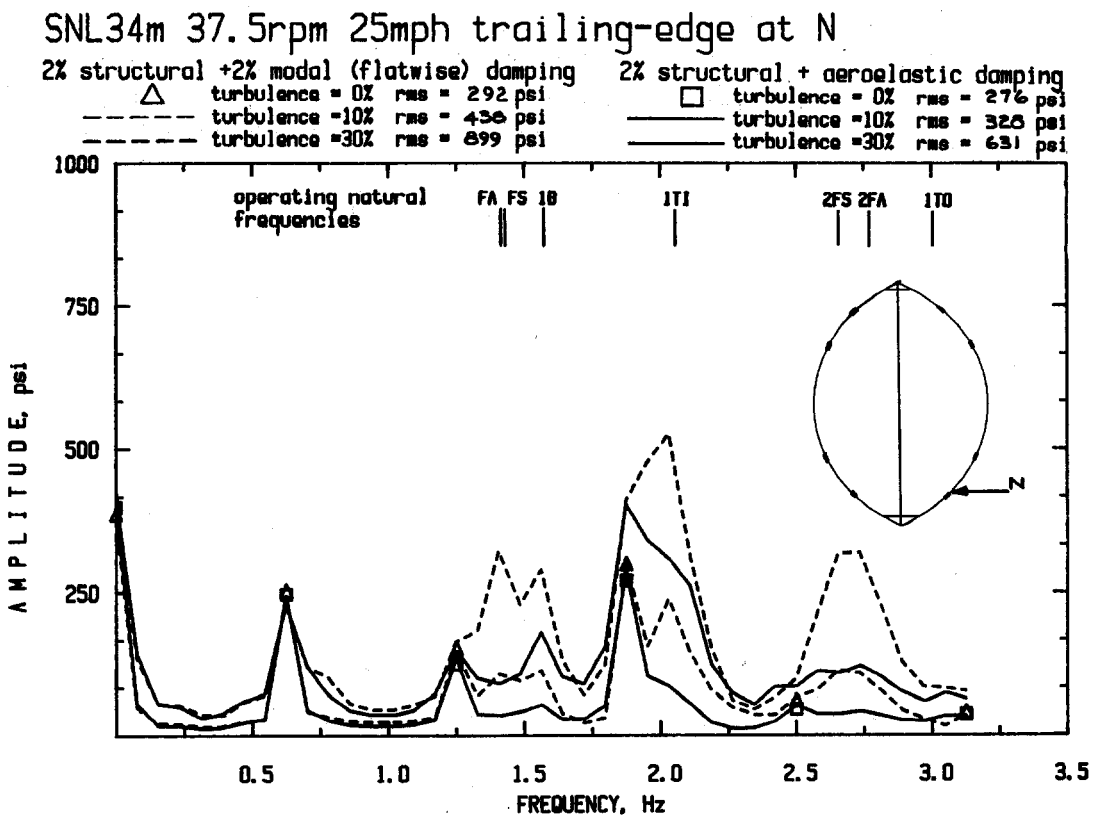


Figure 3.4 a. Spectra of Stress Response at Outer Face at N. 37.5 rpm



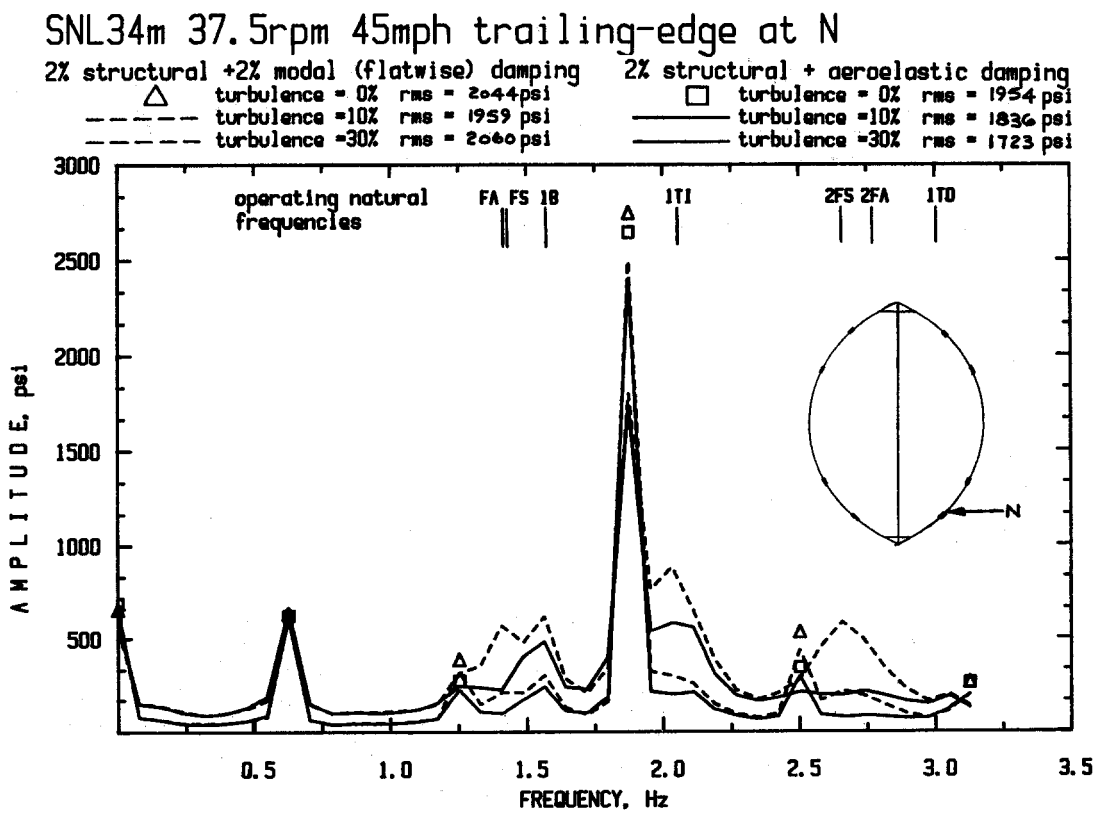
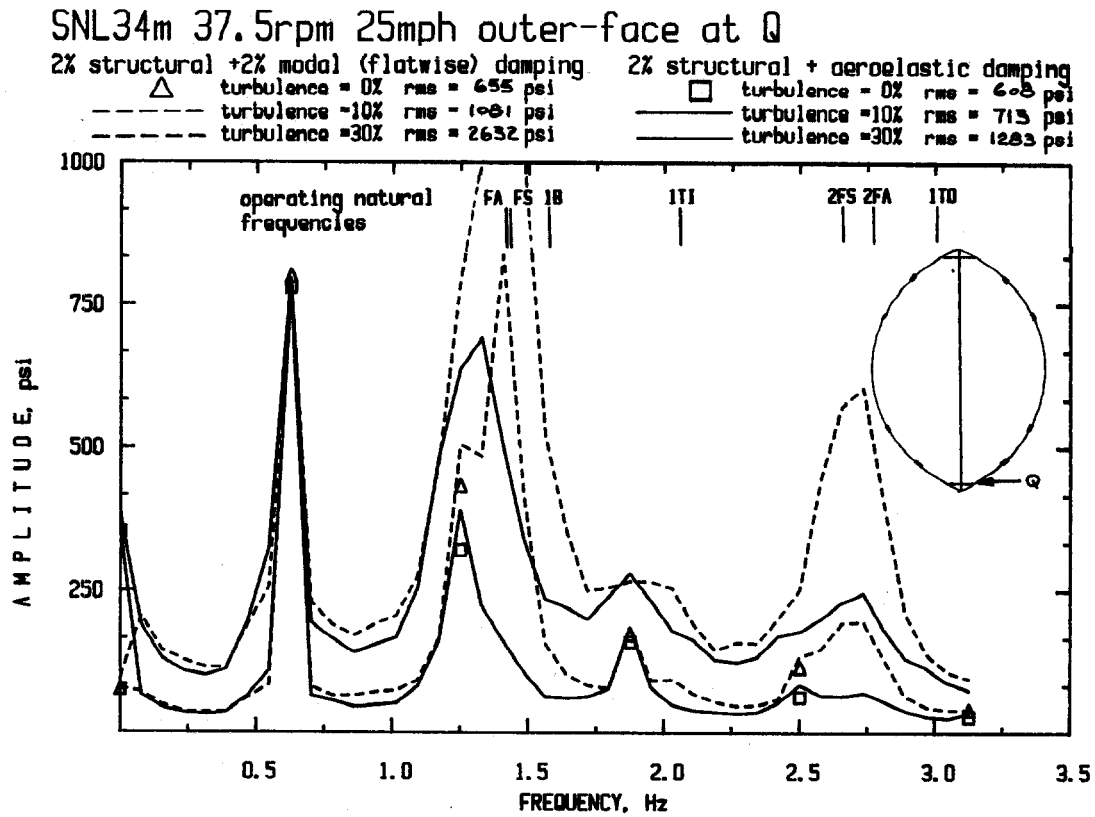


Figure 3.4 b. Spectra of Stress Response at Trailing Edge at N. 37.5 rpm



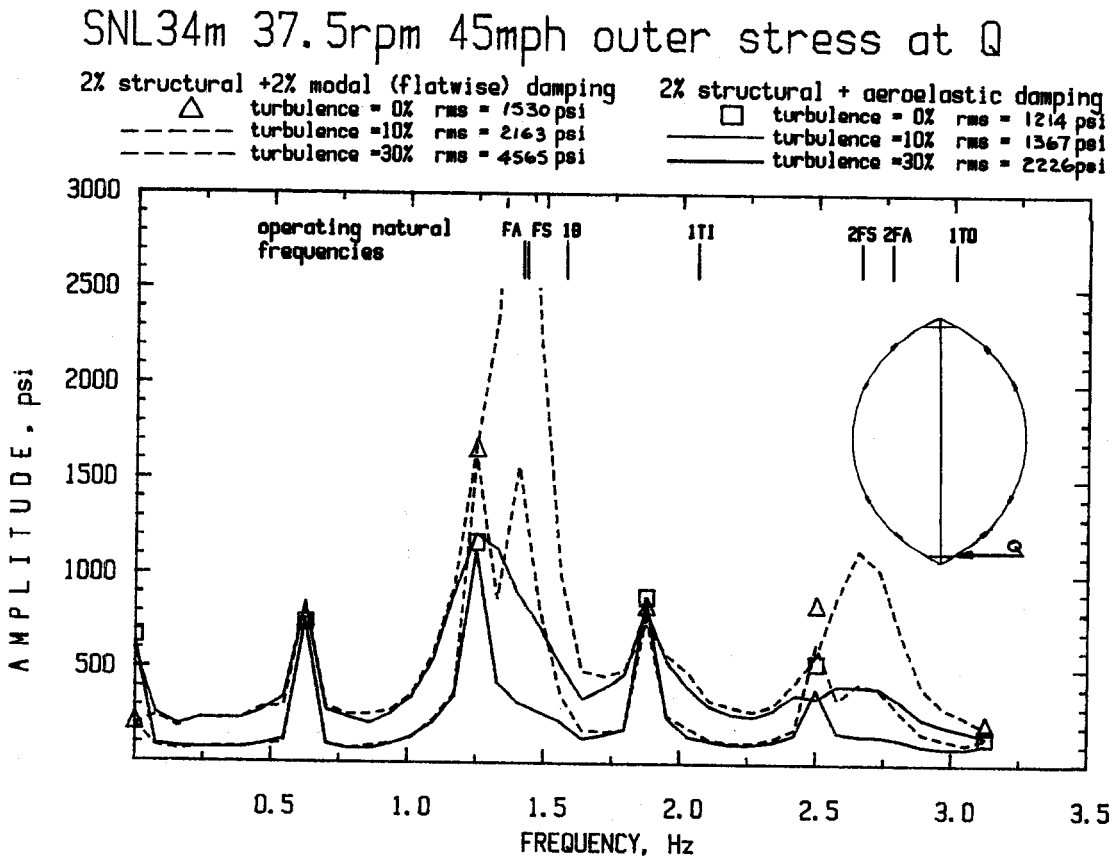
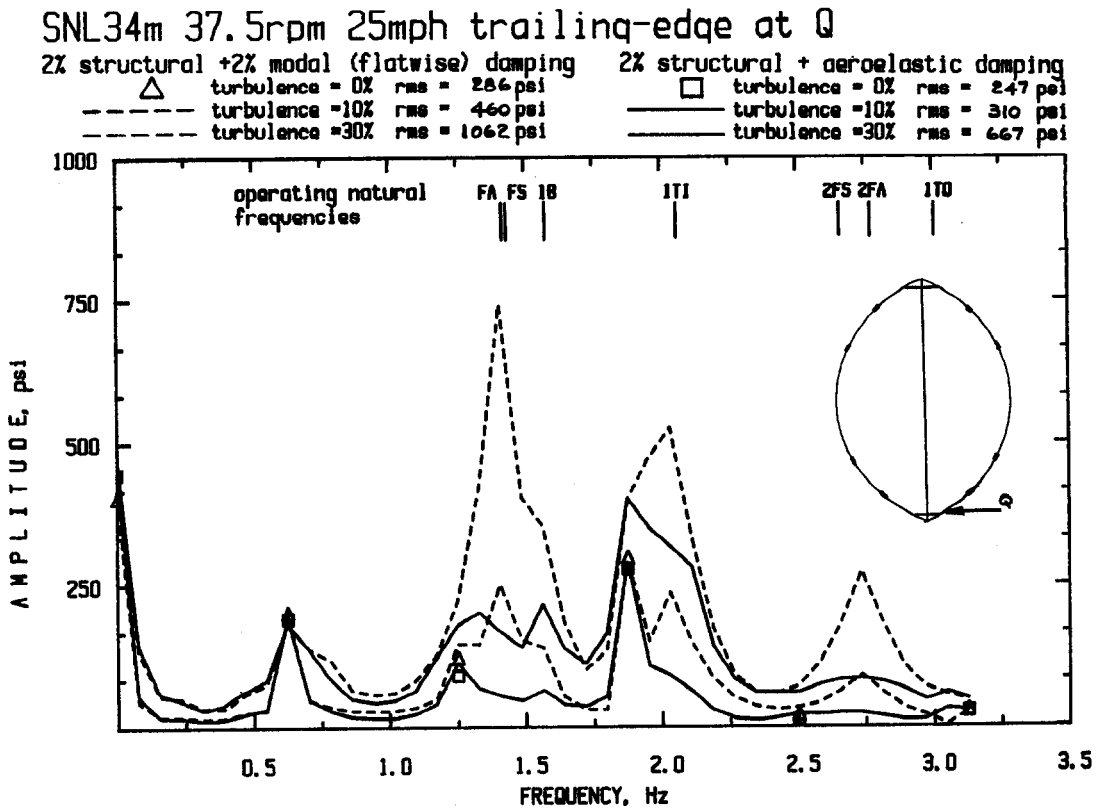


Figure 3.5 a. Spectra of Stress Response at Outer Face at Q. 37.5 rpm



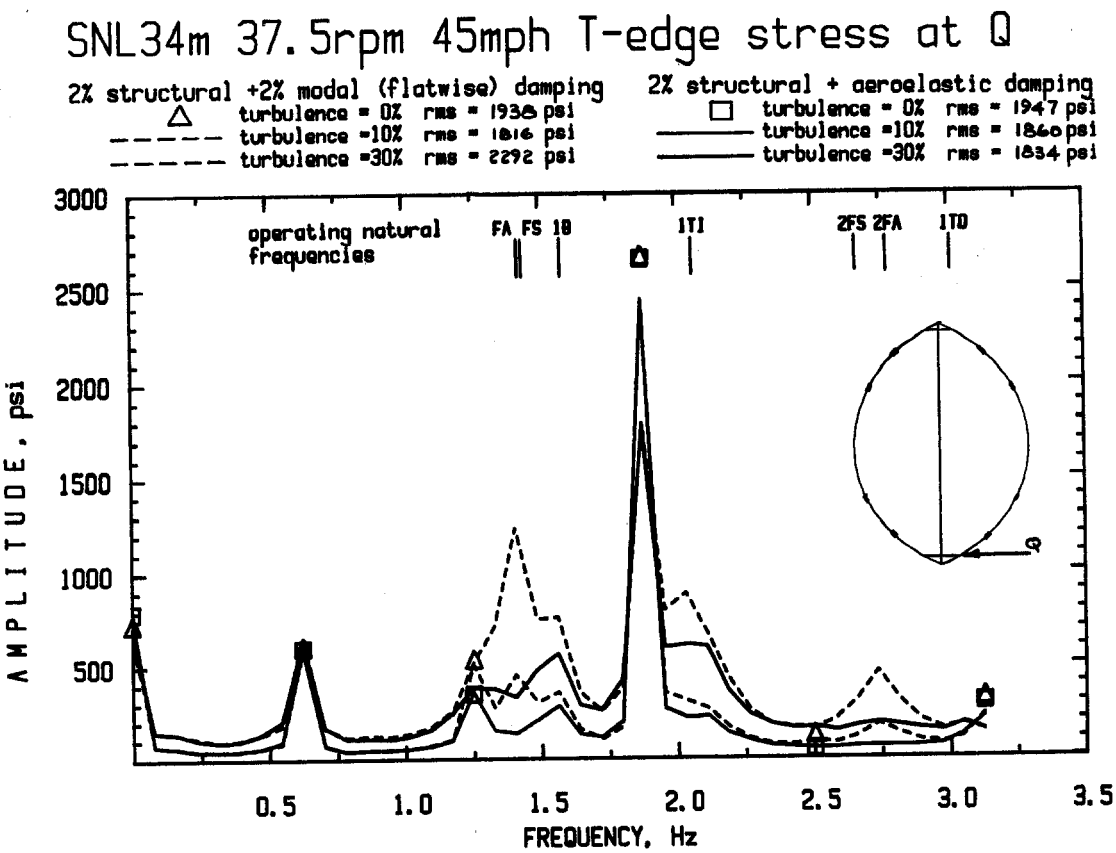
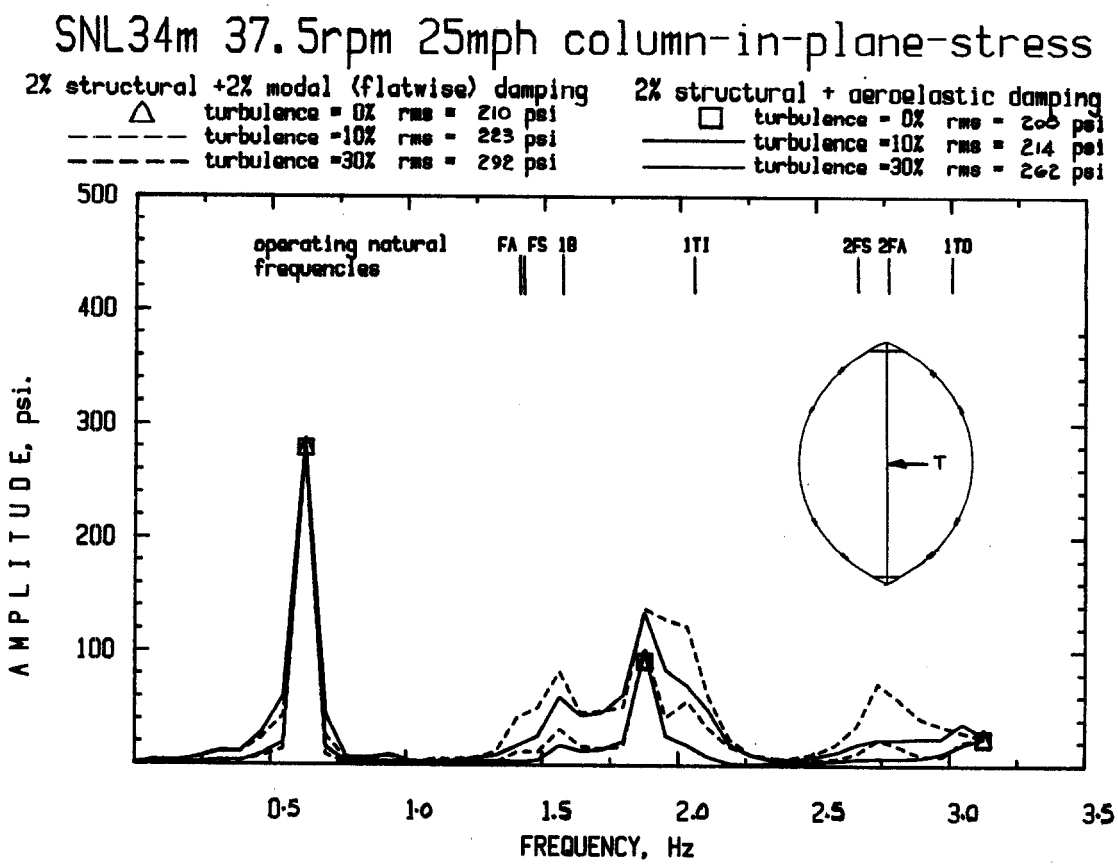


Figure 3.5 b. Spectra of Stress Response at Trailing Edge at Q. 37.5 rpm



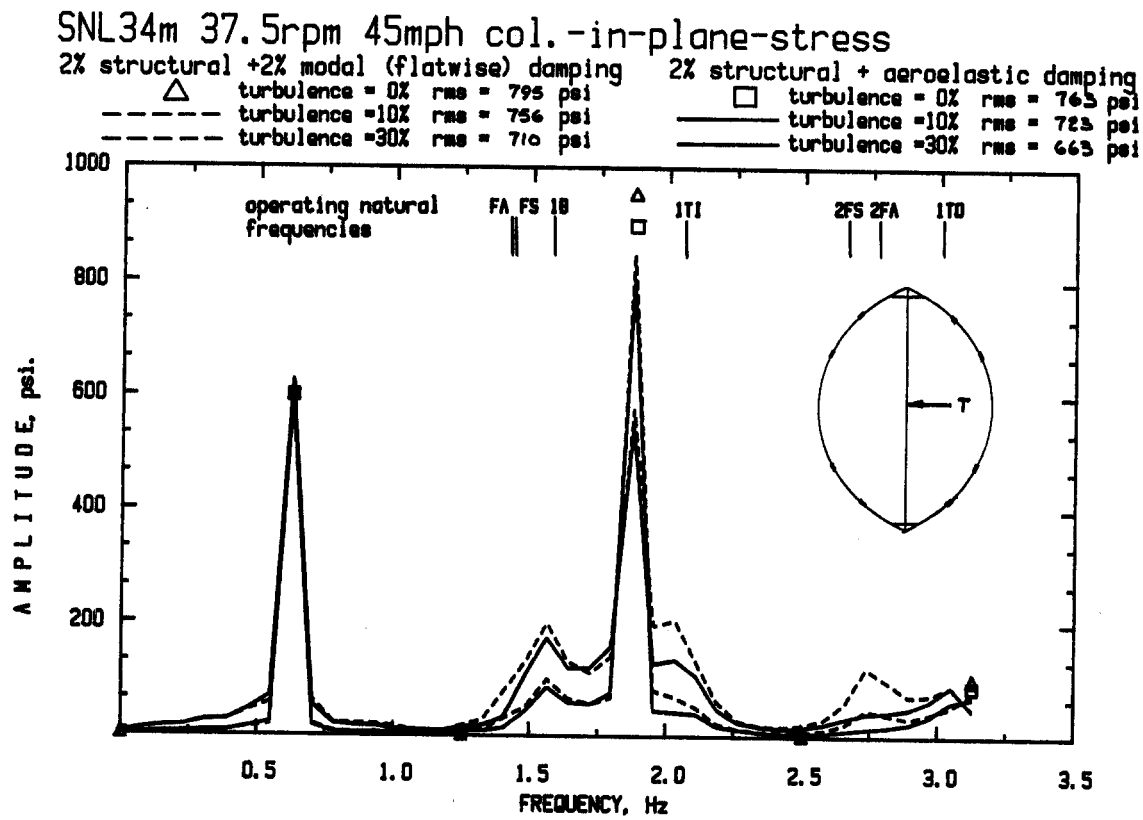


Figure 3.6. Spectra of In-Plane Stress Response at Mid-Column at T. 37.5 rpm

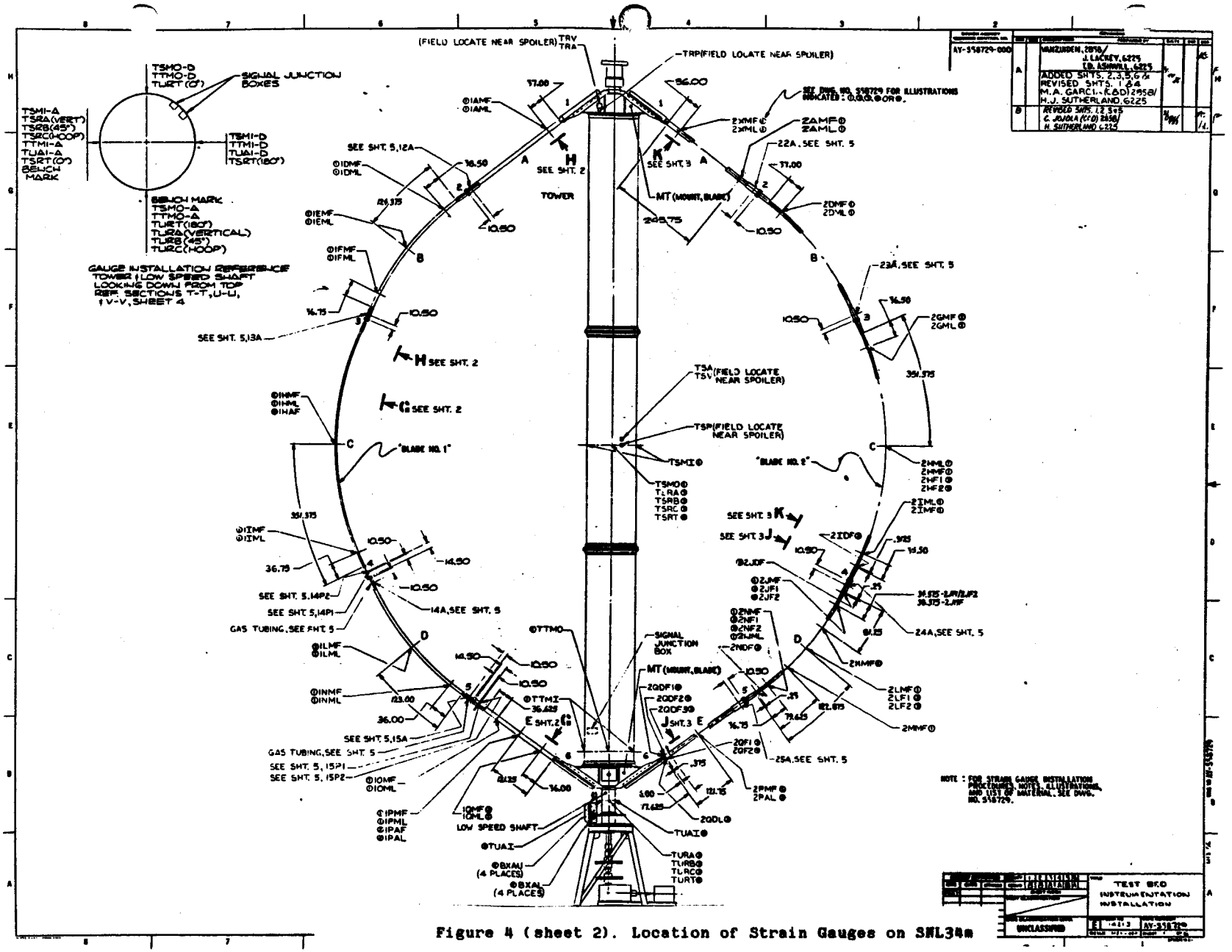


Figure 4 (sheet 2). Location of Strain Gauges on SNL34m

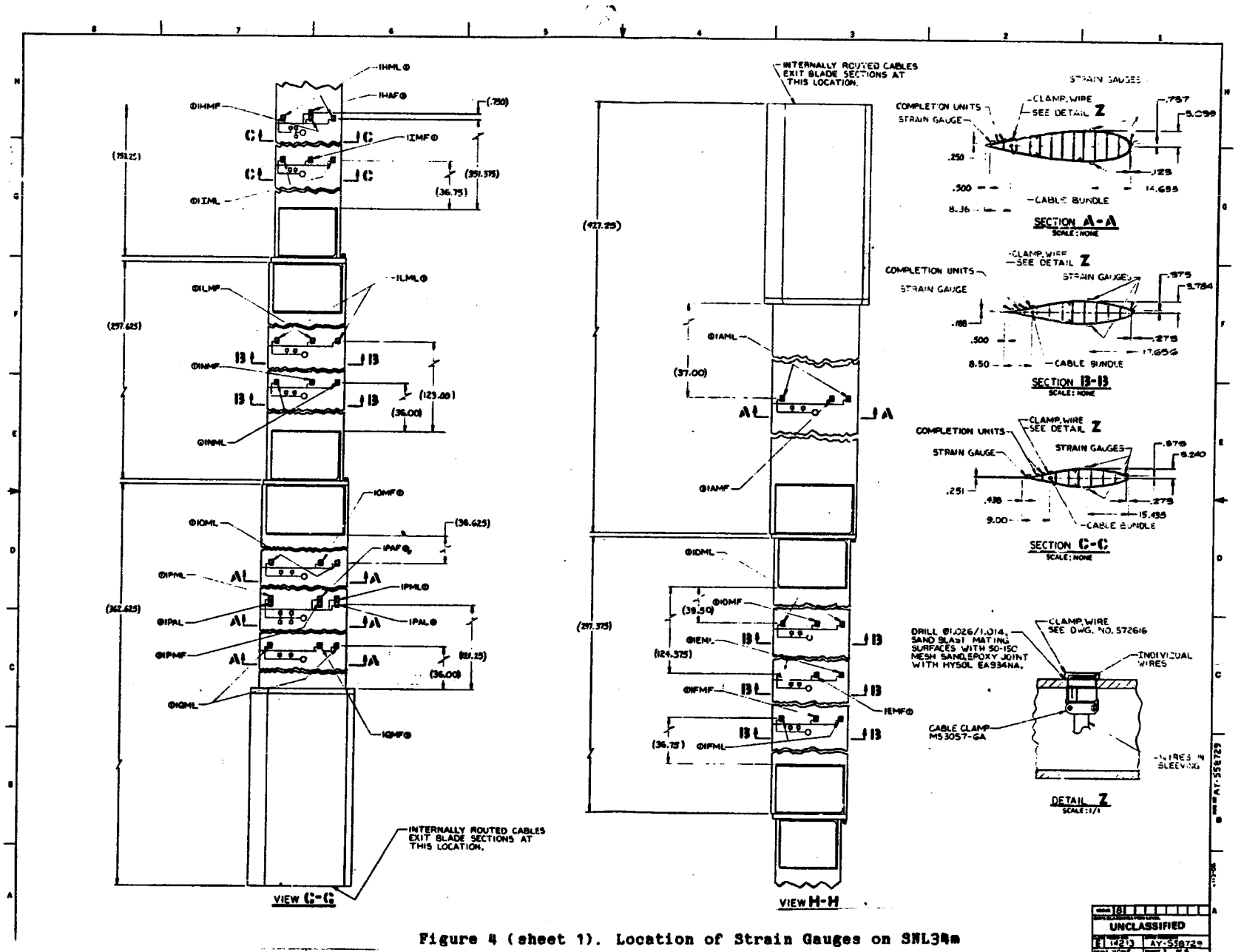


Figure 4 (sheet 1). Location of Strain Gauges on SNL34m

Each figure shows the influence of replacing the modest 2% modal damping of blade bending modes with aeroelastic damping which, as Table 2 indicates, is equivalent to as much as 9% of critical damping of these modes. The 30% turbulence was chosen as an upper bound for possible interest. Most locations will have turbulence levels closer to 10% intensity.

The results shown in Figure 3 indicate several trends. The first is that the stresses in the 45 mph wind are very much greater than those at 25 mph. The deterministic rms values increase by three times (outer face at A) to seven times (trailing edge at A).

A second observation is that with only 2% modal damping the inclusion of turbulence leads to considerable response at natural frequencies corresponding to in-plane blade bending. For a given intensity, the effect of turbulence on the rms stress is greater at 25 mph than at 45 mph. Even 10% turbulence is predicted to increase the rms stress at the outer face at A by 100%.

The replacement of modal damping by aeroelastic forces has significant consequences. There are modest decreases in the predicted rms stresses for the deterministic case (most marked at 25 mph). Another consequence is the attenuation of the stochastic response at the natural frequency values. This attenuation is most apparent at the outer face locations because of their involvement in the in-plane bending modes which are the modes most heavily dampened by aeroelastic forces. The maximum increase in rms stress due to 10% turbulence when aeroelastic forces are present is 34% (outer face at A with V = 25 mph).

It is also of interest to note that the pronounced out-of-plane response at 3P at 45 mph, which is largely responsible for the high rms stress, is partially attenuated by both aeroelastic forces and by turbulent flow.

4.2 Operation at 28 rpm

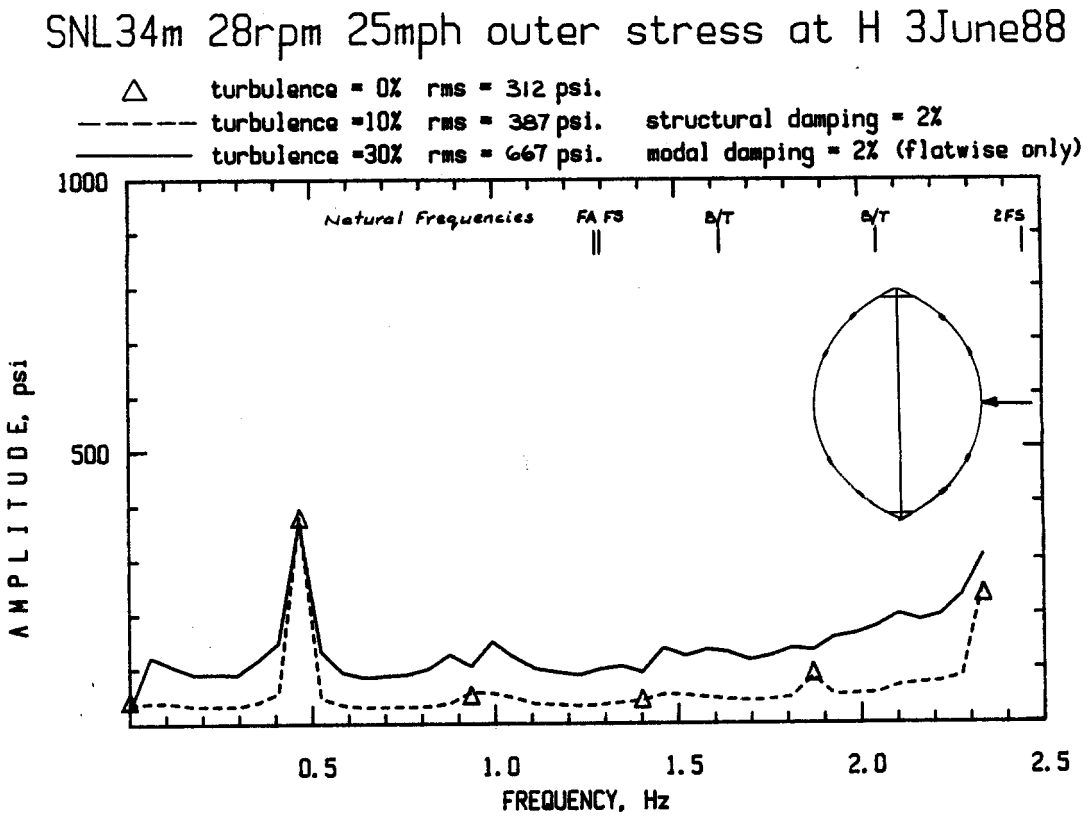
Some frequency response analyses were also carried out on the SNL 34-m operating at 28 rpm and results are summarized in Figure 5. These analyses were limited to the 2% modal damping only and were included in the earlier preliminary report. They are also included in this report for completeness and so that comparison of the response at the two operating speeds can be made.

4.3 Axial Effects

In conjunction with a modal formulation of dynamic response it is common to use the "mode acceleration" method to determine member forces and stresses more accurately. This method involves using the predicted displacements to calculate inertial forces which are then added to the applied forces and a static analysis is carried out. This is sometimes made necessary when the modes selected for the formulation are unable to adequately describe all of the displacements and associated forces. This is the case with the axial effects in the blades and other members of the SNL 34-m rotor.

The mode acceleration technique can be applied to the deterministic frequency response solutions (zero turbulence) because a set of physical loads was applied. However it cannot be applied to the stochastic response analysis because the loads have been applied in modal form only.

This difficulty is not insurmountable. It should be noted that the axial effects in the blade are appreciable at 1P only and are affected little by stochastic effects. Corrections calculated for the deterministic case can, therefore, be applied to stochastic cases. It should also be noted that neglect of the axial effect is equivalent to averaging stresses from opposite faces or edges which is also how most of the strain gauges on the SNL 34-m have been connected.



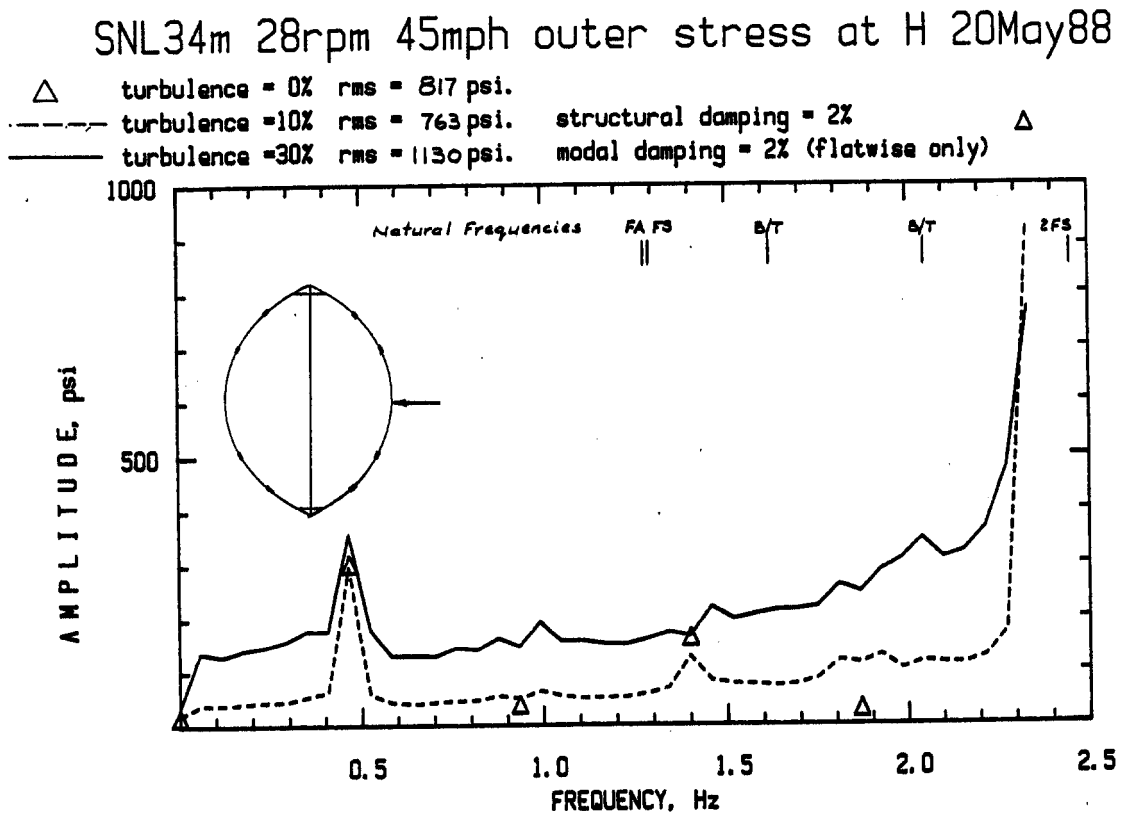
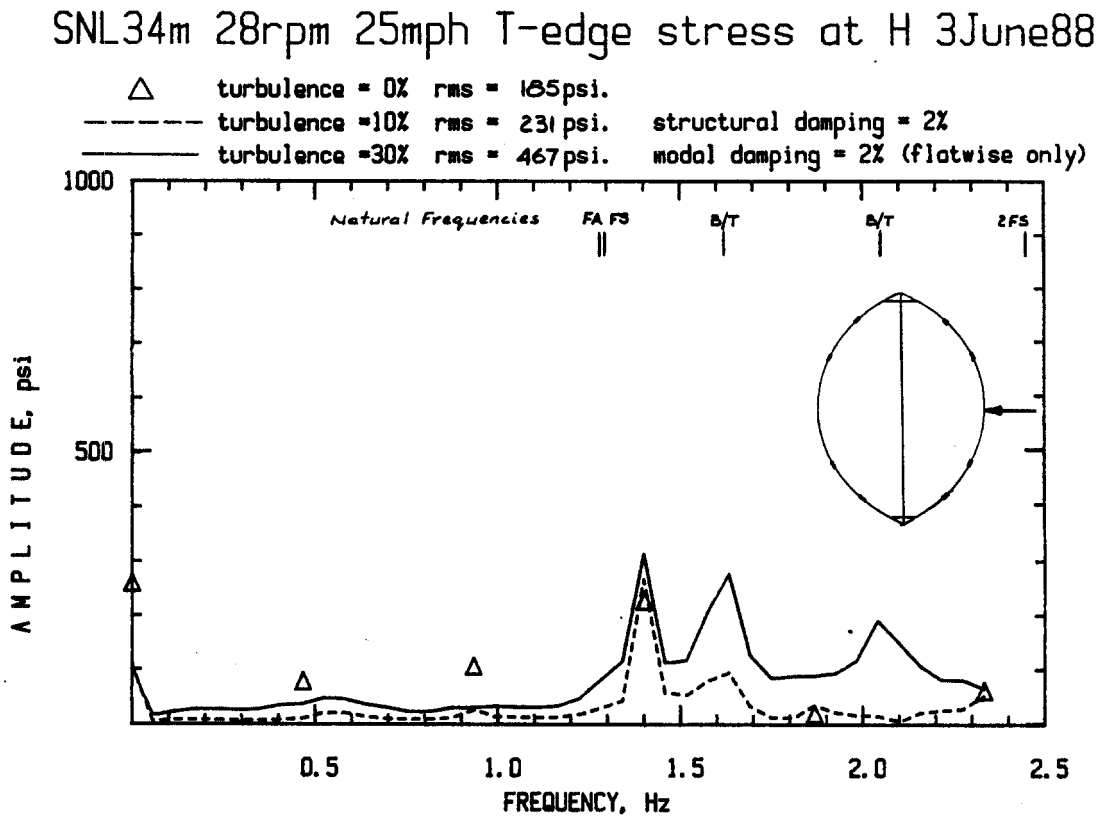


Figure 5.2 a. Spectra of Stress Response at Outer Face at H. 28 rpm



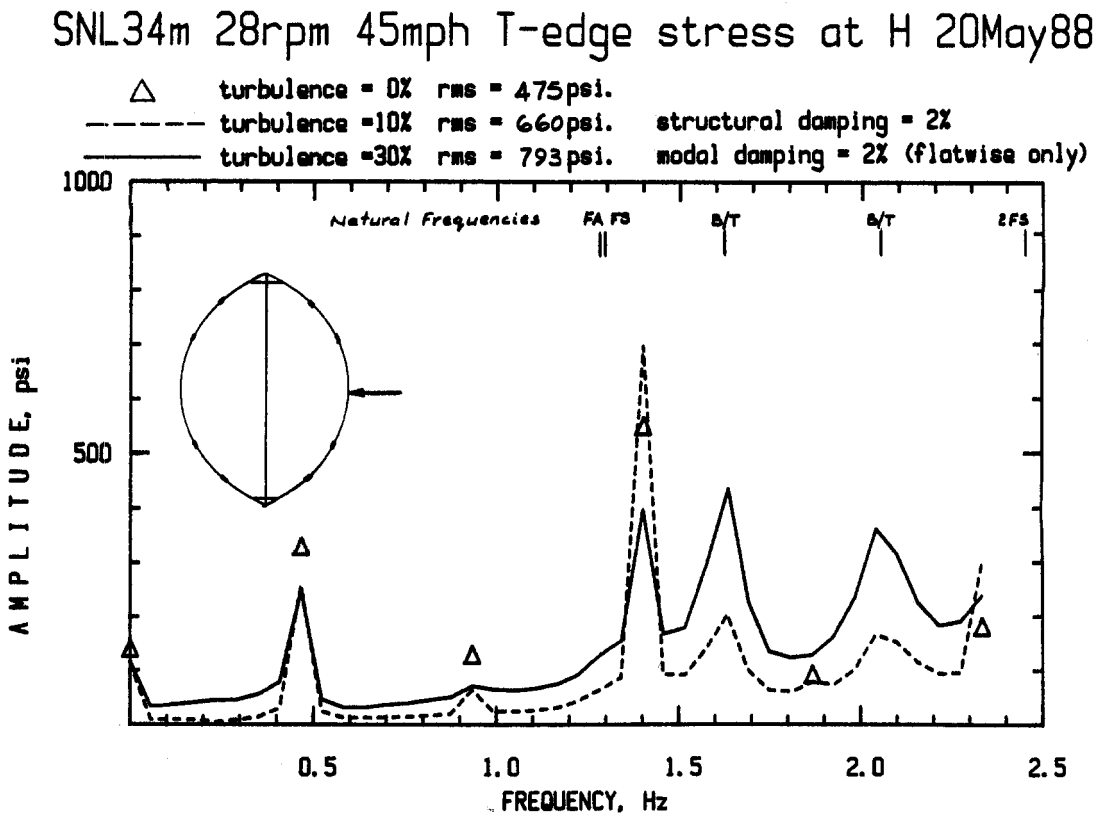
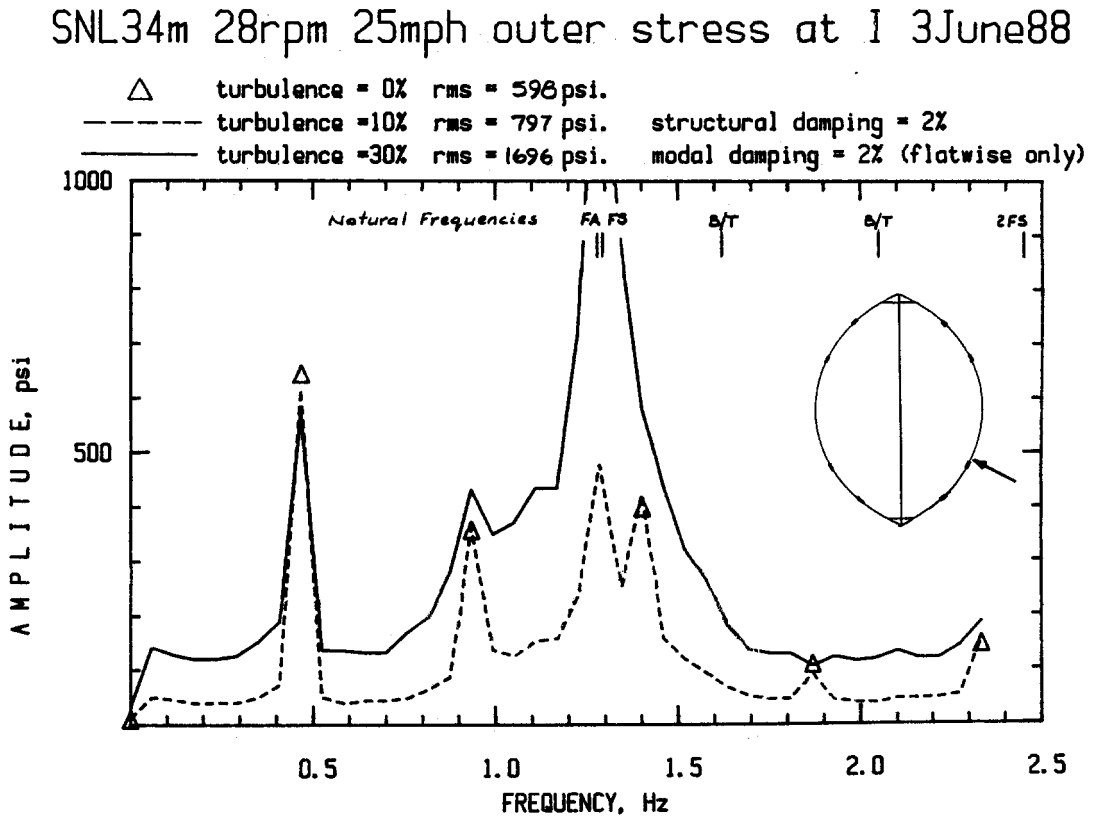


Figure 5.2 b. Spectra of Stress Response at Trailing Edge at H. 28 rpm



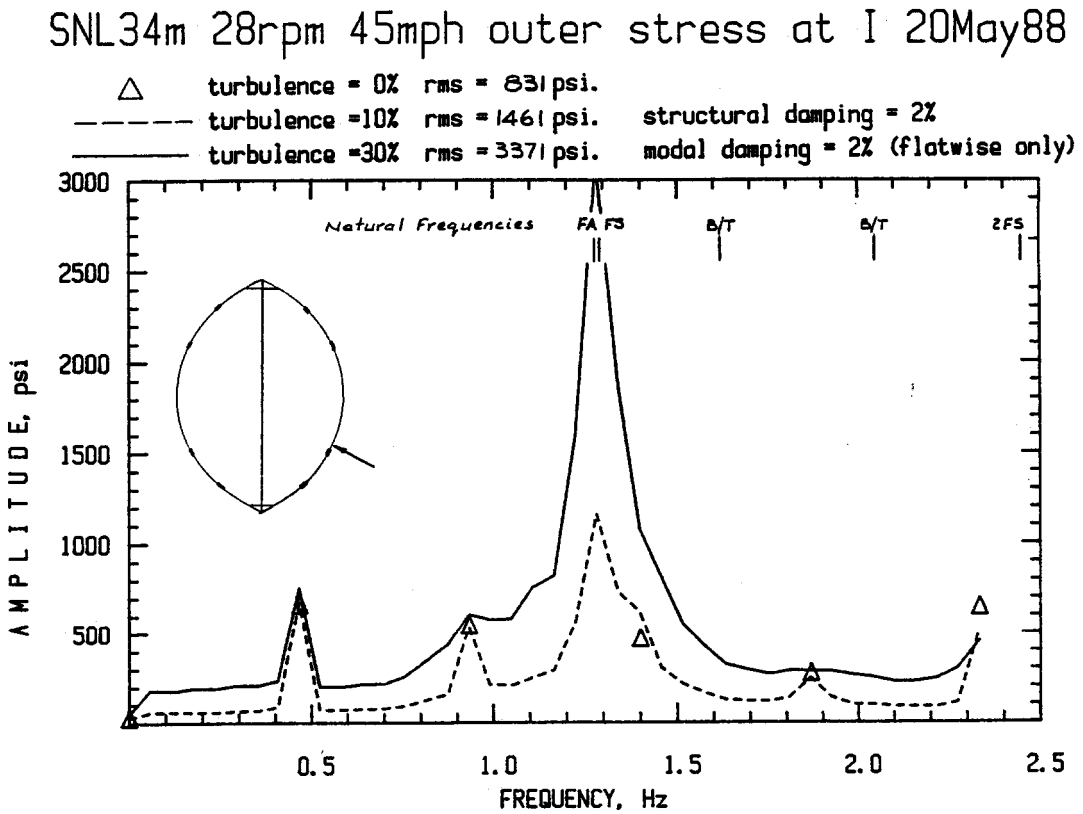
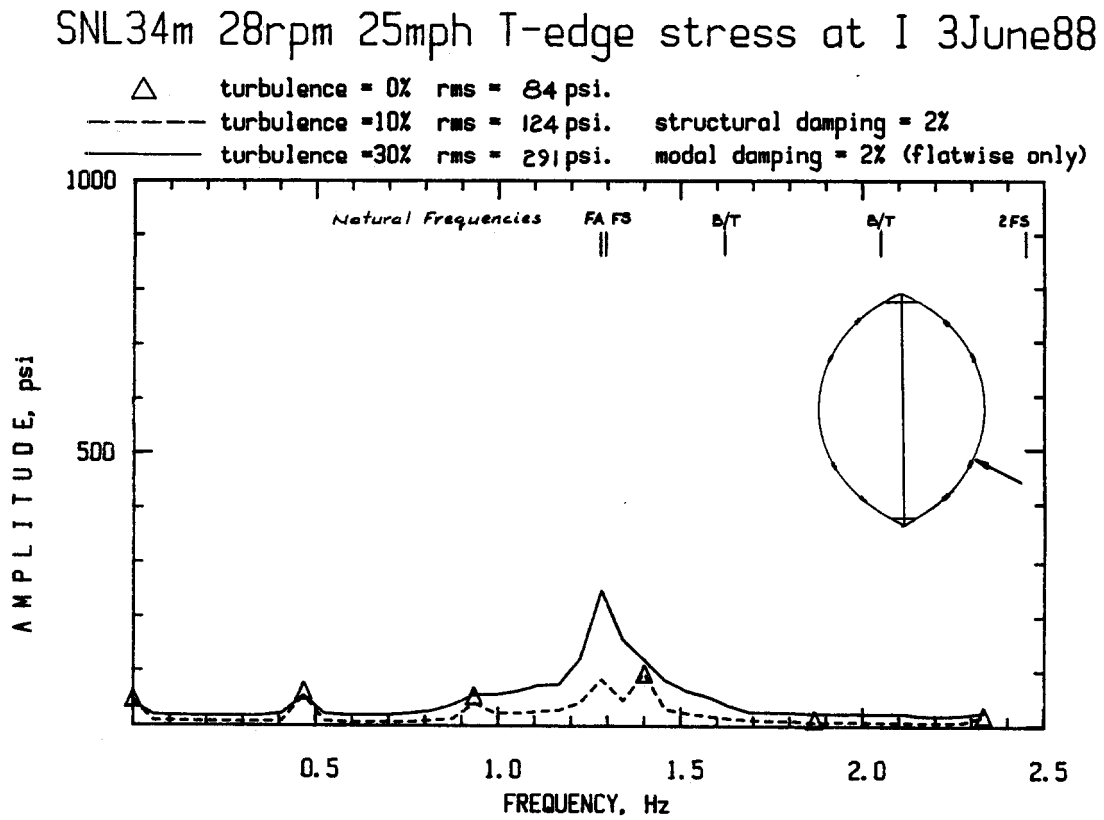


Figure 5.3 a. Spectra of Stress Response at Outer Face at I. 28 rpm



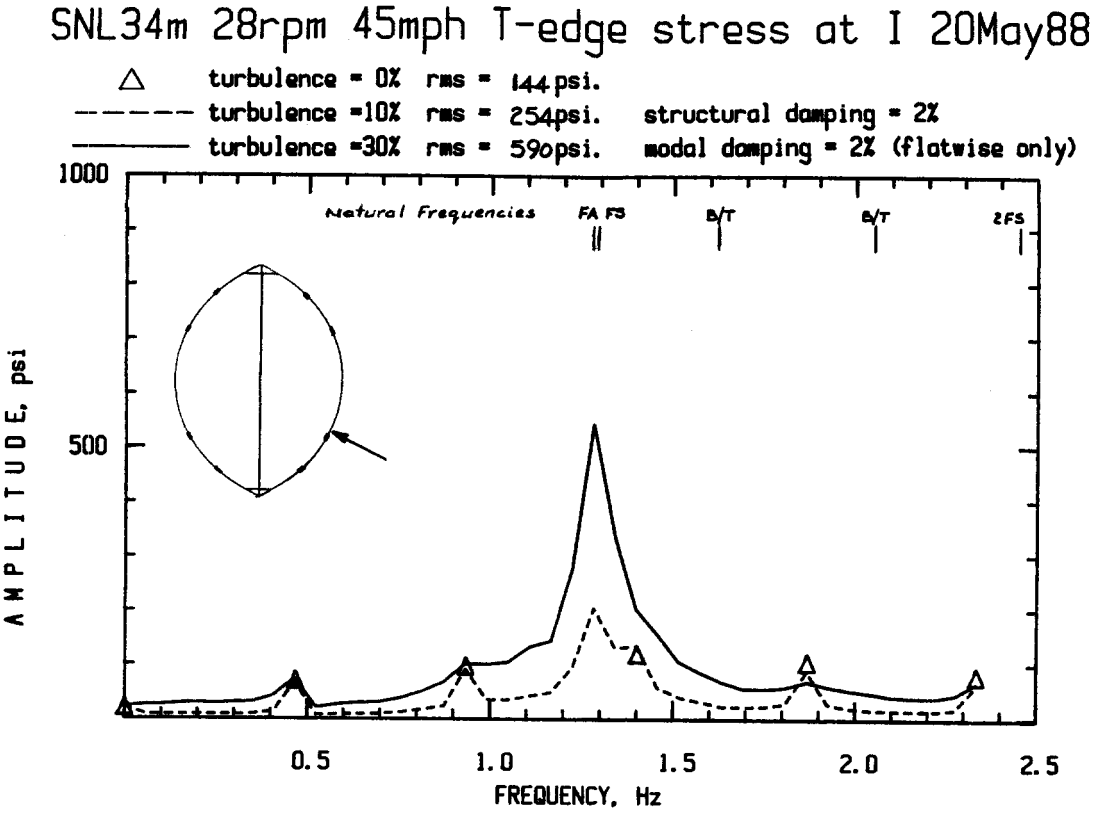
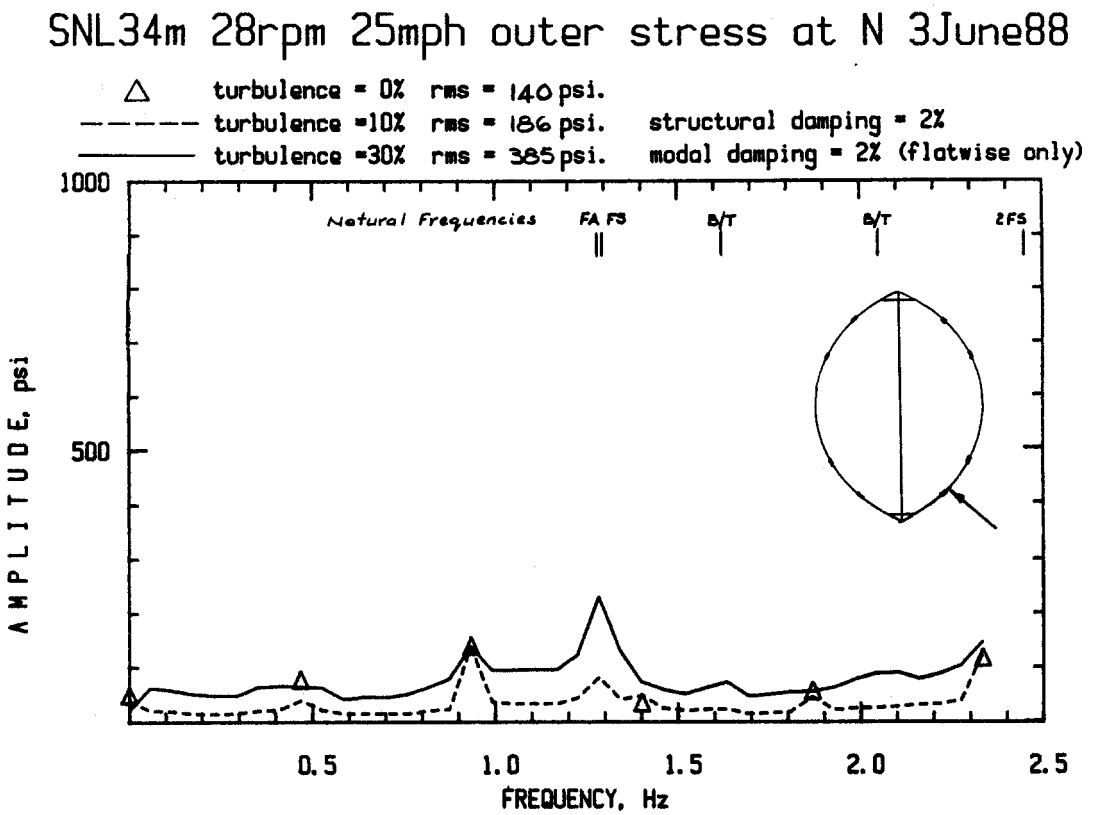


Figure 5.3 b. Spectra of Stress Response at Trailing Edge at I. 28 rpm



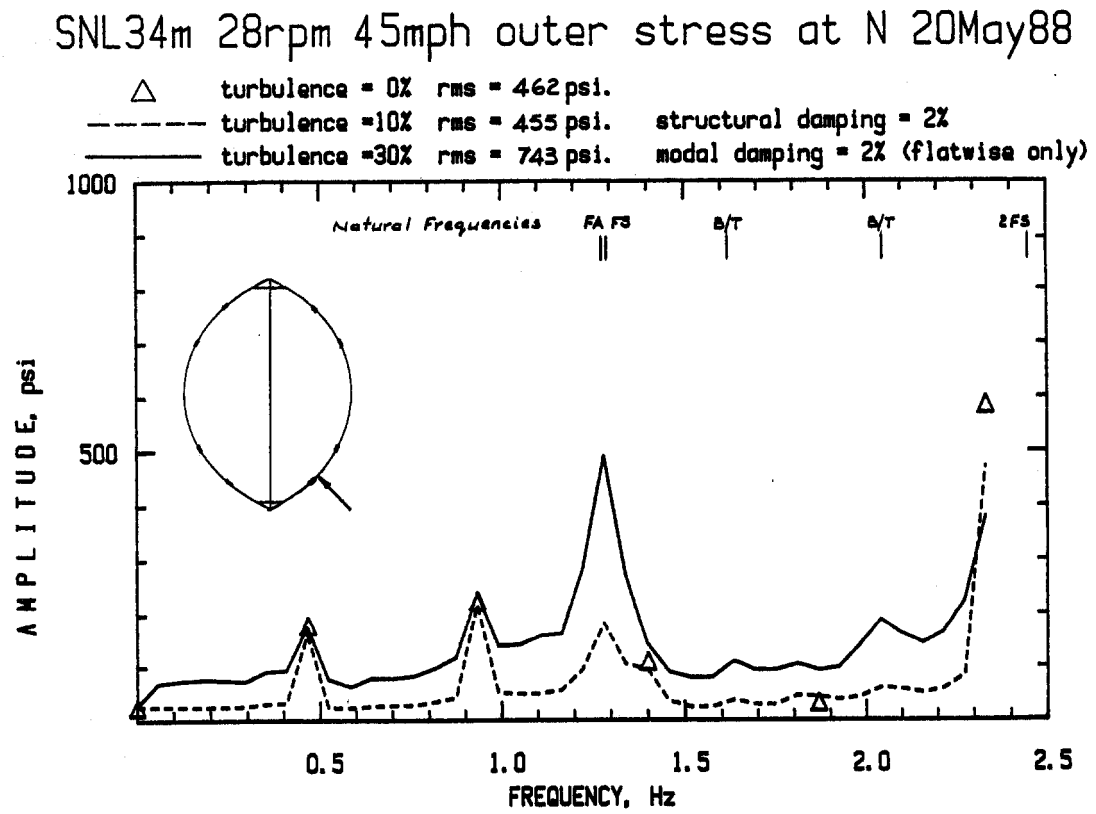
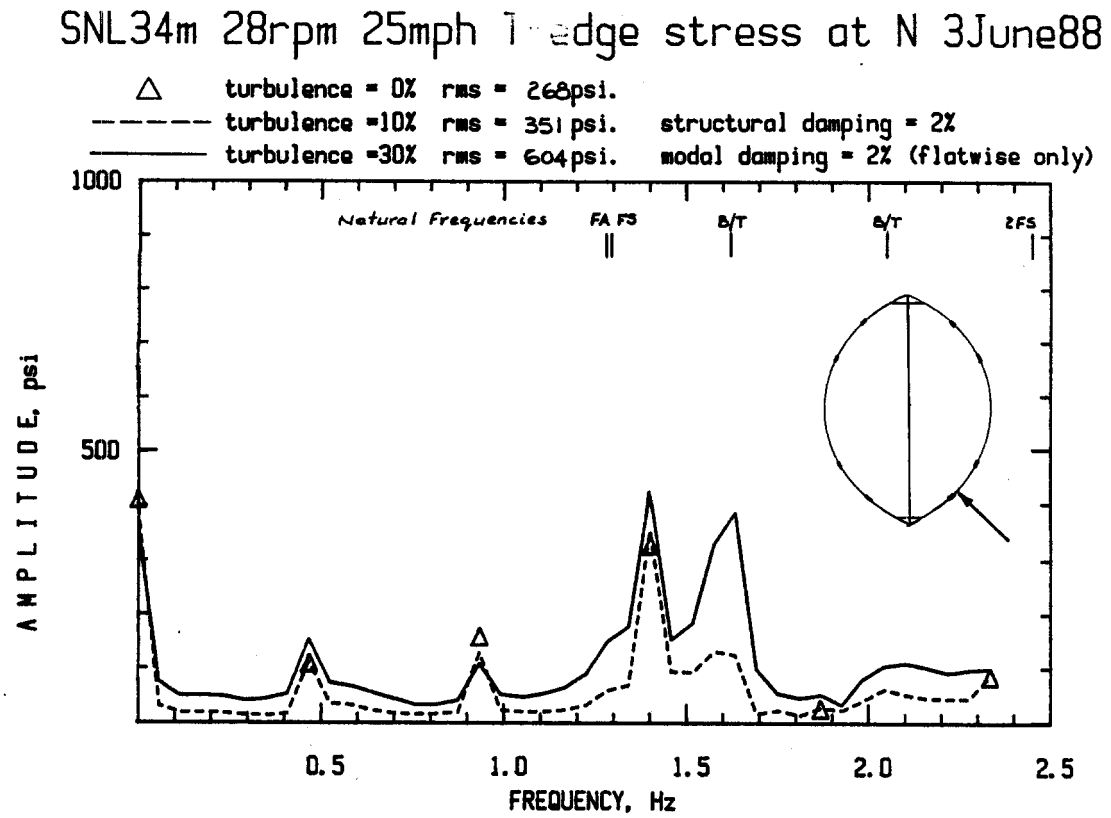


Figure 5.4 a. Spectra of Stress Response at Outer Face at N. 28 rpm



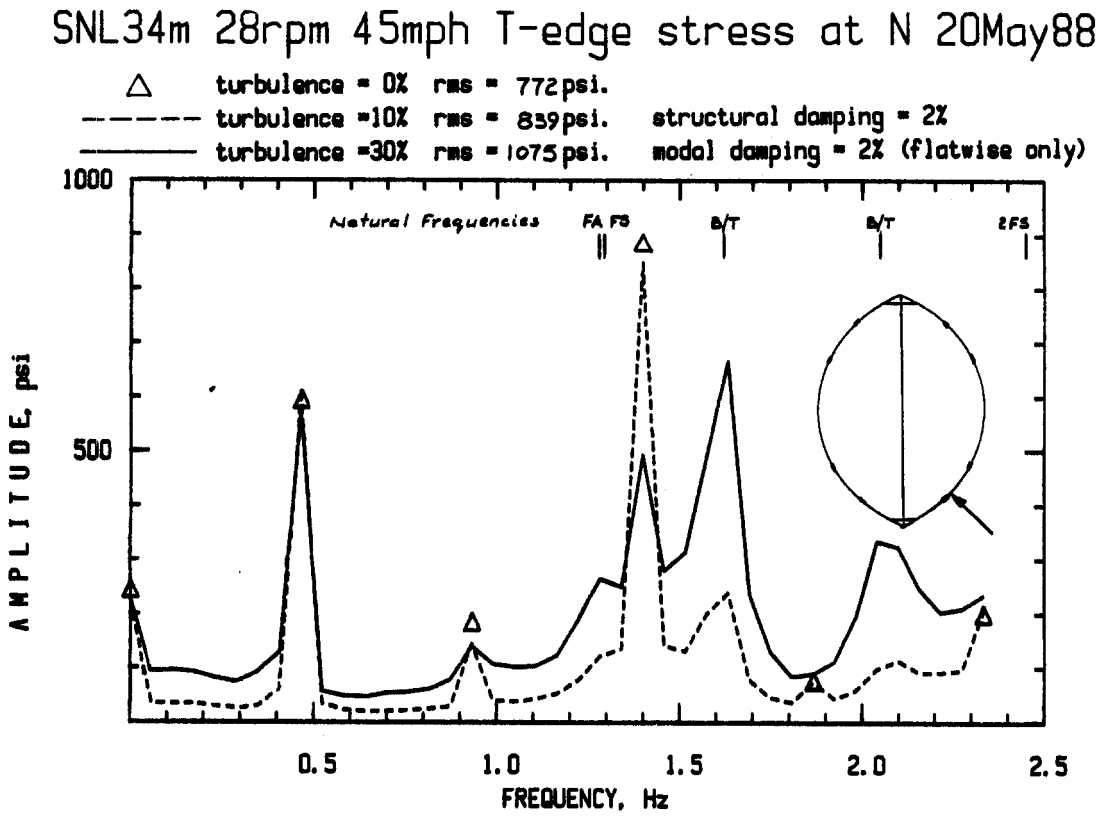
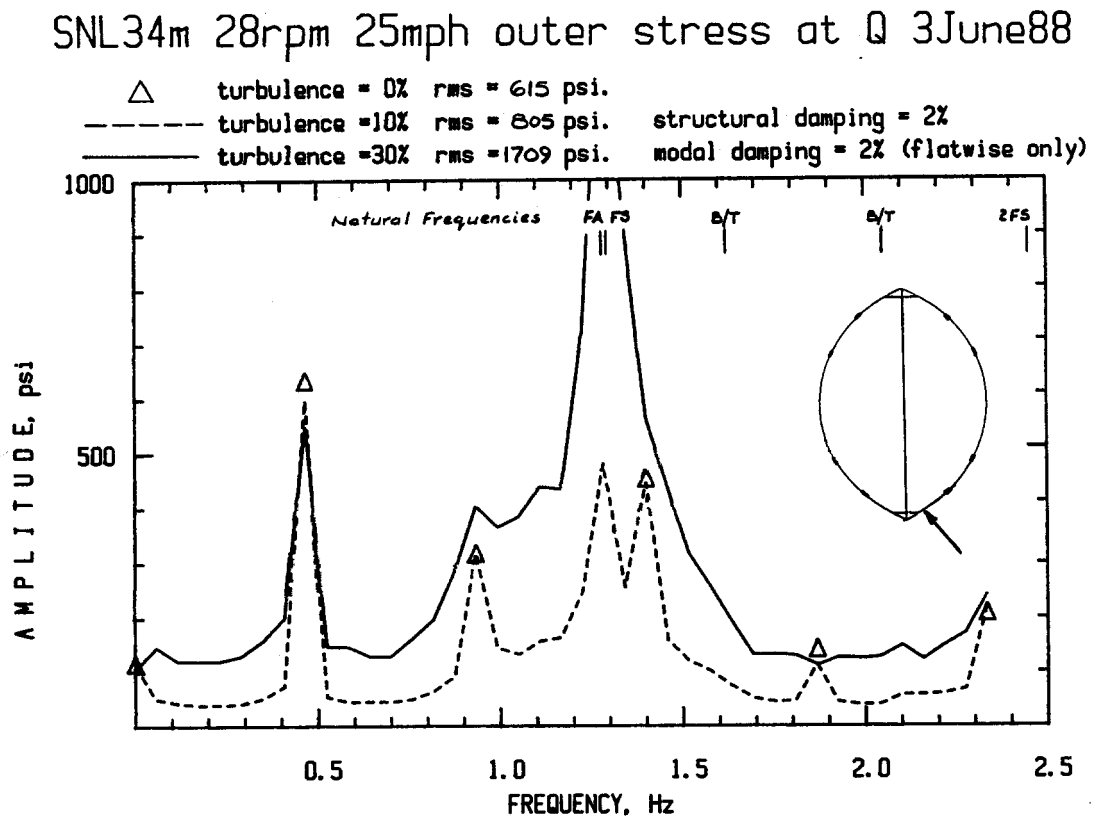


Figure 5.4 b. Spectra of Stress Response at Trailing Edge at N. 28 rpm



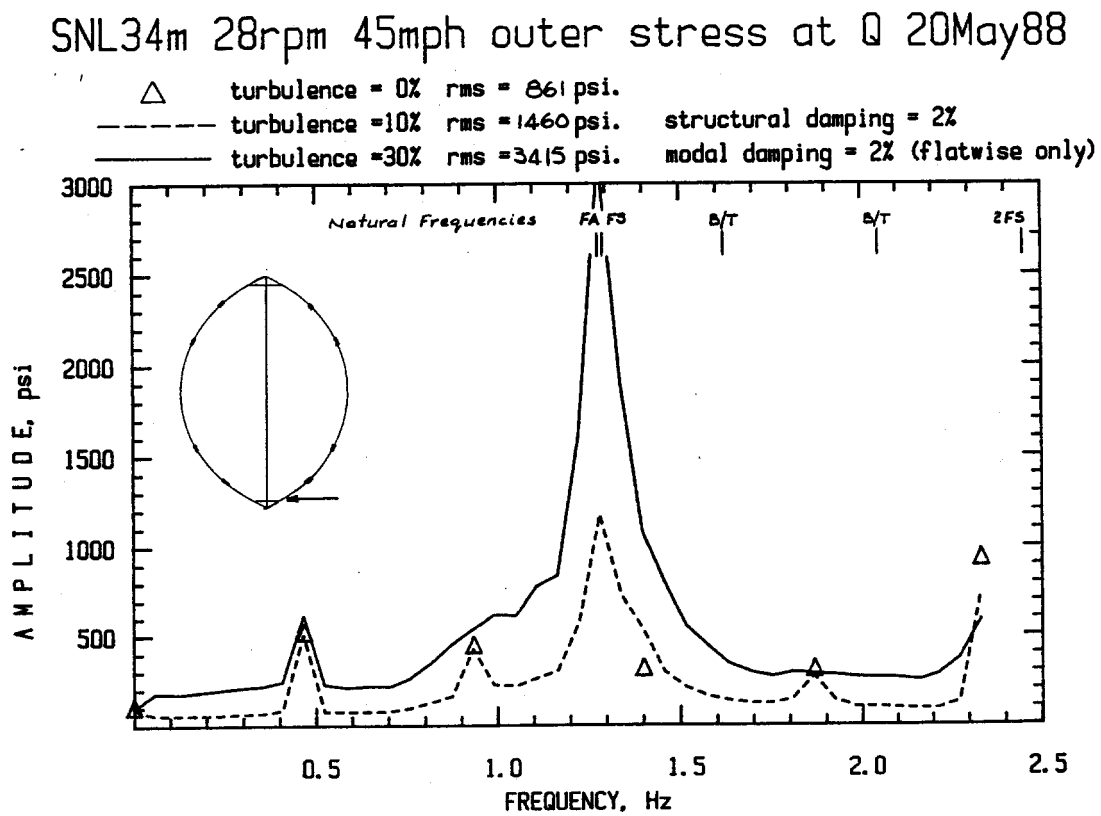
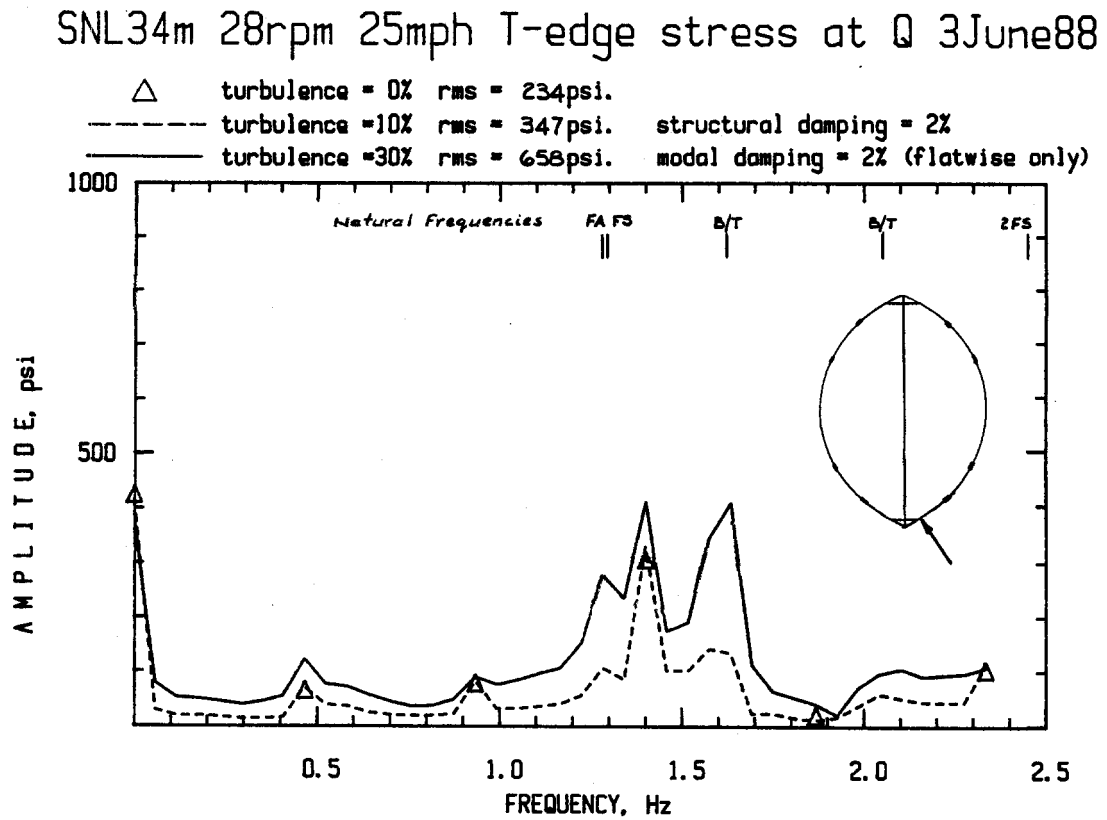


Figure 5.5 a. Spectra of Stress Response at Outer Face at Q. 28 rpm



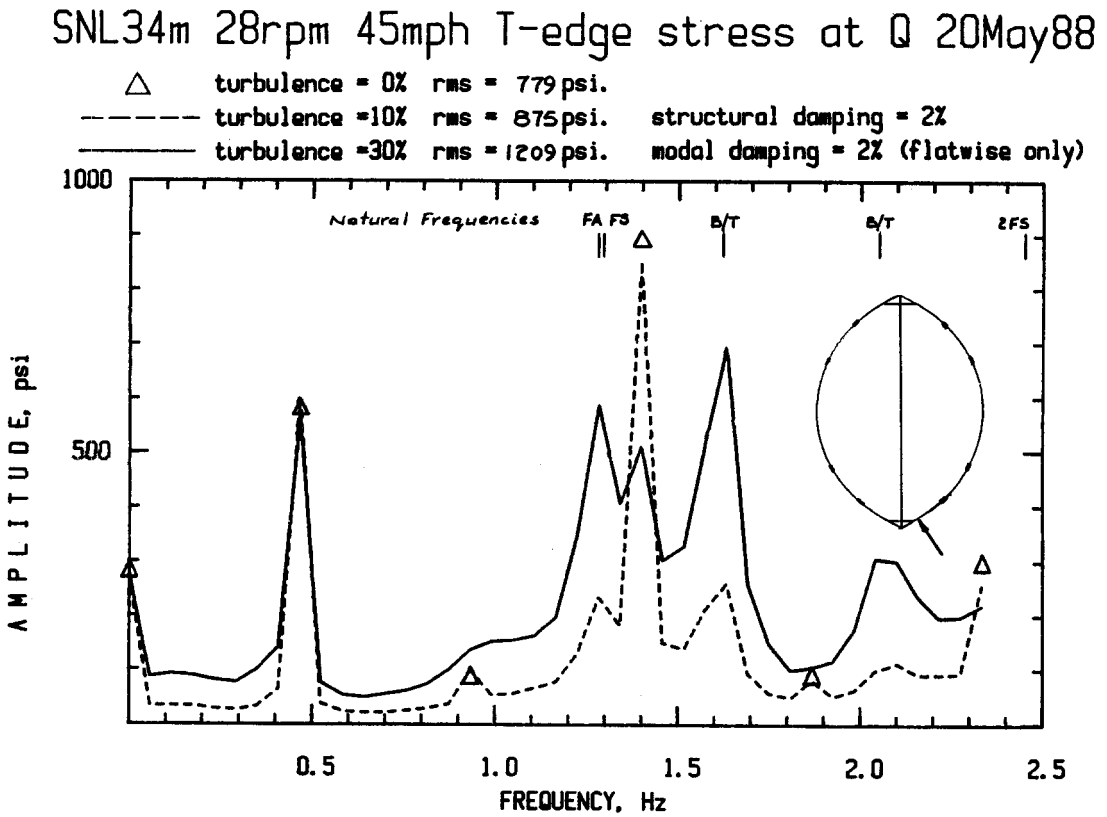


Figure 5.5 b. Spectra of Stress Response at Trailing Edge at Q. 28 rpm

5.0 ALTERNATIVE TURBULENCE SPECTRA

5.1 Different Spectra of Atmospheric Turbulence

The exact prediction of motion in a turbulent airstream has been described as being more ambitious than discovering the secret of the universe. It is, therefore, not surprising that there are several different published formulas to describe the power spectrum of this motion (11, 15, 16, 17, 18). The justification of the formulas is discussed in the listed references and the approach taken in this study was to try to establish whether the different formulas are likely to make substantial differences to the predicted response and stresses in the rotor blades.

The following three spectra were selected for comparison.

(1) Kaimal spectrum for stable atmospheres (11, 15, 16) having the form

$$S(f) = \frac{\sigma^2 \; 11.87 \; fz/u}{f\left[1 + 192\,(fz/u)^{5/3}\right]}$$

where S(f) is the power spectral density as a function of frequency, f(Hz), z is the height above the ground (m), u is the mean ambient velocity at that height (m/s), and σ^2 is the total variance of the spectrum. This form, from which the spectrum used by Frost, Long & Turner (18) is derived, allows the intensity of turbulence to be prescribed and maintained constant with height.

(2) The von Karman spectrum for neutral atmospheres (11, 16) with the form

$$S(f) = \frac{\sigma^2 \; 4{\cdot}0 \; fL/u}{f\left[1 + 70{\cdot}8\,(fL/u)^2\right]^{5/6}}$$

where L is an integral length scale with a value of 120 m. This form also allows the turbulence intensity to be kept constant with height.

(3) The von Karman spectrum for neutral atmospheres (11, 16)having the form

$$S(f) = \frac{3{\cdot}83 \; Lu}{\left[\ln(z/z_0)\right]^2 \left[1 + 70{\cdot}8\,(fL/u)^2\right]^{5/6}}$$

where z_0 is the roughness height. In this form the turbulence intensity is a function of the height, z and decreases with height. The turbulence intensity referred to corresponds to the intensity at mid-rotor height.

Figure 6 compares the three spectra quoted above using values that correspond to an intensity (σ/u) of 0.12) and also correspond to values used in Veers (11). It shows the Kaimal (stable) spectrum to give lower values at very low frequencies (less than 0.01 Hz) but higher values above that frequency. The two versions of the von Karman spectrum are essentially identical while a third version, quoted by Veers (11) agrees more closely with the Kaimal spectrum.

5.2 Comparison of Modal Loads

Figure 7 compares the spectra of modal load #3 obtained from different turbulence formulas. It shows

that the differences are small but the effect of a fully correlated flow is to decrease stochastic loading at low frequencies. The spectra of modal loads 1 thru 8 at windspeeds of 25 and 45 mph are presented in Figure 8. Tables 6 and 7 summarize the variances of the modal loads at low and high windspeeds at 10% and 30% turbulence for uncorrelated and fully correlated flow.

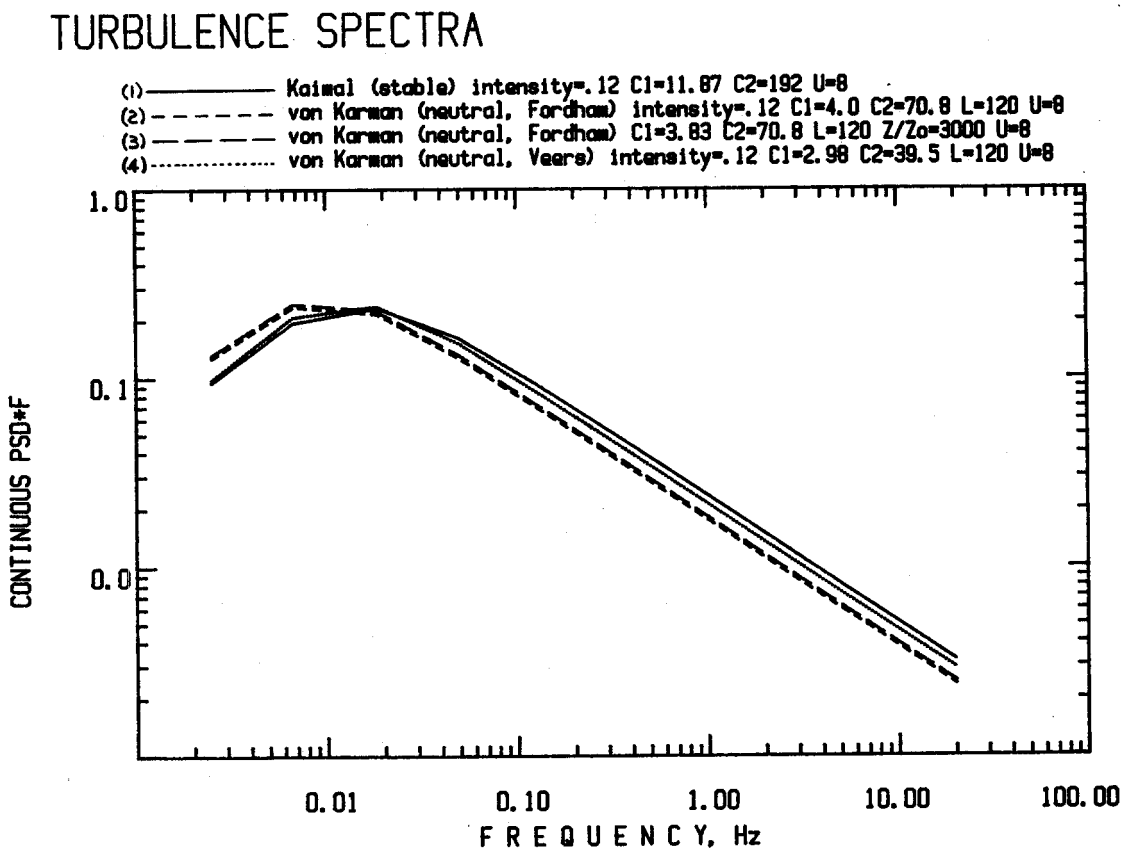


Figure 6. Comparison of Turbulence Spectra

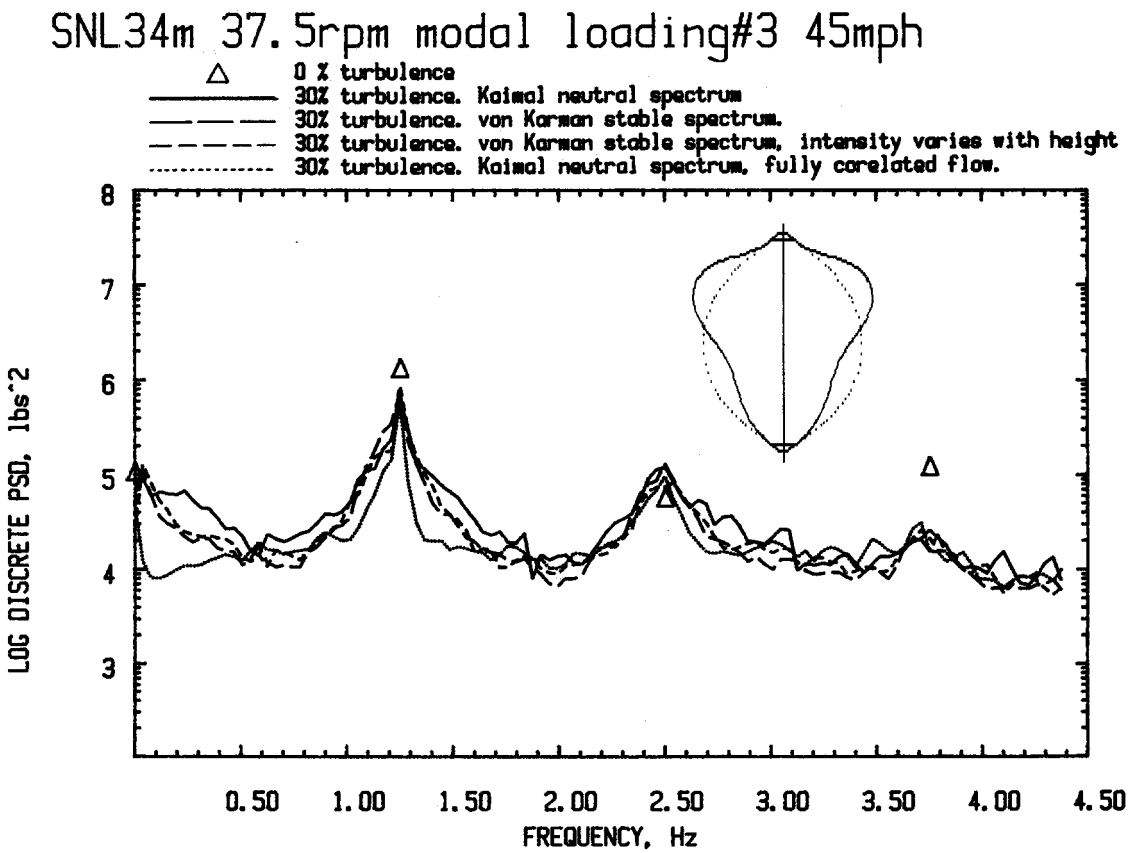
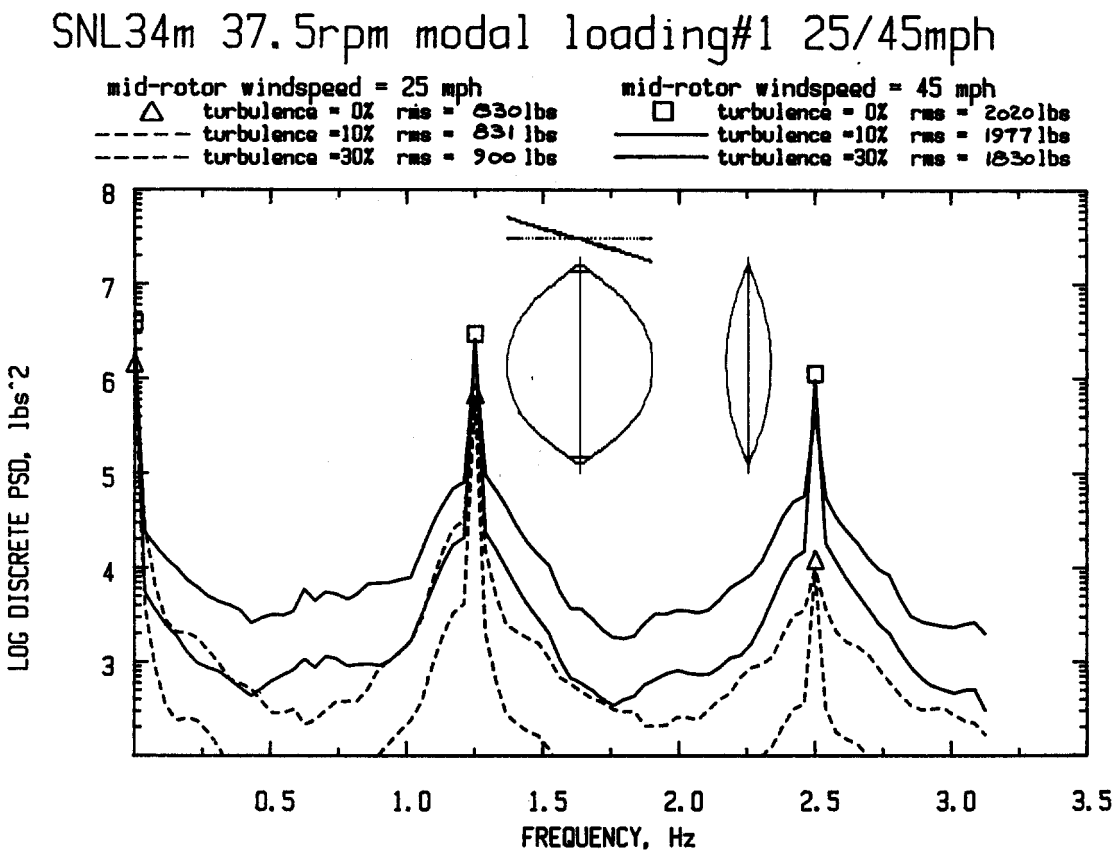


Figure 7. Comparison of Modal Load #3 from Alternative Spectra



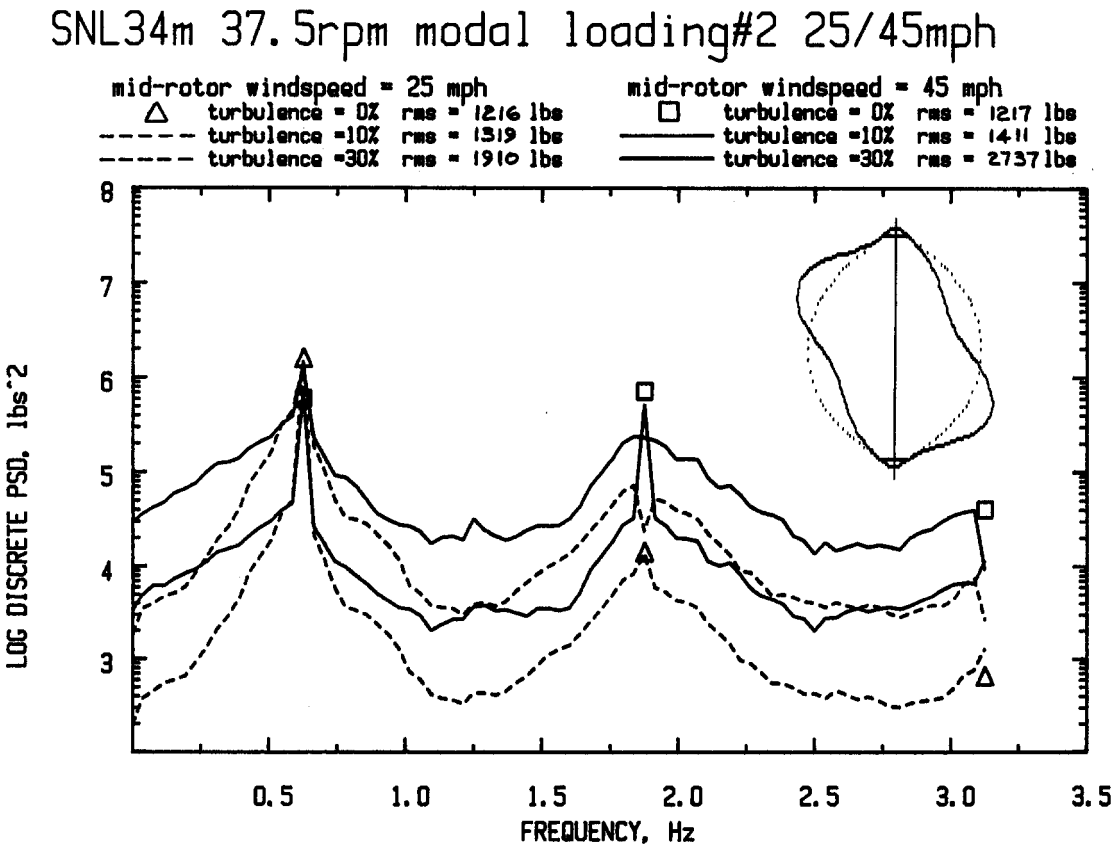
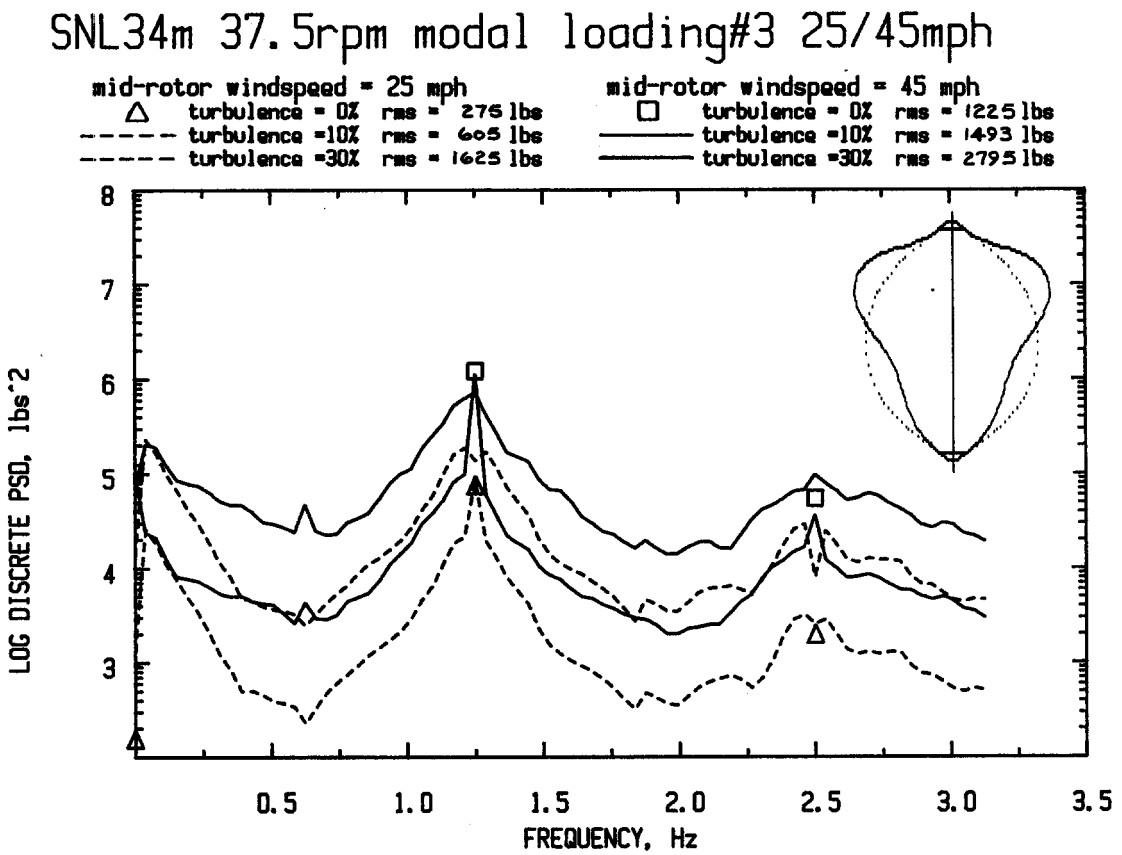


Figure 8.1. Spectra of Modal Loads # 1 & 2. 37.5rpm



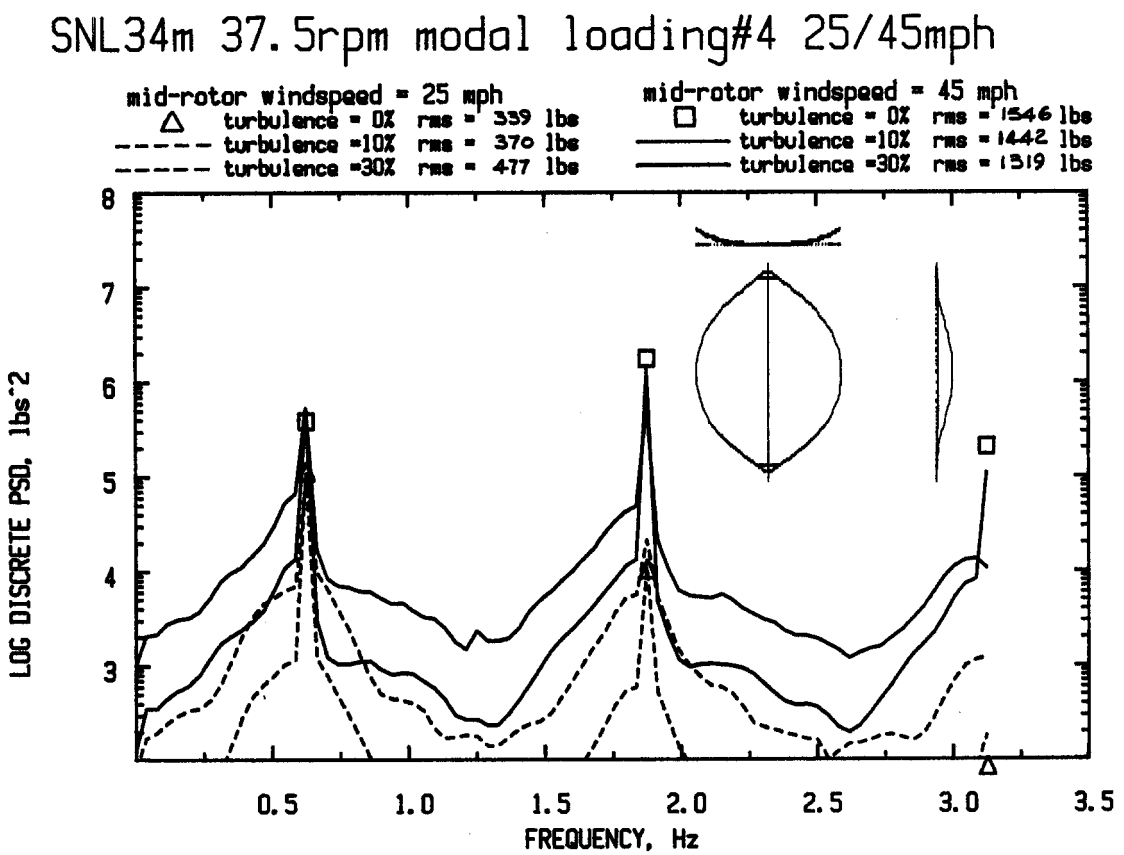
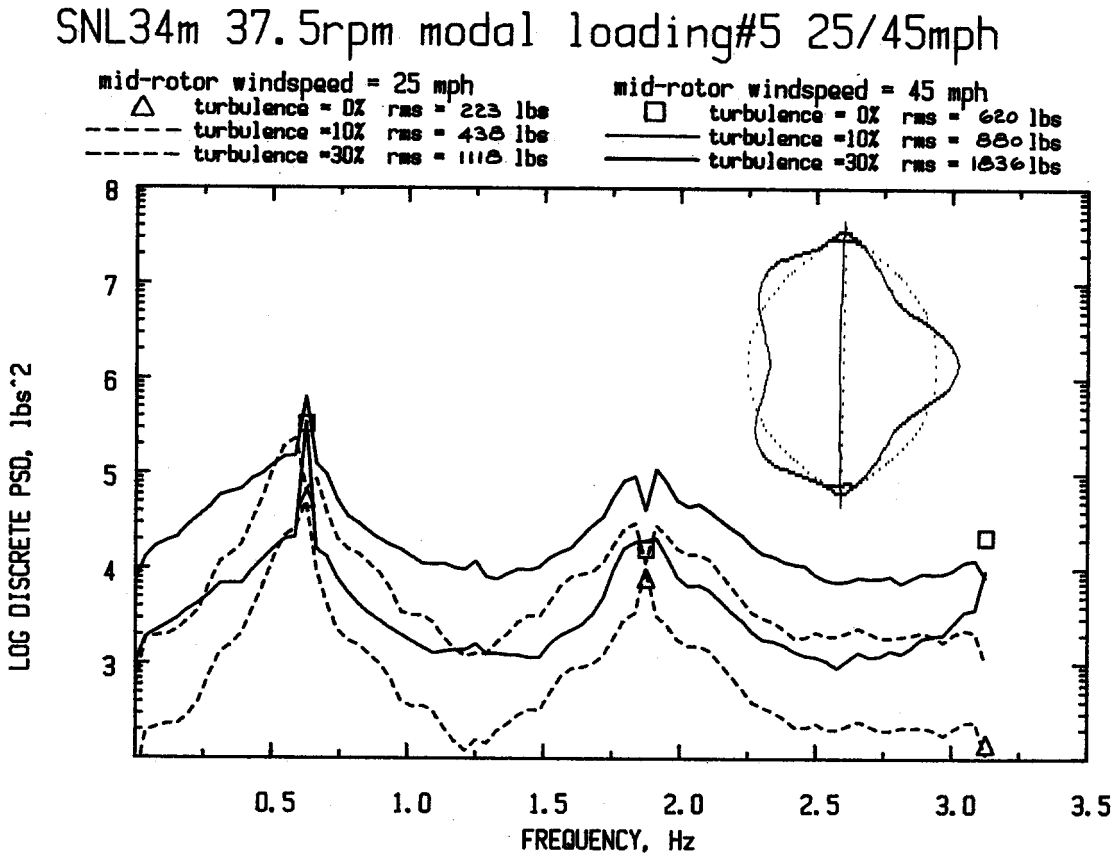


Figure 8.2. Spectra of Modal Loads # 3 & 4. 37.5rpm



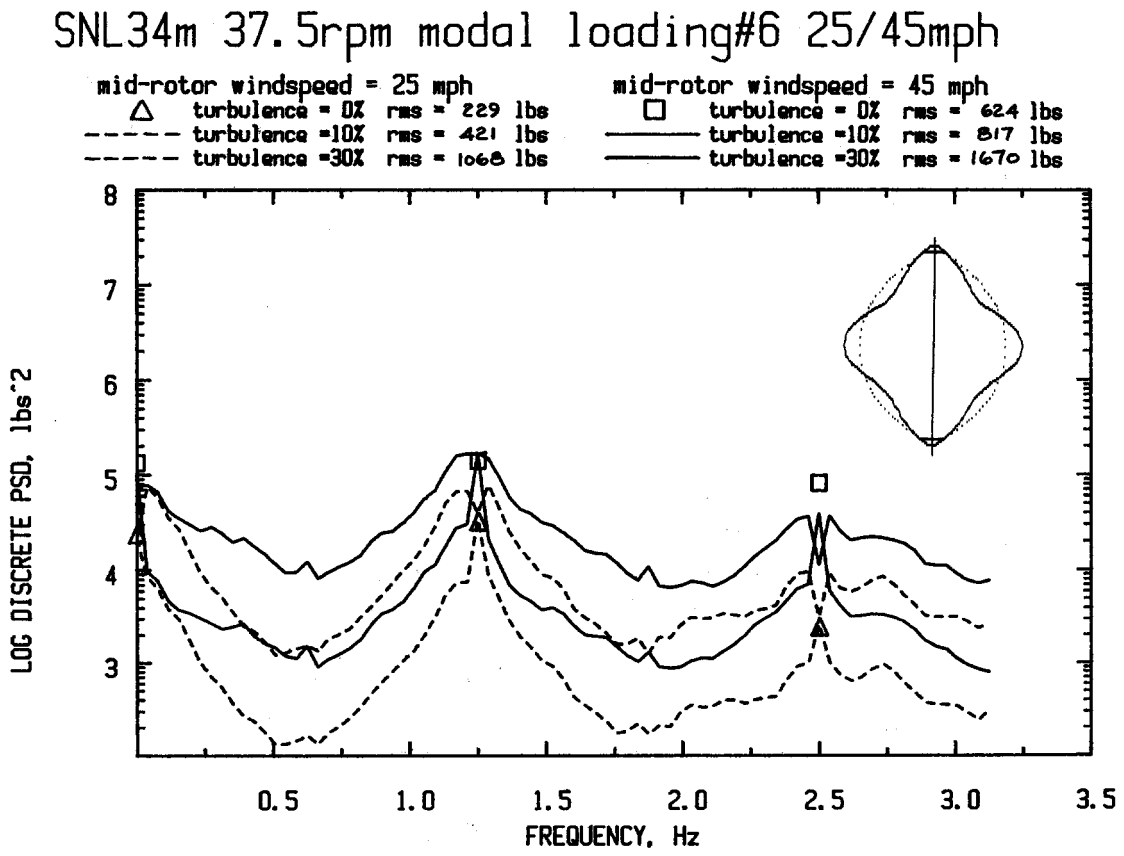
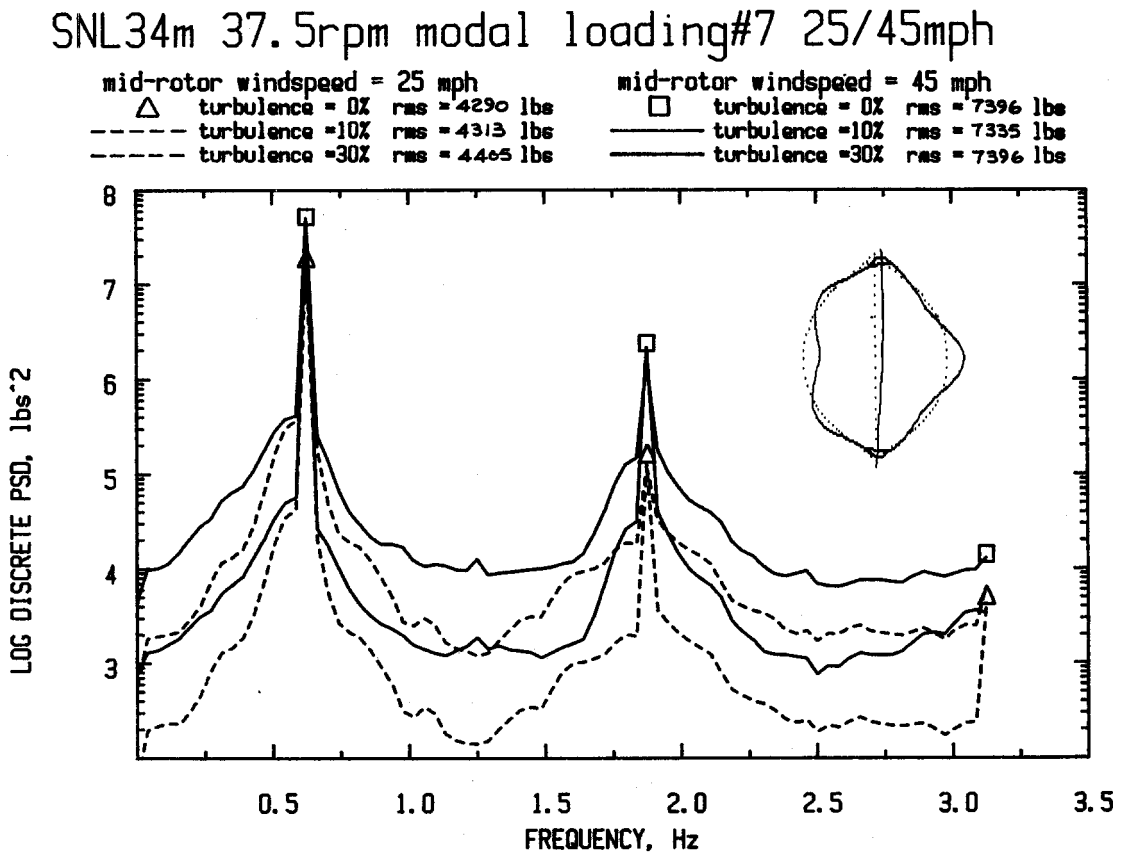


Figure 8.3. Spectra of Modal Loads # 5 & 6. 37.5rpm



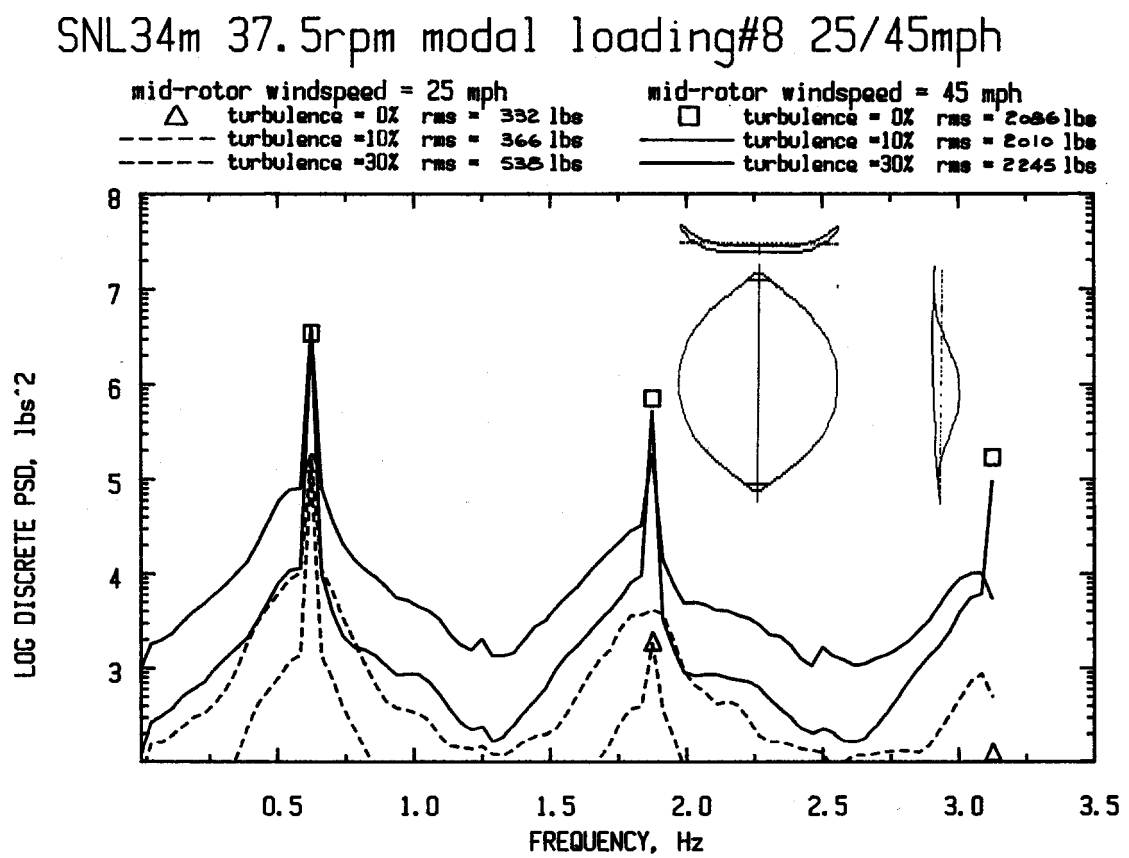


Figure 8.4. Spectra of Modal Loads # 7 & 8. 37.5rpm

Tables 4 and 5 summarize the total and stochastic component of the variance of the modal loads associated with each of the three spectra at windspeeds of 25 and 45 mph and for turbulence intensities of 10% and 30%. The differences due to the different spectra are not great and are not as significant as the differences due to the coherence of the flow which is demonstrated in Table 6. Examination of the modal load summaries on Tables 4, 5 6 and 7 reveal several trends.

1. At low windspeeds (25 mph) most of the energy is in the form of in-plane modes; at high windspeeds (45 mph) the proportion of energy in out-of-plane modes (such as modes 15, 8 and 4) increases. This is probably related to the greater out-of-plane loading and response noted at the 3P frequency.

2. At low windspeed the stochastic loading is dominated by mode no. 3 (1FS), but at high windspeeds much stochastic energy is also represented by mode no. 2 (1FA). In general the modes involving mainly flatwise blade bending receive a greater proportion of their variance from stochastic effects.

3. At low windspeeds an increase of turbulence intensity from 10% to 30% is accompanied by approximately a 10 fold increase in stochastic variance, while at high windspeed the corresponding increase is approximately 6 times.

4. The differences due to the different turbulence spectra are not significant.

5. The main effect of imposing full coherence of the turbulent flow is to reduce the variance due to stochastic effects of those modes that are most strongly affected by turbulence (such as modes #2 and 3).

It should be noted that Tables 4, 5, 6 and 7 and Figures 7 and 8 cover a range of frequencies from 0P to 7P (4.375 Hz) and that the spectra are one-sided discrete power spectral densities with a resolution of 16 divisions between harmonics (0.0391 Hz).

TABLE 4. Variance of Modal Loads of SNL34m, 37.5rpm, 25mph, Uncorrelated Flow

	0% TURBULENCE		10% TURBULENCE TYPE 1				10% TURBULENCE TYPE 2				10% TURBULENCE TYPE 3			
SHAPE	MODE	TOTAL-VAR	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.184E+08	7	.183E+08	.250E+05	.1	7	.185E+08	.214E+05	.1	7	.185E+08	.191E+05	.1
1P	1	.204E+07	1	.207E+07	.241E+05	1.2	1	.202E+07	.306E+05	1.5	1	.211E+07	.244E+05	1.2
1FA	2	.151E+07	2	.174E+07	.505E+05	2.9	2	.176E+07	.313E+05	1.8	2	.169E+07	.387E+05	2.3
4FA	17	.543E+06	17	.548E+06	.674E+04	1.2	17	.558E+06	.506E+04	.9	17	.554E+06	.514E+04	.9
3FA	9	.357E+06	9	.424E+06	.310E+05	7.3	9	.401E+06	.200E+05	5.0	9	.402E+06	.220E+05	5.5
2TO	15	.203E+06	3	.266E+06	.103E+06	38.9	3	.226E+06	.735E+05	32.5	3	.222E+06	.746E+05	33.6
2TI	14	.153E+06	15	.212E+06	.155E+04	.7	15	.217E+06	.130E+04	.6	15	.213E+06	.132E+04	.6
1B	4	.125E+06	14	.184E+06	.678E+04	3.7	14	.212E+06	.490E+04	2.3	14	.182E+06	.515E+04	2.8
3P	12	.115E+06	4	.135E+06	.499E+04	3.7	4	.129E+06	.298E+04	2.3	4	.138E+06	.334E+04	2.4
1TO	8	.102E+06	12	.119E+06	.230E+04	1.9	12	.118E+06	.268E+04	2.3	12	.123E+06	.230E+04	1.9
1FS	3	.813E+05	8	.112E+06	.217E+04	1.9	6	.110E+06	.260E+05	23.5	8	.113E+06	.170E+04	1.5
2FS	6	.543E+05	6	.103E+06	.231E+05	22.3	8	.970E+05	.174E+04	1.8	6	.997E+05	.245E+05	24.5
4FS	16	.518E+05	11	.102E+06	.394E+05	38.5	11	.894E+05	.309E+05	34.6	11	.854E+05	.301E+05	35.2
3FS	11	.382E+05	5	.861E+05	.179E+05	20.8	5	.807E+05	.131E+05	16.2	5	.794E+05	.123E+05	15.5
2FA	5	.333E+05	16	.690E+05	.103E+05	15.0	16	.657E+05	.860E+04	13.1	16	.646E+05	.804E+04	12.4
2P	10	.171E+05	18	.388E+05	.138E+05	35.5	18	.371E+05	.909E+04	24.5	18	.313E+05	.101E+05	32.2
2B	13	.136E+05	19	.312E+05	.147E+05	47.0	19	.283E+05	.946E+04	33.5	19	.224E+05	.101E+05	44.9
5FA	18	.113E+05	10	.223E+05	.282E+04	12.7	10	.202E+05	.269E+04	13.3	10	.205E+05	.233E+04	11.4
3B	20	.587E+04	13	.189E+05	.153E+04	8.1	13	.186E+05	.108E+04	5.8	13	.178E+05	.106E+04	5.9
5FS	19	.487E+04	20	.783E+04	.602E+03	7.7	20	.795E+04	.499E+03	6.3	20	.797E+04	.610E+03	7.7

	0% TURBULENCE		30% TURBULENCE TYPE 1				30% TURBULENCE TYPE 2				30% TURBULENCE TYPE 3			
SHAPE	MODE	TOTAL-VAR	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.184E+08	7	.186E+08	.235E+06	1.3	7	.195E+08	.176E+06	.9	7	.191E+08	.209E+06	1.1
1P	1	.204E+07	2	.347E+07	.464E+06	13.4	2	.340E+07	.381E+06	11.2	2	.361E+07	.340E+06	9.4
1FA	2	.151E+07	1	.240E+07	.212E+06	8.8	1	.246E+07	.235E+06	9.6	1	.253E+07	.240E+06	9.5
4FA	17	.543E+06	3	.171E+07	.953E+06	55.8	3	.141E+07	.754E+06	53.4	3	.142E+07	.777E+06	54.6
3FA	9	.357E+06	9	.963E+06	.280E+06	29.1	9	.841E+06	.212E+06	25.2	9	.942E+06	.226E+06	24.1
2TO	15	.203E+06	17	.648E+06	.599E+05	9.2	17	.634E+06	.515E+05	8.1	17	.646E+06	.592E+05	9.2
2TI	14	.153E+06	11	.649E+06	.352E+06	54.3	11	.533E+06	.276E+06	51.7	11	.552E+06	.301E+06	54.5
1B	4	.125E+06	5	.493E+06	.160E+06	32.4	5	.422E+06	.128E+06	30.3	15	.414E+06	.158E+05	3.8
3P	12	.115E+06	6	.467E+06	.200E+06	42.8	6	.432E+06	.211E+06	48.8	6	.434E+06	.205E+06	47.4
1TO	8	.102E+06	14	.397E+06	.616E+05	15.5	15	.404E+06	.141E+05	3.5	5	.386E+06	.111E+06	28.7
1FS	3	.813E+05	15	.336E+06	.128E+05	3.8	14	.326E+06	.563E+05	17.3	14	.351E+06	.558E+05	15.9
2FS	6	.543E+05	18	.256E+06	.123E+06	48.0	8	.237E+06	.207E+05	8.7	8	.250E+06	.265E+05	10.6
4FS	16	.518E+05	4	.236E+06	.544E+05	23.0	4	.210E+06	.419E+05	20.0	4	.230E+06	.518E+05	22.5
3FS	11	.382E+05	19	.237E+06	.131E+06	55.3	18	.207E+06	.979E+05	47.2	18	.213E+06	.956E+05	44.9
2FA	5	.333E+05	8	.222E+06	.250E+05	11.3	19	.192E+06	.102E+06	52.9	16	.192E+06	.783E+05	40.8
2P	10	.171E+05	16	.216E+06	.911E+05	42.3	16	.185E+06	.769E+05	41.5	19	.184E+06	.101E+06	54.9
2B	13	.136E+05	12	.159E+06	.203E+05	12.8	12	.170E+06	.249E+05	14.6	12	.162E+06	.209E+05	12.9
5FA	18	.113E+05	13	.589E+05	.138E+05	23.5	13	.536E+05	.121E+05	22.6	10	.544E+05	.224E+05	41.2
3B	20	.587E+04	10	.588E+05	.243E+05	41.3	10	.538E+05	.243E+05	45.2	13	.506E+05	.121E+05	23.9
5FS	19	.487E+04	20	.217E+05	.491E+04	22.7	20	.229E+05	.516E+04	22.6	20	.252E+05	.603E+04	23.9

Type 1: Kaimal spectrum (stable atmosphere), constant intensity
Type 2: von Karman spectrum (neutral atmosphere), constant intensity
Type 3: von Karman spectrum (neutral atmosphere), intensity varies with height

Note: specified intensity refers to coefficient of variation of longitudinal flow at mid-rotor height

TABLE 5. Variance of Modal Loads of SNL34m, 37.5rpm, 45mph, Uncorrelated Flow

	0% TURBULENCE		10% TURBULENCE TYPE 1				10% TURBULENCE TYPE 2				10% TURBULENCE TYPE 3			
SHAPE	MODE	TOTAL-VAR	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.523E+08	7	.519E+08	.227E+06	.4	7	.527E+08	.268E+06	.5	7	.524E+08	.218E+06	.4
1P	1	.768E+07	1	.751E+07	.291E+06	3.9	1	.774E+07	.289E+06	3.7	1	.761E+07	.333E+06	4.4
2TO	15	.504E+07	15	.517E+07	.382E+05	.7	15	.541E+07	.542E+05	1.0	15	.526E+07	.419E+05	.8
1TO	8	.387E+07	8	.380E+07	.670E+05	1.8	8	.392E+07	.102E+06	2.6	8	.381E+07	.739E+05	1.9
1B	4	.241E+07	4	.220E+07	.123E+06	5.6	4	.241E+07	.192E+06	8.0	4	.218E+07	.137E+06	6.3
2TI	14	.160E+07	3	.202E+07	.476E+06	23.6	3	.225E+07	.490E+06	21.7	3	.195E+07	.479E+06	24.5
1FA	2	.151E+07	14	.186E+07	.354E+05	1.9	14	.203E+07	.392E+05	1.9	14	.191E+07	.304E+05	1.6
1FS	3	.151E+07	2	.181E+07	.303E+06	16.7	2	.193E+07	.301E+06	15.6	2	.181E+07	.259E+06	14.3
3FA	9	.106E+07	9	.131E+07	.115E+06	8.7	9	.131E+07	.108E+06	8.2	9	.125E+07	.101E+06	8.1
4FA	17	.900E+06	17	.946E+06	.268E+05	2.8	17	.961E+06	.257E+05	2.7	17	.937E+06	.219E+05	2.3
3P	12	.596E+06	16	.586E+06	.403E+05	6.9	12	.608E+06	.499E+05	8.2	12	.589E+06	.540E+05	9.2
4FS	16	.542E+06	12	.582E+06	.498E+05	8.6	16	.592E+06	.294E+05	5.0	16	.585E+06	.400E+05	6.8
2B	13	.389E+06	11	.493E+06	.140E+06	28.3	6	.478E+06	.947E+05	19.8	6	.441E+06	.815E+05	18.5
2FS	6	.389E+06	6	.470E+06	.923E+05	19.7	11	.466E+06	.109E+06	23.4	11	.436E+06	.123E+06	28.2
3FS	11	.274E+06	5	.435E+06	.791E+05	18.2	13	.433E+06	.283E+05	6.5	13	.430E+06	.303E+05	7.1
2FA	5	.259E+06	13	.426E+06	.282E+05	6.6	5	.426E+06	.692E+05	16.2	5	.407E+06	.667E+05	16.4
3B	20	.225E+06	20	.256E+06	.879E+04	3.4	20	.253E+06	.832E+04	3.3	20	.250E+06	.853E+04	3.4
5FA	18	.789E+05	18	.154E+06	.442E+05	28.7	18	.133E+06	.340E+05	25.6	18	.135E+06	.347E+05	25.6
2P	10	.526E+05	19	.114E+06	.471E+05	41.4	19	.977E+05	.338E+05	34.6	19	.999E+05	.369E+05	36.9
5FS	19	.434E+05	10	.754E+05	.235E+05	31.2	10	.714E+05	.214E+05	30.0	10	.747E+05	.255E+05	34.1

	0% TURBULENCE		30% TURBULENCE TYPE 1				30% TURBULENCE TYPE 2				30% TURBULENCE TYPE 3			
SHAPE	MODE	TOTAL-VAR	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.523E+08	7	.517E+08	.115E+07	2.2	7	.534E+08	.113E+07	2.1	7	.542E+08	.115E+07	2.1
1P	1	.768E+07	15	.748E+07	.136E+06	1.8	15	.784E+07	.139E+06	1.8	15	.995E+07	.136E+06	1.4
2TO	15	.504E+07	1	.660E+07	.120E+07	18.2	1	.707E+07	.130E+07	18.5	1	.680E+07	.157E+07	23.0
1TO	8	.387E+07	2	.590E+07	.198E+07	33.5	2	.512E+07	.152E+07	29.6	14	.641E+07	.194E+06	3.0
1B	4	.241E+07	3	.540E+07	.280E+07	51.9	8	.482E+07	.230E+06	4.8	2	.631E+07	.150E+07	23.8
2TI	14	.160E+07	8	.485E+07	.214E+06	4.4	3	.470E+07	.250E+07	53.2	8	.549E+07	.258E+06	4.7
1FA	2	.151E+07	14	.444E+07	.220E+06	5.0	14	.441E+07	.174E+06	3.9	3	.477E+07	.236E+07	49.5
1FS	3	.151E+07	9	.261E+07	.760E+06	29.1	9	.229E+07	.604E+06	26.3	9	.230E+07	.640E+06	27.8
3FA	9	.106E+07	4	.199E+07	.412E+06	20.7	4	.208E+07	.456E+06	22.0	4	.208E+07	.527E+06	25.4
4FA	17	.900E+06	11	.195E+07	.937E+06	48.0	11	.153E+07	.783E+06	51.2	11	.173E+07	.865E+06	49.9
3P	12	.596E+06	5	.156E+07	.449E+06	28.8	5	.144E+07	.387E+06	27.0	5	.158E+07	.395E+06	25.0
4FS	16	.542E+06	17	.131E+07	.189E+06	14.4	17	.126E+07	.149E+06	11.8	17	.137E+07	.174E+06	12.8
2B	13	.389E+06	6	.120E+07	.533E+06	44.5	6	.106E+07	.482E+06	45.4	6	.111E+07	.526E+06	47.3
2FS	6	.389E+06	16	.904E+06	.280E+06	31.0	16	.854E+06	.233E+06	27.3	16	.947E+06	.324E+06	34.3
3FS	11	.274E+06	18	.701E+06	.311E+06	44.4	13	.678E+06	.109E+06	16.1	13	.781E+06	.971E+05	12.4
2FA	5	.259E+06	13	.672E+06	.104E+06	15.5	12	.571E+06	.185E+06	32.4	18	.600E+06	.276E+06	46.0
3B	20	.225E+06	19	.625E+06	.348E+06	55.7	18	.535E+06	.238E+06	44.4	12	.540E+06	.190E+06	35.2
5FA	18	.789E+05	12	.533E+06	.168E+06	31.5	19	.460E+06	.233E+06	50.8	19	.538E+06	.289E+06	53.6
2P	10	.526E+05	20	.379E+06	.410E+05	10.8	20	.371E+06	.393E+05	10.6	20	.415E+06	.418E+05	10.1
5FS	19	.434E+05	10	.212E+06	.121E+06	57.0	10	.185E+06	.111E+06	60.2	10	.194E+06	.116E+06	59.7

Type 1: Kaimal spectrum (stable atmosphere), constant intensity
Type 2: von Karman spectrum (neutral atmosphere), constant intensity
Type 3: von Karman spectrum (neutral atmosphere), intensity varies with height

Note: specified intensity refers to coefficient of variation of longitudinal flow at mid-rotor height

Table 6. Variance of Modal Loads. V=25mph. Correlated vs. Uncorrelated

	UNCORRELATED. 10% TURBULENCE				CORRELATED. 10% TURBULENCE			
SHAPE	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
ITI	7	.183E+08	.250E+05	.1	7	.184E+08	.235E+05	.1
1P	1	.207E+07	.241E+05	1.2	1	.206E+07	.308E+05	1.5
1FA	2	.174E+07	.505E+05	2.9	2	.154E+07	.293E+05	1.9
4FA	17	.548E+06	.674E+04	1.2	17	.537E+06	.288E+04	.5
3FA	9	.424E+06	.310E+05	7.3	9	.377E+06	.133E+05	3.5
1FS	3	.266E+06	.103E+06	38.9	15	.225E+06	.963E+03	.4
2TO	15	.212E+06	.155E+04	.7	14	.163E+06	.293E+04	1.8
2TI	14	.184E+06	.678E+04	3.7	3	.145E+06	.372E+05	25.6
1B	4	.135E+06	.499E+04	3.7	4	.135E+06	.351E+04	2.6
3P	12	.119E+06	.230E+04	1.9	8	.119E+06	.145E+04	1.2
1TO	8	.112E+06	.217E+04	1.9	12	.119E+06	.210E+04	1.8
2FS	6	.103E+06	.231E+05	22.3	6	.811E+05	.143E+05	17.6
3FS	11	.102E+06	.394E+05	38.5	11	.578E+05	.155E+05	26.7
2FA	5	.861E+05	.179E+05	20.8	16	.567E+05	.474E+04	8.4
4FS	16	.690E+05	.103E+05	15.0	5	.521E+05	.827E+04	15.9
5FA	18	.388E+05	.138E+05	35.5	18	.196E+05	.436E+04	22.3
5FS	19	.312E+05	.147E+05	47.0	10	.179E+05	.118E+04	6.6
2P	10	.223E+05	.282E+04	12.7	13	.172E+05	.683E+03	4.0
2B	13	.189E+05	.153E+04	8.1	19	.134E+05	.472E+04	35.1
3B	20	.783E+04	.602E+03	7.7	20	.793E+04	.571E+03	7.2

	UNCORRELATED. 30% TURBULENCE				CORRELATED. 30% TURBULENCE			
SHAPE	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.186E+08	.235E+06	1.3	7	.192E+08	.220E+06	1.1
1FA	2	.347E+07	.464E+06	13.4	1	.246E+07	.272E+06	11.1
1P	1	.240E+07	.212E+06	8.8	2	.210E+07	.273E+06	13.0
1FS	3	.171E+07	.953E+06	55.8	3	.668E+06	.347E+06	52.0
3FA	9	.963E+06	.280E+06	29.1	9	.584E+06	.118E+06	20.3
4FA	17	.648E+06	.599E+05	9.2	17	.571E+06	.246E+05	4.3
3FS	11	.649E+06	.352E+06	54.3	15	.395E+06	.997E+04	2.5
2FA	5	.493E+06	.160E+06	32.4	14	.285E+06	.286E+05	10.0
2FS	6	.467E+06	.200E+06	42.8	8	.269E+06	.217E+05	8.1
2TI	14	.397E+06	.616E+05	15.5	11	.264E+06	.135E+06	51.1
2TO	15	.336E+06	.128E+05	3.8	6	.269E+06	.122E+06	45.2
5FA	18	.256E+06	.123E+06	48.0	4	.237E+06	.493E+05	20.8
1B	4	.236E+06	.544E+05	23.0	5	.199E+06	.710E+05	35.7
5FS	19	.237E+06	.131E+06	55.3	12	.157E+06	.200E+05	12.7
1TO	8	.222E+06	.250E+05	11.3	16	.112E+06	.404E+05	36.0
4FS	16	.216E+06	.911E+05	42.3	18	.904E+05	.405E+05	44.8
3P	12	.159E+06	.203E+05	12.8	19	.801E+05	.421E+05	52.6
2B	13	.589E+05	.138E+05	23.5	13	.434E+05	.705E+04	16.2
2P	10	.588E+05	.243E+05	41.3	10	.310E+05	.110E+05	35.5
3B	20	.217E+05	.491E+04	22.7	20	.207E+05	.454E+04	21.9

Turbulence spectrum: Kaimal (neutral atmosphere), constant intensity

Table 7. Variance of Modal Loads. V=45mph. Correlated vs. Uncorrelated

	UNCORRELATED. 10% TURBULENCE				CORRELATED. 10% TURBULENCE			
SHAPE	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.519E+08	.227E+06	.4	7	.531E+08	.260E+06	.5
1P	1	.751E+07	.291E+06	3.9	1	.768E+07	.367E+06	4.8
2TO	15	.517E+07	.382E+05	.7	15	.570E+07	.322E+05	.6
1TO	8	.380E+07	.670E+05	1.8	8	.404E+07	.805E+05	2.0
1B	4	.220E+07	.123E+06	5.6	4	.219E+07	.157E+06	7.1
1FS	3	.202E+07	.476E+06	23.6	14	.215E+07	.222E+05	1.0
2TI	14	.186E+07	.354E+05	1.9	3	.176E+07	.332E+06	18.8
1FA	2	.181E+07	.303E+06	16.7	2	.155E+07	.172E+06	11.1
3FA	9	.131E+07	.115E+06	8.7	9	.115E+07	.567E+05	4.9
4FA	17	.946E+06	.268E+05	2.8	17	.888E+06	.121E+05	1.4
4FS	16	.586E+06	.403E+05	6.9	12	.597E+06	.571E+05	9.6
3P	12	.582E+06	.498E+05	8.6	16	.562E+06	.264E+05	4.7
3FS	11	.493E+06	.140E+06	28.3	13	.442E+06	.230E+05	5.2
2FS	6	.470E+06	.923E+05	19.7	6	.405E+06	.627E+05	15.5
2FA	5	.435E+06	.791E+05	18.2	5	.378E+06	.522E+05	13.8
2B	13	.426E+06	.282E+05	6.6	11	.340E+06	.681E+05	20.1
3B	20	.256E+06	.879E+04	3.4	20	.260E+06	.771E+04	3.0
5FA	18	.154E+06	.442E+05	28.7	18	.109E+06	.193E+05	17.6
5FS	19	.114E+06	.471E+05	41.4	19	.676E+05	.189E+05	28.0
2P	10	.754E+05	.235E+05	31.2	10	.567E+05	.111E+05	19.6

	UNCORRELATED. 30% TURBULENCE				CORRELATED. 30% TURBULENCE			
SHAPE	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN	MODE	TOTAL-VAR	TOT-RAN-VAR	%RAN
1TI	7	.517E+08	.115E+07	2.2	7	.552E+08	.133E+07	2.4
2TO	15	.748E+07	.136E+06	1.8	15	.946E+07	.103E+06	1.1
1P	1	.660E+07	.120E+07	18.2	1	.724E+07	.166E+07	22.9
1FA	2	.590E+07	.198E+07	33.5	8	.574E+07	.275E+06	4.8
1FS	3	.540E+07	.280E+07	51.9	14	.560E+07	.116E+06	2.1
1TO	8	.485E+07	.214E+06	4.4	2	.362E+07	.108E+07	29.9
2TI	14	.444E+07	.220E+06	5.0	3	.303E+07	.153E+07	50.4
3FA	9	.261E+07	.760E+06	29.1	4	.214E+07	.585E+06	27.4
1B	4	.199E+07	.412E+06	20.7	9	.162E+07	.344E+06	21.2
3FS	11	.195E+07	.937E+06	48.0	5	.114E+07	.234E+06	20.6
2FA	5	.156E+07	.449E+06	28.8	17	.104E+07	.833E+05	8.0
4FA	17	.131E+07	.189E+06	14.4	11	.894E+06	.433E+06	48.4
2FS	6	.120E+07	.533E+06	44.5	13	.691E+06	.682E+05	9.9
4FS	16	.904E+06	.280E+06	31.0	16	.702E+06	.181E+06	25.8
5FA	18	.701E+06	.311E+06	44.4	6	.669E+06	.261E+06	39.0
2B	13	.672E+06	.104E+06	15.5	12	.570E+06	.199E+06	34.9
5FS	19	.625E+06	.348E+06	55.7	20	.393E+06	.350E+05	8.9
3P	12	.533E+06	.168E+06	31.5	18	.306E+06	.115E+06	37.5
3B	20	.379E+06	.410E+05	10.8	19	.236E+06	.122E+06	51.6
	10	.212E+06	.121E+06	57.0	10	.103E+06	.530E+05	51.3

Turbulence spectrum: Kaimal (neutral atmosphere), constant intensity

6. CONCLUSIONS

The simulation of turbulent winds has been made more sophisticated and the effect of changes in the description of turbulence have been studied. This has demonstrated that the choice of turbulence spectrum is less important than the degree of coherence of the turbulent flow. A fully correlated flow results in a considerable decrease in loading at low frequencies (less than 1.5 Hz).

The reformulation of the aeroelastic forces has shown

1. that the damping of the complex modes of vibration at operating speeds reported by Lobitz (3) has been confirmed;

2. the effects of including rotating frame effects and elastic centre offset within the aeroelastic formulation to be negligible;

3. there appears to be some considerable discrepancy between the results from (3) and the present report at a rotor speed of 90 rpm. Some of this discrepancy may lie in the labelling of the complex modes.

It was noted that the aeroelastic formulation was a linear one and is, strictly, inapplicable to cases where stall is occurring. In addition the variation in some coefficients due to an ambient windspeed have been neglected.

The amplitude spectra of stresses corresponding to operation at 37.5 rpm indicate several important trends.

1. Inclusion of turbulence (even 10%) can cause considerable increases in the rms stress if damping is low. These increases are most noticeable at locations on the inner and outer faces of the blades.

2. Addition of aeroelastic forces causes an attenuation of both stochastic and deterministic spectral peaks. This attenuation is most apparent at locations on the inner and outer surfaces where the stress is caused largely by in-plane blade bending.

3. Attenuation of trailing edge stresses by aeroelastic forces is less severe than that of outer face stresses.

4. Both the inclusion of turbulence and the incorporation of aeroelastic damping reduce the value of some 3P trailing edge stresses.

7. REFERENCES

1. D.J. Malcolm, "Dynamic Response of a Darrieus Rotor Wind Turbine Subject to Turbulent Flow", Engineering Structures, Vol. 10, April 1988, pp. 125-134.

2. D.J. Malcolm, "A Model for the Response of Vertical Axis Wind Turbines to Turbulent Flow, Parts 1 and 2", Sandia National Laboratories Report SAND88-7021, July 1988.

3. D.W. Lobitz and T.D. Ashwill, "Aeroelastic Effects in the Structural Dynamics Analysis of Vertical Axis Wind Turbines", Sandia National Laboratories, SAND85-0957, April 1986.

4. D. Popelka, "Aeroelastic Stability Analysis of a Darrieus Wind Turbine", Sandia National Laboratories, SAND82-0672, 1982.

5. N.D. Ham, "Aeroelastic Analysis of the Troposkein-Type Wind Turbine", Sandia National Laboratories, SAND77-0026, April 1977.

6. A.J. Vollan, "Aeroelastic Stability of a Vertical Axis Wind Energy Converter", Dornier System Report EMSB-44/77, Oct. 1977.

7. A.J. Vollan, "The Aeroelastic Behaviour of Large Darrieus- Type Wind Energy Converters Derived from the Behaviour of a 5.5 m Rotor", Proc. 2nd Int. Symposium on Wind Energy on Wind Energy Systems, BHRA, Amsterdam, 1978.

8. E.E. Meyer and C.E. Smith, "An Aeroelastic Analysis of the Darrieus Wind Turbine", AIAA 2nd Terrestrial Energy Systems Conference, Colorado Springs, Dec. 1981.

9. M.B. Anderson, S.J.R. Powles, and M.S. Courtney, "Dynamic Analysis of Vertical Axis Wind Turbines - A Comparison of Theories with Experimental Data", Proc. European Wind Energy Association Conference and Exhibition, Rome, 7-9 Oct. 1986.

10. "Response of the SNL 34-m VAWT to Turbulent Flow", Indal Technologies Inc. on behalf of Sandia National Laboratories, contract 32-3044, June 1988.

11. P.S. Veers, "Three-Dimensional Wind Simulation", Sandia National Laboratories Report SAND88-0152. UC-261, March 1988.

12. Y.C. Fung, "An Introduction to the Theory of Aeroelasticity", Dover Publications Inc., New York, 1969.

13. P.S. Veers, "Modelling Stochastic Wind Loads on Vertical Axis Wind Turbines", Sandia National Laboratories, SAND83-1909, Sept. 1984.

14. M. Shinozuka, "Simulation of Multivariate and Multi-dimensional Random Processes", J. Acoustial Society of America, Vol. 49, no. 1, 1971, pp. 357-367.

15. G.F. Homicz, "VAWT Stochastic Loads Produced by Atmospheric Turbulence", Proc. 7th ASME Wind Energy Symposium, Ed. A. Swift & R. Thresher, New Orleans, Jan. 1988, pp. 127-138.

16. E.J. Fordham, "The Spatial Structure of Turbulence in the Atmospheric Boundary Layer", Wind Engineering, Vol. 9, No. 2, 1985, pp. 95-133.

17. J.H. Strickland, "VAWT Stochastic Wind Simulator", Sandia National Laboratories Report SAND87-0501. UC-60, April 1987.

18. W. Frost, D. Long and R.E. Turner, "Engineering Handbook on the Atmospheric Environment Guideline for Use in Wind Turbine Generator Development", NASA Tech. paper 1359, Dec. 1979.

APPENDIX A

FORTRAN PROGRAM TRES4

A.1 Flowchart

A.2 Listing

A.3 Input File

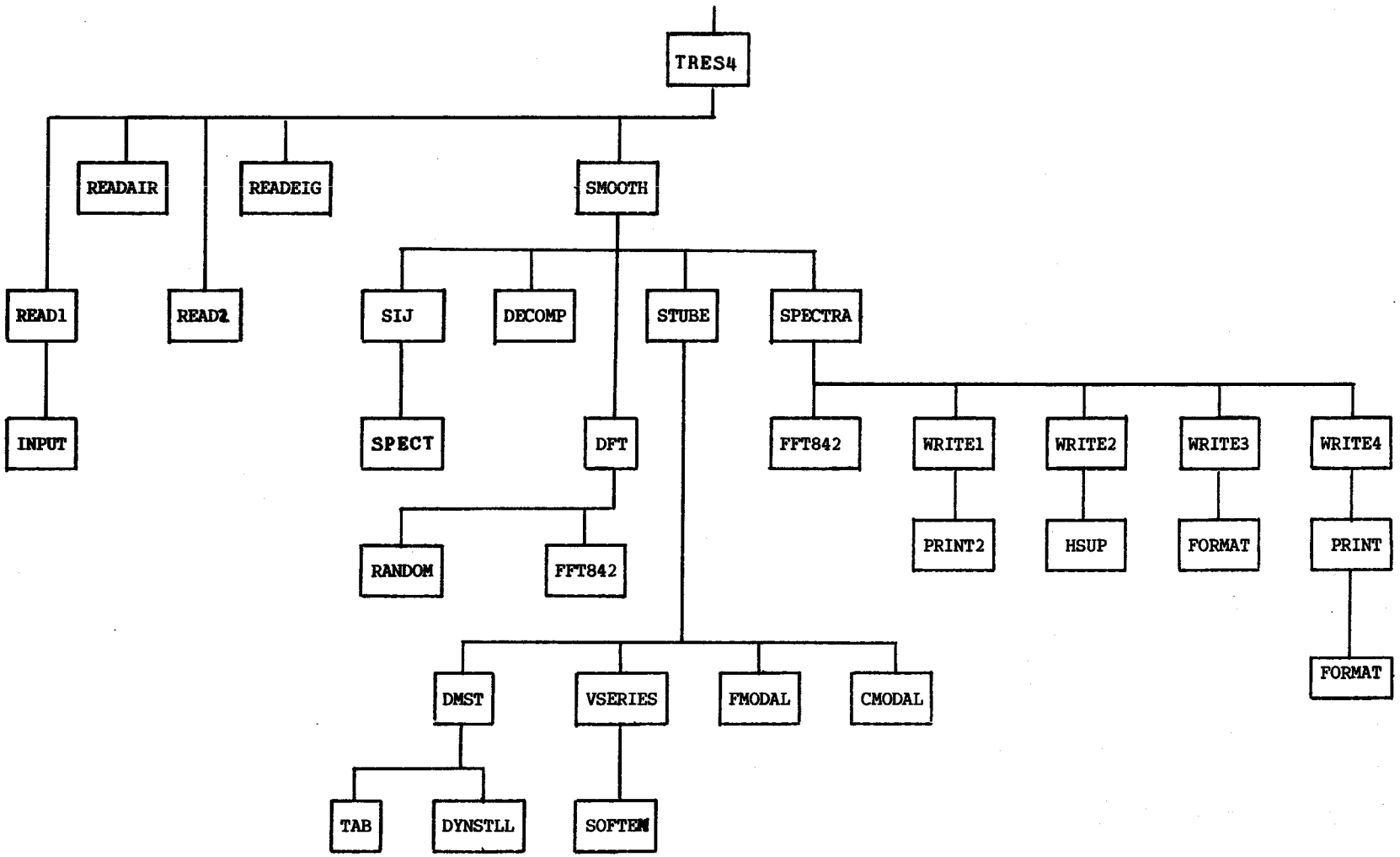


Figure A1. Schematic Flowchart of Program TRES4

```
      PROGRAM TRES4
      WRITE(*,*)' enter basic input data file name'
      OPEN(1,FILE=' ')
      WRITE(*,*)' enter airfoil data file name'
      OPEN(2,FILE='AIR2.DAT')
      WRITE(*,*)' enter NASTRAN bulkdata filename'
      OPEN(5,FILE=' ')
      WRITE(*,*)' enter eigenvector filename'
      OPEN(3,FILE=' ')
      OPEN(6,FILE='TRES.OUT')
      OPEN(7,FILE='TRES1.OUT')
      OPEN(8,FILE='d:TRES.TMP',ACCESS='DIRECT',RECL=4,FORM='BINARY')
      OPEN(4,FILE='TRES2.TMP',ACCESS='DIRECT',RECL=4,FORM='BINARY')
      WRITE(6,111)
111   FORMAT(' TRES4. CALCULATION OF ROTOR MODAL LOADS WITH TURBULENT ',
     1'WINDS USING DMST MODEL. ZSET OPTION ADDED',/,' D.J.MALCOLM, ',
     2'SEPT 1988',/,'ALTERNATIVE SPECTRA ADDED OCT 88.')
C
      CALL READ1(IDS,ICL,IZS)
      CALL READ2(IZS)
      CALL READAIR
      CALL READEIG
      CALL SMOOTH(IDS,ICL)
      END
```

```
      SUBROUTINE CMODAL(II,IIM)
C
C  contributes column loads to modal loads
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      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,
     1        V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/SPECT/S(512,7),TRH(128,630)
C  check vertical numbering of blade nodes
      ZII=Z(II)
      ZIIM=Z(IIM)
      IF(ZII.LT.ZIIM) THEN
        ZII=Z(IIM)
        ZIIM=Z(II)
      ENDIF
C  locate neighbouring column nodes closest to (ZSET) blade element and calculates
C  appropriate colum height interval (DZC).
      IC=1
2     IC=IC+1
      ZIC=ZCOL(IC)
      ZICM=ZCOL(IC-1)
      IF(ZIC.LE.ZIIM) THEN
        GO TO 2
      ELSEIF(ZICM.LE.ZII) THEN
        IF(ZIC.GT.ZII) THEN
          IF(ZICM.LE.ZII) THEN
            IF(ZICM.GT.ZIIM) THEN
              DZC=ZII-ZICM
            ELSE
              DZC=ZII-ZIIM
            ENDIF
          ENDIF
        ELSEIF(ZICM.GT.ZIIM) THEN
          DZC=ZIC-ZICM
        ELSE
          DZC=ZIC-ZIIM
        ENDIF
C  loop on rotor revs and orientation
          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.GE.NTRAN) WRITE(6,*)' KV >=NTRAN'
            KL=(IREV-1)*NT+IT
            V=SQRT((VBARZ+S(KV,1))**2+S(KV,2)**2)
            PHIC=ASIN(S(KV,2)/V)
            V=V*VDEF
            THETAC=2.*PI*IT/NT
C  mean column diameter, total load on element, sharing between column nodes
            D=(DCOL(IC)+DCOL(IC-1))/2.
            DRAG=ARHOG*V*V/2.*D*DZC*1.0
            DRAG1=DRAG/2.
            DRAG2=DRAG/2.
C  loop on eigenmodes
              DO 10 I=1,NEIG
```

```
10            GLOAD(KL,I)=GLOAD(KL,I)-(EIGV(IC,1,I)*DRAG1+EIGV(IC-1,1,I
     1              )* DRAG2)*SIN(THETAC+PHIC)  - COS(THETAC+PHIC)*(EIGV(
     2               IC,2,I)*DRAG1+EIGV(IC-1,2,I)*DRAG2)
40          CONTINUE
      ENDIF
      IF(ZIC.LT.ZII) THEN
        GO TO 2
      ENDIF
      RETURN
      END
```

```
      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/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(512,7),TRH(128,630)
      NN=(NHT+1)*(NDIA+1)
      NSP=NN*(NN+1)/2
C  loop on frequencies
      DO 10 M=1,NTRAN/2
C  initialize first column
       TRH(M,1)=SQRT(TRH(M,1))
       DO 20 IND=2,NN
        ICOL=IND*(IND-1)/2+1
        TRH(M,ICOL)=TRH(M,ICOL)/TRH(M,1)
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(M,INDX1)*TRH(M,INDX2)
           IF(IND2.LT.IND1) THEN
             INDX21=INDX2+1
             TRH(M,INDX)=(TRH(M,INDX)-SUM)
     1                            /TRH(M,INDX21)
           ELSE
             TRH(M,INDX)=SQRT(TRH(M,INDX)-SUM)
           ENDIF
30       CONTINUE
10     CONTINUE
C  store on disc
        DO 50 ICOL=1,NSP
50      WRITE(8)(TRH(M,ICOL),M=1,NTRAN/2)
      RETURN
```

```
      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/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(512,7),TRH(128,630)
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      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)=TRH(M1,INDX)*SIN(PHASE)
            TRH(M1,INDX)=TRH(M1,INDX)*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)
          WORK2(M)=-TRH(M2,INDX)
          WORK1(NTRAN-M+2)=TRH(M1,INDX)
40        WORK2(NTRAN-M+2)=TRH(M2,INDX)
        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)=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=1,NN
          ICOL=IND1*(IND1-1)/2+2
          TEMP=0.0
            DO 72 IND2=1,IND1
            INDX=ICOL-2+IND2
72          TEMP=TEMP+TRH(M,INDX)
```

```
C store longitudinal series in GLOAD array
          IF(IXY.EQ.1)THEN
            GLOAD(M,IND1)=TEMP
          ELSE
             TRH(M,IND1*2-1)=TEMP
          ENDIF
70        CONTINUE
60      CONTINUE
C  combine longitudinal and lateral series
      IF(IXY.EQ.2) THEN
        DO 71 IND1=1,NN
          DO 71 M=1,NTRAN
71        TRH(M,2*IND1)=GLOAD(M,IND1)
      ENDIF
      RETURN
      END
```

```
      SUBROUTINE DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
C
C iterative solution to momentum balance based on method by R J Templin
C  Programmed by D J Malcolm
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      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(15),TC(5),NA(5),ANG(50)
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1          V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/SPECT/S(512,7),TRH(128,630)
      VDRW=VRW*.90
      IF(INIT.EQ.1) VDRW=VRW/(1.+CDD/4.)
      DMP=.75
      CRIT=0.010
      JDS=1
      IF(IDS.EQ.0) JDS=0
      IC=0
      BETA=THETA+ISIGN*PHI
C   iterate to converge on disc drag coefficient
2006  IC=IC+1
      AA=RR/VDRW+COS(BETA)
      BB=SIN(BETA)*COSD
      QQD=AA*AA+BB*BB
      ALPH=ATAN2(BB/SQRT(QQD),AA/SQRT(QQD))
      IALPH=SIGN(1.0,ALPH)
      ALPHABS=ABS(ALPH)
C relative velocity, stall angle, local Reynolds number (initial pass only)
      IF(INITRE.EQ.0) THEN
        VR=VDRW*DIA/2.*OMEGA*SQRT(QQD)
        RE1=VR*CH(KS)*6394./144.
        AS1=AS(KA,1)
      ENDIF
C  dynamic stall
      IF(QQD.LT.0.01.OR.VR.LT.DIA*OMEGA/20.) JDS=0
      IF(ALPHABS.LT.5./57.3.OR.ALPHABS.GT.3.*AS1/57.3) JDS=0
      DADT=0.0
      ALPHR=ALPHABS
      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+S(KV+1,1))**2+S(KV+1,2)**2)
            VM1=SQRT((VBARZ+S(KV-1,1))**2+S(KV-1,2)**2)
            DADT=DADT+(VP1-VM1)*VDEF1/2./DELT
     1            *SIN(BETA)*COSD*RR/DIA*2./OMEGA/VRW/VDRW/QQD
            PHIP1=ASIN(S(KV+1,2)/VP1)
            PHIM1=ASIN(S(KV-1,2)/VM1)
            DADT=DADT+(PHIP1-PHIM1)/2./DELT*COSD*(1.+RR/VDRW*
     1             COS(BETA))/QQD*ISIGN
          ENDIF
          CALL DYNSTLL(DADT,CH(KS),ALPHABS,ALPHR,TC(KA))
      ENDIF
C  interpolate between data to obtain lift and drag coeffs.
      IF(ALPHR.GT.PI) THEN
      WRITE(6,101)II,JJ,KV,INIT,IC,JDS,DADT,ALPH,ALPHR,PHI,QQD,VDRW,BETA
```

```
101     FORMAT('II JJ KV INIT IC JDS DADT ALPH ALPHR PHI QQD VDRW BETA',
     1  6I3,7E9.2)
        ALPHR=0.0
        ALPH=0.0
        JDS=0
      ENDIF
      CALL TAB(ALPHR,CL,CD,CDM,INITRE,KA)
      INITRE=1
      IF(ALPHABS.NE.0.0) CL=CL*ALPHABS/ALPHR
      CN=IALPH*CL*COS(ALPH)+CD*SIN(ALPH)
      CT=IALPH*CL*SIN(ALPH)-CD*COS(ALPH)
      IF(INIT.EQ.0) THEN
        CDD=2.*CH(KS)*QQD/2./PI/SIN(THETA)/RMEAN*(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,KS,IC,ISIGN,CDD,CRIT
          V1RW=VDRW
        ELSE
          VRWA=VDRW*(1.+CDD/4.)
          IF(ABS((VRWA-VRW)/VRW).LE.CRIT) THEN
            V1RW=VDRW*(1.-CDD/4.)
            CDD=4.*(VRW/VDRW-1.)
          ELSE
            VDRW=VDRW-DMP*(VRWA-VRW)
            GO TO 2006
          ENDIF
        ENDIF
      ENDIF
C calculate nodal forces
      TEMP=CH(KS)*QQD*(DIA/2.*OMEGA*VDRW)**2*ARHOG/2.*ABS(DZ)/COSD
      FNODE(1)=-CN*TEMP*COSD*ISIGN
      FNODE(2)=CT*TEMP
      FNODE(3)=CN*TEMP*SIN(DEL)*ISIGN
      IF(INIT.EQ.0) POWER=POWER+2.*FNODE(2)*RMEAN*RPM/NT/84484.
100   FORMAT(' CONVERGENCE NOT MET, II=',I3,' JJ=',I3,' KS=',
     1I3,' IC=',I3,' ISIGN=',I3,' CDD=',F7.3,'CRIT=',F6.3)
      RETURN
      END
```

```
      SUBROUTINE DYNSTLL(DADT,C,ALPH,ALPHR,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,
     1       V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      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
```

```
      SUBROUTINE FMODAL(IBLADE,II,IIM,KL)
C
C  this routine adds contributions to the modal load time series
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1          V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
C  identify column in matrix EIGV corresponding to blade node II and blade # IBLADE
      ICOL=NGRIDB*(IBLADE-1)+II +NGRIDC
      ICOLM=NGRIDB*(IBLADE-1)+IIM+NGRIDC
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)+EIGV(ICOLM,J,I))/2.*FNODE(J)
10    GLOAD(KL,I)=GLOAD(KL,I)+SUM
      RETURN
      END
```

```
      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
```

```
      SUBROUTINE HSUP
C
C  supress omitted subcases (modes)
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15), VAR, ISUP(10), IZSET(50), NZSET
      COMMON/GEO/HT, DIA, HMR, NHT, NDIA, NT, NREV, NEIG, NLOOP, NOUT, NSOFT
     1, NPMAX, NDIV, NVECT, NF, NRD, IPRINT, KTAB, KRAN, VMIN, DELF, FMIN, NSUP, CMIN
      COMMON/EIGEN/EIGV(120, 3, 22), GLOAD(512, 37), EVALUE(22), IGLOAD(22)
      WRITE(7, 118) 0, 2, 1, 0, NEIG, 1
118   FORMAT('$', /, '$ DE-ACTIVATE UNWANTED MODES', /, '$', /,
     1          'DMI      HSUP     ', 4I8, 8X, 2I8)
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
```

```
      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
```

```
      SUBROUTINE PRINT(WORK)
C
C  writes NASTRAN TABLE for cross spectra using chosen option
      CHARACTER SC(256)
      COMMON/GEO/HT, DIA, HMR, NHT, NDIA, NT, NREV, NEIG, NLOOP, NOUT, NSOFT
     1, NPMAX, NDIV, NVECT, NF, NRD, IPRINT, KTAB, KRAN, VMIN, DELF, FMIN, NSUP, CMIN
      COMMON/EIGEN/EIGV(120, 3, 22), GLOAD(512, 37), EVALUE(22), IGLOAD(22)
      COMMON/SPECT/S(512, 7), TRH(128, 630)
      DIMENSION WORK(256), NC(256), FREQ(128), W2(256), IV(256)
      WRITE(7, 100) KRAN, KTAB
100   FORMAT('TABRND1 ', I8, 56X, '+TAB', I4)
C  remove all values where more than 2 consecutive zeroes
      IF(IPRINT.EQ.1) THEN
        W2(1)=WORK(1)
        IV(1)=1
        J=1
          DO 11 I=2, NF-1
          IF(ABS(WORK(I-1)).GT.CMIN.OR.ABS(WORK(I)).GT.CMIN.OR.ABS(WORK
     1                (I+1)).GT.CMIN) THEN
            J=J+1
            IV(J)=I
            W2(J)=WORK(I)
          ENDIF
11        CONTINUE
        W2(J+1)=WORK(NF)
        IV(J+1)=NF
        NN=J+1
        CALL FORMT(W2, SC, NC, NN)
      ELSE
        CALL FORMT(WORK, SC, NC, NF)
      ENDIF
C  print full cross spectra
      IF(IPRINT.EQ.1) THEN
        NCARD=NN/4
        IF(NCARD.GT.0) THEN
            DO 12 I=1, NCARD
            WRITE(7, 113) KTAB, (DELF*(IV(L)-1), W2(L), SC(L), NC(L), L=I
     1                *4-3, I*4), KTAB+1
113         FORMAT('+TAB', I4, 4(F8.3, F6.4, A1, I1), '+TAB', I4)
12          KTAB=KTAB+1
        ENDIF
        NREM=NN-NCARD*4
        IF(NREM.EQ.0) THEN
          WRITE(7, 114) KTAB
114       FORMAT('+TAB', I4, '     ENDT')
        ELSEIF(NREM.EQ.1) THEN
          WRITE(7, 115) KTAB, DELF*(IV(NN)-1), W2(NN), SC(NN), NC(NN)
115       FORMAT('+TAB', I4, F8.3, F6.4, A1, I1, '     ENDT')
        ELSEIF(NREM.EQ.2) THEN
          WRITE(7, 111) KTAB, (DELF*(IV(I)-1), W2(I), SC(I), NC(I), I=NN-1, NN)
111       FORMAT('+TAB', I4, 2(F8.3, F6.4, A1, I1), '     ENDT')
        ELSE
          WRITE(7, 112) KTAB, (DELF*(IV(I)-1), W2(I), SC(I), NC(I), I=NN-2, NN)
112       FORMAT('+TAB', I4, 3(F8.3, F6.4, A1, I1), '     ENDT')
        ENDIF
      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
        NG=NPMAX*3+1
        NCARD=NG/4
        NREM=NG-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(NG),WORK(NG),SC(NG),NC(NG)
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=NG-1,NG)
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=NG-2,NG)
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            ,NF,NDIV)
110     FORMAT('+TAB',I4,2(F8.3,F6.4,A1,I1),'      ENDT')
      ENDIF
      KTAB=KTAB+1
      RETURN
      END
```

```
      SUBROUTINE PRINT2
C
C  prints out all of auto spectral densities onto unit #6
      COMMON/GEO/HT, DIA, HMR, NHT, NDIA, NT, NREV, NEIG, NLOOP, NOUT, NSOFT
     1, NPMAX, NDIV, NVECT, NF, NRD, IPRINT, KTAB, KRAN, VMIN, DELF, FMIN, NSUP, CMIN
      COMMON/EIGEN/EIGV(120, 3, 22), GLOAD(512, 37), EVALUE(22), IGLOAD(22)
      COMMON/SPECT/S(512, 7), TRH(128, 630)
      COMMON/ROTOR/R(50), Z(50), RPM, CH(15), NSECT, NFOIL, INDEX(50), DAMP(30)
     1, ITYPE(15), ZCOL(30), DCOL(30), ICBEAM(50, 2), NGRIDB, NGRIDC, INDEXC(30)
      DELF=RPM/60./NREV
      IF(NREV.GT.1) THEN
        NN=NEIG
        IF(NEIG.GT.14) NN=14
C  smooth spectra
          DO 2 I=1, NN
          IG=IGLOAD(I)
            DO 2 J=1, NPMAX
              DO 2 K=1, NREV-2
              M=NREV*(J-1)+K+1
2             TRH(IG, M)=(TRH(IG, M)+TRH(IG, M+1))/2.
C  print spectra
        WRITE(6, 100)(I, I=1, NN)
100     FORMAT(/,' AUTO SPECTRAL DENSITIES',/,4X,'FREQ',10X,'MODE NO.',/,
     18X, 14I9)
          DO 1 M=1, NREV*NPMAX+1
          FREQ=(M-1)*DELF
1         WRITE(6, 101) M, FREQ, (TRH(I, M), I=1, NN)
101       FORMAT(I3, F6.3, 14E9.3)
      ELSEIF(NREV.EQ.1) THEN
        WRITE(6, 102)
102     FORMAT('NODE#  OP        1P        2P        3P        4P        5P')
          DO 3 I=1, NEIG
          IG=IGLOAD(I)
3         WRITE(6, 103) IG, (TRH(IG, M), M=1, 6)
103       FORMAT(I3, 6E9.3)
      ENDIF
      RETURN
      END
```

```
      FUNCTION RANDOM(XSEED)

C
C  based on HP-35 applications manual (S. MIKHAIL)
      X=EXP(5.*ALOG(XSEED+3.1415926))
      XSEED=X-INT(X)
      RANDOM=XSEED
      RETURN
      END
```

```
      SUBROUTINE READAIR
C
C  reads and stores the required airfoil datasets with corresponding Reynolds
C  numbers, static stall, and Cdmin
      CHARACTER*8 AA,TYPE,NAME
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/AIRFOIL/DSET(5,50,11),DSET1(50,2),RE(5,5),AS(5,5),
     1CDMIN(5,5),NRE(15),TC(5),NA(5),ANG(50)
C
C loop on no of airfoils.
      DO 9 I=1,NFOIL
C  search for airfoil name
      J1=0
11    J1=J1+1
      IF(J1.LE.NSECT) THEN
        IF(ITYPE(J1).NE.I) GO TO 11
        NAME=TYPE(J1)
      ELSE
        WRITE(6,*)' ERROR IN  READAIR'
        STOP
      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.NAME) 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
```

```
      SUBROUTINE READEIG
C
C  reads in eigenvalues from NASTRAN punched output file and stores in EVALUE().
C  Note that punched file format puts grid #s in ascending order. This proram
C  assumes that all column nodes lie between 1 thru 99 and that blade 1 nodes
C  lie within 101 thru 199. Any nodes not associated with the column or the
C  blades must lie above 299. Eigenvectors are stored in EIGV(i,j,k).
      CHARACTER*10 AA
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      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
          DO 50 J=1,NGRIDC
          READ(3,100)NODE,(EIGV(J,K,I),K=1,3)
50        READ(3,100)
C  loop on no. of (both) blade nodes
          DO 30 J=NGRIDC+1,NGRIDC+2*NGRIDB
          READ(3,100)NODE,(EIGV(J,K,I),K=1,3)
C         WRITE(6,100)NODE,(EIGV(J,K,I),K=1,3)
30        READ(3,100)
10      CONTINUE
C  write eigenvalues
      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)
106   FORMAT(7X,I3)
      RETURN
      END
```

```
      SUBROUTINE READ1(IDS,ICL,IZS)
C
C  reads in some basic data from unit #1 and writes to unit #6
C
      CHARACTER*3 AA
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
C  read and write basic variables
      CALL INPUT(1)
      READ(1,*)HT,DIA,HMR,RPM,VBAR,WSE,DELT,ARHO
      CALL INPUT(1)
      READ(1,*)C1X,C2X,C1Y,C2Y,ZO,DECAY,VAR,NSOFT,FMIN,CMIN
      CALL INPUT(1)
      READ(1,*)ISPECT
      CALL INPUT(1)
      READ (1,*)NHT,NDIA,NEIG,NT,NREV,NSECT,NLOOP,NPMAX,NDIV,NOUT,NSUP
      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(6,146)ISPECT
      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(6,135)VAR
      WRITE(6,141)FMIN
      WRITE(6,142)CMIN
      WRITE(6,139)NSOFT
      WRITE(6,113)NEIG
      WRITE(6,114)NT
      WRITE(6,118)NREV
      WRITE(6,119)NPMAX
      WRITE(6,130)NDIV
      WRITE(6,120)NLOOP
      WRITE(6,136)NOUT
      CALL INPUT(1)
C  flags for dynamic stall, column loading, use of ZSET, print option
      READ(1,103)AA
103   FORMAT(A3)
      IDS=0
      IF(AA.EQ.'YES') IDS=1
      WRITE(6,131)AA
      CALL INPUT(1)
      READ(1,103)AA
      ICL=0
      IF(AA.EQ.'YES') ICL=1
```

```
      WRITE(6,133)AA
      CALL INPUT(1)
      READ(1,103)AA
      IZS=0
      IF(AA.EQ.'YES') IZS=1
      WRITE(6,143)AA
      CALL INPUT(1)
      READ(1,*)IPRINT
      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(' TURB. SPECTRUM CONST. C1X ',F6.2)
123   FORMAT(' TURB. SPECTRUM CONST. C2X ',F6.2)
128   FORMAT(' TURB. SPECTRUM CONST. C1Y ',F6.2)
129   FORMAT(' TURB. SPECTRUM CONST. C2Y ',F6.2)
124   FORMAT(' SURFACE ROUGHNESS           ',F6.3,' M')
125   FORMAT(' DECAY COEFFICIENT FOR CSDs',F6.3)
130   FORMAT(' OUTPUT: # DIVISIONS/CYCLE ',I6)
131   FORMAT(' DYNAMIC STALL?                  ',A3)
133   FORMAT(' COLUMN LOADING?                 ',A3)
134   FORMAT(' PRINT OPTION # FOR CSDs     ',I6)
135   FORMAT(' LONGIT TURB INTENSITY       ',F6.3)
136   FORMAT(' PRINT LOOP INTERVAL#        ',I6)
139   FORMAT(' # TIME INTERVALS SMOOTHED ',I6)
141   FORMAT(' VMIN:CSD-VAR CUTOFF FRACT ',F6.3)
142   FORMAT(' CMIN CSD:CUTOFF MAGNITUDE ',E9.3)
143   FORMAT(' ZSET USED?                      ',A3)
146   FORMAT(' TURBULENCE SPECTRUM NO.     ',I6)
C  select length of time series (to nearest power of 2)
      TIME=NREV*60./RPM
      NTRAN=(TIME+DIA*1.50/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
      NN=(NHT+1)*(NDIA+1)
      WRITE(6,140)NN*(NN+1)/2
126   FORMAT(/,' LENGTH OF WINDSPEED SERIES=',I6)
127   FORMAT(' LENGTH OF LOAD SERIES       ',I6)
140   FORMAT(' # SPATIAL ARRAY ELEMENTS    ',I6)
C  read data on blade sections, chords, and associated airfoil types
C  and type #s
      CALL INPUT(1)
      WRITE(6,105)
```

```
105   FORMAT(/,'SECTION# FOIL# FOIL-TYPE   CHORD(IN)   ')
      K=0
        DO 2 I=1,NSECT
        READ(1,138)II,TYPE(I),CH(I)
138     FORMAT(I4,A8,F10.2)
        J=0
5       J=J+1
        IF(J.LT.I) THEN
          IF(TYPE(I).NE.TYPE(J)) GO TO 5
          ITYPE(I)=ITYPE(J)
        ELSE
          K=K+1
          ITYPE(I)=K
        ENDIF
2       CONTINUE
      NFOIL=K
      WRITE(6,137)(I,ITYPE(I),TYPE(I),CH(I),I=1,NSECT)
137   FORMAT(2I6,2X,A8,F8.2)
C  read in mode numbers and critical modal damping factors (default = 0.00)
        DO 4 I=1,NEIG
4       DAMP(I)=0.00
      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
C  read in eigenvector #s to be suppressed
      IF(NSUP.GT.0) THEN
        CALL INPUT(1)
        WRITE(6,144)
144     FORMAT(/,' SUPPRESSED EIGENVECTORS')
          DO 6 I=1,NSUP
          READ(1,*)ISUP(I)
6         WRITE(6,145)ISUP(I)
145       FORMAT(20X,I3)
      ENDIF
      RETURN
      END
```

```
      SUBROUTINE READ2(IZS)
C
C reads required geometry data from NASTRAN bulkdata and writes to unit 6
      CHARACTER*8 TYPE
      CHARACTER*4 AA
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      NGRIDB=0
      NGRIDC=0
      NCBEAM=0
1     READ(5,100)AA
100   FORMAT(A4)
      IF(AA.EQ.'GRID') THEN
        BACKSPACE 5
        READ(5,101)II,RR,ZZ,DD
101     FORMAT(8X,I8,8X,F8.2,8X,F8.2,24X,F8.2)
        IF(II.GE.100.AND.II.LT.200) THEN
C  blade #1 coordinates
          NGRIDB=NGRIDB+1
          INDEX(NGRIDB)=II
          R(NGRIDB)=RR
          Z(NGRIDB)=ZZ
C  column coordinates and diameters
        ELSEIF(II.LT.100) THEN
          NGRIDC=NGRIDC+1
          INDEXC(NGRIDC)=II
          ZCOL(NGRIDC)=ZZ
          DCOL(NGRIDC)=DD
        ENDIF
        GO TO1
      ELSEIF(AA.EQ.'CBEA') THEN
        BACKSPACE 5
        READ(5,102)IB,IP
102     FORMAT(8X,2I8)
        IF(IB.GE.100.AND.IB.LT.200) THEN
C  blade #1 elements
          NCBEAM=NCBEAM+1
          ICBEAM(NCBEAM,1)=IB
          ICBEAM(NCBEAM,2)=IP
        ENDIF
        GO TO 1
C  read ZSET nodes for blade #1
      ELSEIF(AA.EQ.'$ZSE') THEN
        BACKSPACE 5
        READ(5,107)(IZSET(I),I=1,20)
107     FORMAT(5X,20I4)
        NZSET=0
2       NZSET=NZSET+1
        IF(IZSET(NZSET+1).GT.0) THEN
          GO TO 2
        ENDIF
        GO TO 1
      ELSEIF(AA.NE.'ENDD') THEN
        GO TO 1
      ENDIF
      WRITE(6,103)NGRIDB+1
      WRITE(6,104)NGRIDC
```

```
103   FORMAT(/,' # OF ELEMENTS PER BLADE   =',I6)
104   FORMAT(' TOTAL # OF COLUMN NODES   =',I6)
C  fill in missing diameters using linear interpolation
      JJ1=0
62    JJ1=JJ1+1
63    II=JJ1
64    II=II+1
      IF(II.LE.NGRIDC-1) 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.NGRIDC-3) THEN
          JJ1=JJ2
          GO TO 63
        ENDIF
      ENDIF
C  if ZSET not used then replace with complete set
      IF(IZS.EQ.0) THEN
        NZSET=NGRIDB
          DO 5 I=1,NGRIDB
5         IZSET(I)=I+100-1
      ELSE
        WRITE(6,108)(IZSET(I),I=1,NZSET)
108     FORMAT(/,' ZSET=',20I4)
      ENDIF
      RETURN
      END
```

```
      SUBROUTINE SIJ(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/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(512,7),TRH(128,630)
      DIMENSION WORK(512)
      NN=(NHT+1)*(NDIA+1)
      NSP=NN*(NN+1)/2
      DELHT=HT/NHT
      DELF=1./NTRAN/DELT
C  establishes the (continuous 1-sided) power spectral densities for NHT+1
C  vertical levels. PSD stored in S(i,j). Note: present max spatial array size
C  is 6 x 4 divisions (corresponding to NSP=630)
        DO 30 I=1,NHT+1
        HM=HMR-HT/2.+(I-1)*DELHT/39.37
        VM=VBAR*(H/HMR)**WSE*447
        IF(IXY.EQ.1) THEN
          C1=C1X
          C2=C2X
        ELSE
          C1=C1Y
          C2=C2Y
        ENDIF
        DELF=1./NTRAN/DELT
        WORK(1)=1.
          DO 50 M=1,NTRAN/2
          F=(M-2)*DELF
50        WORK(M)=(TSPECT(VM,HM,C1,C2,F)+TSPECT(VM,HM,C1,C2,F+DELF))/2.
C  calculate and print the rms of spectrum
        RMS=0.0
          DO 40 J=1,NTRAN/2
          IF(J.GT.1) RMS=RMS+WORK(J)
40        S(J,I)=WORK(J)
        RMS=SQRT(RMS*DELF)*2.237
        WRITE(6,100)IXY,I,RMS,RMS/V
100     FORMAT('IXY=',I2,' HEIGHT LEVEL=',I2,' RMS=',F5.2,' MPH COEFF',
     1        ' OF VARIATION=',F4.3)
30      CONTINUE
C  loop on frequencies
      DO 10 M=1,NTRAN/2
      FR=(M)*DELF
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
          IND2=(K-1)*(NDIA+1)+L
          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(M,INDX)=SQRT(GAMMA*S(M,I)*S(M,K))*DELF/2.
          ENDIF
20      CONTINUE
10    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SMOOTH(IDS,ICL)
C
C  This routine organizes an ensemble of spectra for modal loads
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(512,7),TRH(128,630)
C  # of terms in load series, # of spatial array points, elements in matrix
C  of spectra
      NL=NT*NREV
      NN=(NHT+1)*(NDIA+1)
      NSP=NN*(NN+1)/2
C  set up transfer matrices, H, for longitudinal and lateral directions
      REWIND 8
        DO 60 IXY=1,2
          CALL SIJ(IXY)
60        CALL DECOMP(IXY)
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
        REWIND 8
          DO 50 IXY=1,2
            DO 13 ICOL=1,NSP
13          READ(8)(TRH(2*M-1,ICOL),M=1,NTRAN/2)
50        CALL DFT(XSEED,IXY)
C  DMST aerodynamics
        CALL STUBE(IDS,ICL,XSEED)
C generate modal spectra, store and print
        CALL SPECTRA(ILOOP,IOUT)
        WRITE(*,*)' COMPLETED LOOP #',ILOOP
10      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SOFTEN(IXY,RMS,RMSA,XSEED)
C
C  corrects time series for particular streamtube to have correct rms
C  and carries out any required smoothing
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      COMMON/SPECT/S(512,7),TRH(128,630)
C  add white noise to supply missing variance (as proposed by P Veers)
      RMS2=0.0
      IF(RMSA.GT.RMS) THEN
        DO 1 M=1,NTRAN
        RAN=(RANDOM(XSEED)-0.5)
        S(M,IXY)=S(M,IXY)+SIGN(1.0,RAN)*SQRT(ABS(RAN)*3.*
     1                                  (RMSA*RMSA-RMS*RMS))
1       RMS2=RMS2+S(M,IXY)**2/NTRAN
      ENDIF
C  carry out any smoothing
        IF(NSOFT.GT.1) THEN
          DO 2 M=1,NTRAN-NSOFT+1
            DO 3 MM=M+1,M+NSOFT-1
3           S(M,IXY)=S(M,IXY)+S(MM,IXY)
2         S(M,IXY)=S(M,IXY)/NSOFT
        ENDIF
      RETURN
      END
```

```
      SUBROUTINE SPECTRA(ILOOP,IOUT)
C
C  generates the auto and cross spectral densities of modal loads
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(512,7),TRH(128,630)
      DIMENSION U(512),V(512)
      REWIND 4
      NL=NREV*NT
C  NSP=total no of modal spectral densities
      NSP=NEIG*(NEIG+1)/2
C  loop for FFTS of modal loads. Store output in GLOAD.
        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
C  read in previous auto spectra and calc new (averaged) spectra
          DO 70 M=1,NL/2
          IF(ILOOP.GT.1) THEN
            READ(4)TRH(I,M)
          ELSE
            TRH(I,M)=0.0
          ENDIF
          F=2.
          IF(M.EQ.1) F=1.
70        TRH(I,M)=(TRH(I,M)*(ILOOP-1)+F*(GLOAD(2*M-1,I)**2+
     1            GLOAD(M*2,I)**2))/ILOOP
10      CONTINUE
C  prepare output (intermediate loops or last loop only)
      IOUT=IOUT+1
      IF(IOUT.EQ.NOUT) THEN
        IOUT=0
        CALL WRITE1
        IF(ILOOP.EQ.NLOOP) THEN
          CALL WRITE2
          CALL WRITE3
        ENDIF
      ENDIF
C  write auto spectra onto disk
      REWIND 4
        DO 90 I=1,NEIG
          DO 90 M=1,NL/2
90        WRITE(4)TRH(I,M)
C  generate & update (upper triangle) of csds - Sij - one at a time
      NREC=NEIG*NL/2+1
        DO 2 JJ=2,NEIG
          DO 2 II=1,JJ-1
           DO 3 M=1,NL/2
           IF(ILOOP.GT.1) THEN
             READ(4,REC=NREC)(S(M,K),K=1,2)
           ELSE
             S(M,1)=0.0
             S(M,2)=0.0
           ENDIF
```

```
          M2=2*M
          M1=M2-1
          CSD1=GLOAD(M1,JJ)*GLOAD(M1,II)+GLOAD(M2,JJ)*GLOAD(M2,II)
          CSD2=+GLOAD(M1,JJ)*GLOAD(M2,II)-GLOAD(M2,JJ)*GLOAD(M1,II)
          F=2.
          IF(M.EQ.1)  F=1.
          S(M,1)=(S(M,1)*(ILOOP-1)+F*CSD1)/ILOOP
          S(M,2)=(S(M,2)*(ILOOP-1)+F*CSD2)/ILOOP
3         NREC=NREC+2
         IF(ILOOP.EQ.NLOOP)  THEN
           CALL WRITE4(II,JJ)
           IF(JJ.EQ.3)  WRITE(7,100)
100        FORMAT('ECHOOFF')
         ELSE
           NREC=NREC-NL
           WRITE(4,REC=NREC)((S(M,K),K=1,2),M=1,NL/2)
           NREC=NREC+NL
         ENDIF
2     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STUBE(IDS,ICL,XSEED)
C
C  defines the loop on all ZSET streamtubes and calls relevant subroutines.
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      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,
     1      V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(512,7),TRH(128,630)
      PI=3.141593
      OMEGA=RPM*0.10472
      POWER=0.0
      ARHOG=ARHO/1728./386.
      KV=2
      GAP=DIA/2.*2.60
      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 (ZSET) blade elements; set up blade angle
        DO 10 IZ=2,NZSET
        II=IZSET(IZ)-100+1
        IIM=IZSET(IZ-1)-100+1
C check location for airfoil type (KA) and section type(KS)
        KS=ICBEAM(II,2)-100
        KA=ITYPE(KS)
        DR=R(II)-R(IIM)
        DZ=Z(II)-Z(IIM)
        DEL=ATAN(DR/DZ)
        COSD=COS(DEL)
        RMEAN=(R(II)+R(IIM))/2.
        RR=RMEAN/DIA*2.
C check location for airfoil type (KA) and section type(KS)
        KS=ICBEAM(II,2)-100
        KA=ITYPE(KS)
C  mean windspeed (in/sec)
        ZMEAN=(Z(II)+Z(IIM))/2.
        VBARZ=VBAR*((ZMEAN-Z((NGRIDB+1)/2)+HMR)/HMR)**WSE*17.6
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
          INITRE=0
          ITURB=0
          PHI=0.0
          ISIGN=+1
          CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
          VDEF=V1RW/VRW
C  generate time series for this streamtube
         CALL VSERIES(XSEED)
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+S(KV,1))**2+S(KV,2)**2)
        PHI=ASIN(S(KV,2)/VRW)
        VRW=VRW/DIA*2./OMEGA
C
        CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
C
        CALL FMODAL(1,II,IIM,KL)
C  blade # 2
        KV=KV+PI/DELT/OMEGA
        IF(KV.GE.NTRAN) WRITE(6,*)' KV >=NTRAN II,JJ,KV',II,JJ,KV
        KL=KL+NT/2
        VRW=SQRT((VBARZ+S(KV,1))**2+S(KV,2)**2)
        PHI=ASIN(S(KV,2)/VRW)
        VRW=VRW/DIA*2./OMEGA
        CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
        FNODE(1)=-FNODE(1)
        FNODE(2)=-FNODE(2)
        CALL FMODAL(2,II,IIM,KL)
20      CONTINUE
C  column loading
      IF(JJ.EQ.NT/4.AND.ICL.EQ.1) THEN
        CALL CMODAL(II,IIM)
      ENDIF
C  loop for downstream disk
      INIT=0
      INITRE=0
      ISIGN=-1
C  calc CDD for downstream mean velocity
      ITURB=0
      PHI=0.0
      VRW=VDEF*VBARZ/DIA*2./OMEGA
      CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
C  include turbulence. loop on # of revs
      ITURB=1
      INIT=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.GE.NTRAN) WRITE(6,*)' KV >=NTRAN II,JJ,KV',II,JJ,KV
        VRW=SQRT((VBARZ+S(KV,1))**2+S(KV,2)**2)
        PHI=ASIN(S(KV,2)/VRW)
        VRW=VRW/DIA*2./OMEGA*VDEF
        KL=IREV*NT-JJ+1
        IJ=NT-JJ+1
        CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
        CALL FMODAL(1,II,IIM,KL)
C  blade # 2
        KV=KV-PI/DELT/OMEGA
        IF(KV.LE.1) WRITE(6,*)' WARNING: KV=',KV
        KL=KL-NT/2
```

```
            VRW=SQRT((VBARZ+S(KV,1))**2+S(KV,2)**2)
            PHI=ASIN(S(KV,2)/VRW)
            VRW=VRW/DIA*2./OMEGA*VDEF
            CALL DMST(ISIGN,II,JJ,KS,KA,KV,ITURB,INIT,INITRE,IDS)
            FNODE(1)=-FNODE(1)
            FNODE(2)=-FNODE(2)
            CALL FMODAL(2,II,IIM,KL)
30          CONTINUE
11        CONTINUE
10      CONTINUE
      WRITE(6,101)POWER
101   FORMAT(' POWER=',F6.1,' KW')
      RETURN
      END
```

```
      SUBROUTINE TAB(ALPHR,CL,CD,CDM,INITRE,KA)
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(15),TC(5),NA(5),ANG(50)
      COMMON/AERO/VDEF,THETA,DTHETA,DEL,COSD,OMEGA,RR,DZ,ARHOG,VRW,
     1          V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      IF(INITRE.EQ.0) THEN
C if only one Re for this airfoil no need to interpolate
        IF(NRE(KA).EQ.1) THEN
          AS1=AS(KA,1)
          CDM=CDMIN(KA,1)
            DO 10 J=1,NA(KA)
            ANG(J)=DSET(KA,J,1)
            DO 10 K=1,2
10          DSET1(J,K)=DSET(KA,J,K+1)
        ELSE
          RE2=RE1
          IF(RE1.LT.RE(KA,1)) RE2=RE(KA,1)
          IF(RE1.GT.RE(KA,NRE(KA))) RE2=RE(KA,NRE(KA))
            DO 1 I=2,NRE(KA)
            IF(RE2.LT.RE(KA,I)) GO TO 2
1           CONTINUE
2         G=(RE2-RE(KA,I-1))/(RE(KA,I)-RE(KA,I-1))
          CDM=CDMIN(KA,I-1)*(1.-G)+G*CDMIN(KA,I)
          AS1=AS(KA,I-1)*(1.-G)+G*AS(KA,I)
            DO 4 J=1,NA(KA)
            ANG(J)=DSET(KA,J,1)
            DO 4 K=1,2
4           DSET1(J,K)=(1.-G)*DSET(KA,J,2*(I-2)+K+1)+DSET(KA,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(J.GE.NA(KA)) THEN
        WRITE(6,100)J,KA,INIT,NA(KA),AB
100     FORMAT('  J=',I4,'KA=',I4,'  INIT=',I4,'  NA(KA)=',I4,'  ANG=',F6.2)
        WRITE(6,101)VDEF,THETA,RR,RE1,AS1,PHI
101     FORMAT('  VDEF THETA RR RE1 AS1 PHI',6E10.3)
      ENDIF
      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
```

```
      FUNCTION TSPECT(VM,HM,C1,C2,F)
C
C  calculates  value of turbulence spectra (SI units) using appropriate formula
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET,ISPECT
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/WND/VBAR,WSE,C1X,C2X,C1Y,C2Y,ZO,DECAY,DELT,NTRAN,VBARZ,ARHO
      IF(F.LT.0.0) F=0.0
      IF(ISPECT.EQ.1) THEN
C  Kaimal(stable/ strickland)
        TSPECT=(VAR*VM)**2*C1*HM/VM/(1.+C2*(F*HM/VM)**1.667)
      ELSEIF(ISPECT.EQ.2) THEN
C  Frost et alia
        VREF=VBAR*(393.7/HMR)**WSE/2.237
        TSPECT=C1*HM*VREF/(ALOG(HM/ZO+1)*ALOG(10./ZO+1))/(1.+C2*(F*HM/VREF
     1       *ALOG(10./ZO+1)/ALOG(HM/ZO+1))**1.667)
      ELSEIF(ISPECT.EQ.3) THEN
C  Kaimal neutral
        TSPECT=C1*VM*HM/(1.+C2*F*HM/VM)**1.667/(ALOG(HM/ZO))**2
      ELSEIF(ISPECT.EQ.4) THEN
C  Von Karman (neutral) (Fordham )
        AL=120.
        TSPECT=(VAR*VM)**2*C1*AL/VM/(1.+C2*(F*AL/VM)**2)**0.833
      ELSEIF(ISPECT.EQ.5) THEN
C  von Karman ( Fordham neutral) dependent on height and roughness
        AL=120.
        TSPECT=C1*AL*.958*VM/(ALOG(HM/ZO))**2/(1.+C2*(F*AL/VM)**2)**.833
      ENDIF
      RETURN
      END
```

```
      SUBROUTINE VSERIES(XSEED)
C
C  extracts the time series for this streamtube by linear interpolation
C  between the 4 neighbouring locations in the spatial array.
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/ROTOR/R(50),Z(50),RPM,CH(15),NSECT,NFOIL,INDEX(50),DAMP(30)
     1,ITYPE(15),ZCOL(30),DCOL(30),ICBEAM(50,2),NGRIDB,NGRIDC,INDEXC(30)
      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,
     1         V1RW,PI,POWER,FNODE(3),VR,RE1,AS1,PHI,CDD,RMEAN,ZMEAN,GAP
      COMMON/SPECT/S(512,7),TRH(128,630)
C  determine the lower row no in array and fractional spacing in interval
      ZZ=ZMEAN
C  adjust for rotor coordinates
      IF(Z(1).LT.0.0) ZZ=ZMEAN+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.-RMEAN*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  synthesize time series from 4 neighbouring vectors and calc rms (in/sec)
C    of synthesized time and the average of neighbouring points
        DO 10 IXY=1,2
        RMS=0.0
        RMSA=0.0
          DO 11 M=1,NTRAN
          S(M,IXY)=((1.-ZZ)*(1.-YY)*TRH(M,2*I1-IXY+1)
     1              +YY*(1.-ZZ)*TRH(M,2*I2-IXY+1)
     2              +ZZ*(1.-YY)*TRH(M,2*I3-IXY+1)
     3              +ZZ*YY*TRH(M,2*I4-IXY+1))*39.37
          RMS=RMS+S(M,IXY)**2
11        RMSA=RMSA+TRH(M,2*I1-IXY+1)**2+TRH(M,2*I2-IXY+1)**2
     1              +TRH(M,2*I3-IXY+1)**2+TRH(M,2*I4-IXY+1)**2
        RMS=SQRT(RMS/NTRAN)
        RMSA=SQRT(RMSA/4./NTRAN)*39.37
C  adjust time series for correct rms and carry out any smoothing
        CALL SOFTEN(IXY,RMS,RMSA,XSEED)
10      CONTINUE
      RETURN
      END
```

```
      SUBROUTINE WRITE1
C
C  this routine reorders, prints (on unit6), and smooths the auto spectra
      COMMON/GEO/HT, DIA, HMR, NHT, NDIA, NT, NREV, NEIG, NLOOP, NOUT, NSOFT
     1, NPMAX, NDIV, NVECT, NF, NRD, IPRINT, KTAB, KRAN, VMIN, DELF, FMIN, NSUP, CMIN
      COMMON/ROTOR/R(50), Z(50), RPM, CH(15), NSECT, NFOIL, INDEX(50), DAMP(30)
     1, ITYPE(15), ZCOL(30), DCOL(30), ICBEAM(50,2), NGRIDB, NGRIDC, INDEXC(30)
      COMMON/EIGEN/EIGV(120,3,22), GLOAD(512,37), EVALUE(22), IGLOAD(22)
      COMMON/SPECT/S(512,7), TRH(128,630)
      DIMENSION U(30), V(30)
      NF=NDIV*NPMAX+1
      NRD=NREV/NDIV
      KTAB=1000
C  re-order GLOAD vectors on basis of total variance of power spectra
        DO 91 I=1,NEIG
        V(I)=0.0
          DO 91 M=1,NREV*NPMAX+1
          V(I)=V(I)+TRH(I,M)
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
C  determine minimum variance
      K=IGLOAD(NEIG)
      VMIN=0.0
        DO 94 M=1,NREV*NPMAX+1
94      VMIN=VMIN+TRH(K,M)
C calc % of random contribution to each auto spectrum
      WRITE(6,*)'MODE TOTAL-VAR TOT-RAN-VAR %RAN'
        DO 81 II=1,NEIG
        I=IGLOAD(II)
        TOTAL=0.0
        RAN=0.0
        IC=0
          DO 82 M=1,NREV*NPMAX+1
          V(M)=TRH(I,M)
          IC=IC+1
          IF(IC.EQ.NDIV.OR.M.EQ.1) THEN
            IC=0
          ELSE
            RAN=RAN+V(M)
          ENDIF
82        TOTAL=TOTAL+V(M)
      WRITE(6,107)I,TOTAL,RAN,RAN/TOTAL*100.
107   FORMAT(I3,2E10.3,F7.1)
81    CONTINUE
C print out full auto spectra
      CALL PRINT2
      RETURN
      END
```

```
      SUBROUTINE WRITE2
C
C  write preliminary NASTRAN output and power spectra for NASTRAN
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15), VAR, ISUP(10), IZSET(50), NZSET
      COMMON/GEO/HT, DIA, HMR, NHT, NDIA, NT, NREV, NEIG, NLOOP, NOUT, NSOFT
     1, NPMAX, NDIV, NVECT, NF, NRD, IPRINT, KTAB, KRAN, VMIN, DELF, FMIN, NSUP, CMIN
      COMMON/ROTOR/R(50), Z(50), RPM, CH(15), NSECT, NFOIL, INDEX(50), DAMP(30)
     1, ITYPE(15), ZCOL(30), DCOL(30), ICBEAM(50, 2), NGRIDB, NGRIDC, INDEXC(30)
      COMMON/EIGEN/EIGV(120, 3, 22), GLOAD(512, 37), EVALUE(22), IGLOAD(22)
      DELF=RPM/60./NDIV
C  suppression of unwanted modes
      IF(NSUP.GT.0) CALL HSUP
C  define dummy load
      WRITE(7,100)
100   FORMAT('$',/,'$ DEFINITION OF DUMMY LOAD',/,'$')
        WRITE(7,101)99,99,99,99,2,1,0.0
101     FORMAT('RLOAD1  ',2I8,16X,I8,/,'DAREA   ',3I8,F8.2)
      WRITE(7,102)99,0.0,1.0,100.0,1.0
102   FORMAT('TABLED1 ',I8,56X,'+TABD100',/,'+TABD100',4F8.1,'     ENDT')
C  frequency response range
      WRITE(7,111)
111   FORMAT('$',/,'$ FREQUENCY RESPONSE RANGE',/,'$')
      IF(IPRINT.EQ.3) THEN
        WRITE(7,112)101,0.0,DELF*NDIV,NPMAX
      ELSE
        WRITE(7,112)101,0.0,DELF,NF-1
      ENDIF
112   FORMAT('FREQ1   ',I8,2F8.5,I8)
C  modal (critical) damping
      WRITE(7,113)
113   FORMAT('$',/,'$   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')
      RETURN
      END
```

```
      SUBROUTINE WRITE3
C
C  this routine formulates the auto spectra for NASTRAN input
      CHARACTER SC(256)
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(512,7),TRH(128,630)
      DIMENSION WORK(256),NC(256)
C  smooth spectra by bracketing
      IF(NRD.GT.1) THEN
        DO 80 I=1,NEIG
          DO 80 M=2,NF
          M1=NRD*(M-2)+2
          SUM=0.
            DO 90 K=M1,M1+NRD-1
90          SUM=SUM+TRH(I,K)
80        TRH(I,M)=SUM
      ENDIF
C  definition of discrete spectral densities
      WRITE(7,103)
103   FORMAT('$',/'$ DEFINITION OF DISCRETE PSDS',/,'$')
      KRAN=1000
        DO 20 II=1,NEIG
        IF(II.EQ.5) WRITE(7,116)
116     FORMAT('ECHOOFF')
        J=0
2       J=J+1
        IF(ISUP(J).EQ.II) THEN
          GO TO 20
        ELSEIF(J.LT.NSUP) THEN
          GO TO 2
        ELSE
          KRAN=KRAN+1
          WRITE(7,104)101,II,II,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(II,M)
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,
     1                NF1+3),KTAB+1
106         FORMAT('+TAB',I4,4(F8.3,F6.4,A1,I1),'+TAB',I4)
70          KTAB=KTAB+1
          NREM=NF-NF1-3
          IF(NREM.EQ.0) THEN
            WRITE(7,109)KTAB
109         FORMAT('+TAB',I4,'     ENDT')
          ELSEIF(NREM.EQ.1) THEN
            WRITE(7,110)KTAB,DELF*(NF-1),WORK(NF),SC(NF),NC(NF)
110         FORMAT('+TAB',I4,F8.3,F6.4,A1,I1,'     ENDT')
          ELSEIF(NREM.EQ.2) THEN
            WRITE(7,111)KTAB,(DELF*(I-1),WORK(I),SC(I),NC(I),I=NF-1,NF)
111         FORMAT('+TAB',I4,2(F8.3,F6.4,A1,I1),'     ENDT')
```

```
          ELSE
            WRITE(7,112)KTAB,(DELF*(I-1),WORK(I),SC(I),NC(I),I=NF-2,NF)
112         FORMAT('+TAB',I4,3(F8.3,F6.4,A1,I1),'     ENDT')
          ENDIF
        KTAB=KTAB+1
        ENDIF
20      CONTINUE
      WRITE(7,115)
115   FORMAT('ECHOON')
      WRITE(7,108)
108   FORMAT('$',/,'$ DEFINITION OF (UPPER TRIANGLE) CROSS SPECTRAL',
     1                '  DENSITIES',/,'$')
      RETURN
      END
```

```
      SUBROUTINE WRITE4(II,JJ)
C
C  definition of cross spectral densities
      CHARACTER SC(256)
      CHARACTER*8 TYPE
      COMMON/ALPHA/TYPE(15),VAR,ISUP(10),IZSET(50),NZSET
      COMMON/GEO/HT,DIA,HMR,NHT,NDIA,NT,NREV,NEIG,NLOOP,NOUT,NSOFT
     1,NPMAX,NDIV,NVECT,NF,NRD,IPRINT,KTAB,KRAN,VMIN,DELF,FMIN,NSUP,CMIN
      COMMON/EIGEN/EIGV(120,3,22),GLOAD(512,37),EVALUE(22),IGLOAD(22)
      COMMON/SPECT/S(512,7),TRH(128,630)
      DIMENSION WORK(256),NC(256)
C  ignore suppressed dofs
        DO 1 I=1,NSUP
        IF(ISUP(I).EQ.II.OR.ISUP(I).EQ.JJ) RETURN
1       CONTINUE
C  smooth spectra by bracketing
      IF(NRD.GT.1) THEN
        DO 80 M=2,NF
        M1=NRD*(M-2)+2
        SUM1=0.
        SUM2=0.0
          DO 90 K=M1,M1+NRD-1
          SUM1=SUM1+S(K,1)
90        SUM2=SUM2+S(K,2)
        S(M,1)=SUM1
80      S(M,2)=SUM2
      ENDIF
C  print out real components ; first +ve then -ve
            DO 62 IS=1,2
            A=(-1.0)**(IS-1)
            SUM=0.0
              DO 50 M=1,NF
              WORK(M)=S(M,1)*A
              IF(WORK(M).LT.0.0) WORK(M)=0.0
              SUM=SUM+WORK(M)
50            CONTINUE
            IF(SUM.GE.VMIN*FMIN) THEN
              KRAN=KRAN+1
              WRITE(7,109)101,II,JJ,A,KRAN
109           FORMAT('RANDPS  ',3I8,F8.1,8X,I8)
              CALL PRINT(WORK)
            ENDIF
62          CONTINUE
C  print out imaginary components ; +ve and -ve values
            DO 63 IS=1,2
            A=(-1.0)**(IS-1)
            SUM=0.0
              DO 60 M=1,NF
              WORK(M)=S(M,2)*A
              IF(WORK(M).LT.0.0) WORK(M)=0.0
              SUM=SUM+WORK(M)
60            CONTINUE
C  supress output if variance is too small
            IF(SUM.GE.VMIN*FMIN) THEN
              KRAN=KRAN+1
              WRITE(7,110)101,II,JJ,A,KRAN
110           FORMAT('RANDPS  ',3I8,8X,F8.1,I8)
              CALL PRINT(WORK)
            ENDIF
63          CONTINUE
      RETURN
      END
```

EXAMPLE OF AN INPUT FILE FOR PROGRAM TRES4

```
$ TRESL.DAT supplies basic data for turbulent response of SNL 34m VAWT
$
$ HT     DIA     HMR     RPM    VBAR    WSE   DELT    ARHO in free format
1780.0  1320.   1134.   37.5   45.0   0.16   0.24   0.0766
$
$ C1X   C2X    C1Y    C2Y    ZO    DECAY   VAR NSOFT FMIN   CMIN   in free format
11.87 192.   4.00   70.0  .001 .001    0.300  1    0.25   2.E3
$
$ TURBULENCE SPECTRUM TYPE # free format
1
$
$ NHT,NDIA,NEIG,NT,NREV,NSECT,NLOOP,NPMAX,NDIV,NOUT,NSUP in free format
   6    4    20    16   16     9     20      7      4    10     0
$
$ INCLUDE DYNAMIC STALL? "YES" OR "NO ", A3 FORMAT
YES
$ INCLUDE COLUMN LOADING? "YES" OR "NO ", A3 FORMAT
YES
$ USE A REDUCED ZSET OF BLADE NODES?
YES
$ select option (1,2,or 3) for printing of cross spectra (free format)
1
$ NSECT(I,TYPE(I), CH(I)) in  format (I4,A8,F10.2)
   1NACA0021 48.0
   2NACA0021 48.0
   3NACA0021 48.0
   4NACA0021 48.0
   5SNLA1850 42.0
   6SNLA1850 42.0
   7SNLA1850 42.0
   8SNLA1850 36.0
   9SNLA1850 36.0
$ eigenvalue numbers and associated critical damping factors, free format
$ default value=.00 If no input, enter one dummy line, then end with "$"
2,0.00
$
$ list of eigenvectors to be suppressed (one to a line, free format)
  18
  19
$ end
```

APPENDIX B. PROGRAM AEROB5

B.1 Documentation

B.2 Listing (alphabetically by subroutine name)

B.3 Sample Input File

B.1 DOCUMENTATION

The purpose of this program is to prepare NASTRAN DMIG input according to the equations presented in Section 3.1 and according to the geometry blade properties etc. of the particular wind turbine. Some documentation is included as comment cards in the listing (see B.2) and some additional clarification is given below.

Language. The program was written for a Microsoft FORTRAN 4.01 compiler. However the code should run without too many alterations on any FORTRAN compiler based on FORTRAN 77.

Input. The program prompts the user for the name of two input files. The first is the "input data file name", an example of which is included as B.3. The second prompt requires the file name containing the NASTRAN bulkdata. A third input file is assumed to be AIR2.DAT but this may be changed.

Output. Two output files are created. One, with the name DMIG.OUT, contains all of the DMIG cards with a header card and appropriate ECHOOFF and ECHOON cards. The second is named AEROB.OUT and contains an echo of much of the input information.

Flowchart. A schematic flowchart showing the calling relationship of the subroutines is shown in Figure B1.

Subroutine READ1. This routine reads in basic data from the input file. The meaning and value of the input variables can be obtained by examination of the output file AEROB.OUT. Included in this input are flags for the selection of rotational terms, apparent mass terms and whether a reduced ZSET of nodes is to be used.

The blade may be divided into up to 15 different section types (NSECT), corresponding to NASTRAN PBEAM ids 101 thru 115 and corresponding to different chord values. However, for reasons of storage and reality, the number of different airfoil types (NFOIL) is limited to five. It is, therefore, necessary to associate the section types with the correct airfoil type through the ITYPE vector.

Subroutine READ2. This routine reads all necessary information from the NASTRAN bulkdata file. This includes blade grid coordinates, blade beam element numbers and associated PBEAM numbers. It is necessary that the numbering of grid points and element numbers follow a convention: blade no. 1 nodes must begin with 100 and run sequentially, and blade elements must also start at 100 and run sequentially; PBEAM ids must start at 101 and be sequential.

The ZSET is defined by a card which must be inserted into the bulkdata file. It must begin with the letters "$ZSET" and up to twenty node numbers may then follow in ascending order and in I4 format.

Subroutine AIRDATA. This routine reads in airfoil data from file AIR2.DAT. This information is needed only to calculate the rate of change of the lift coefficient. This value is always close to 6.3.

Subroutine AEROEL organizes the preparation of the aeroelastic terms and writes some header lines onto the DMIG.OUT file. It consists of three main loops: one for the number of blades (assumed to be two), one for the number of selected blade grid points, and a third for the type of matrix terms (stiffness, damping or mass). At each grid point it examines both the "previous" element and the "next" element, calculating the respective terms and printing them using subroutine PRNT.

Subroutine MATRIX calculates the values for the three basic 6 x 6 matrices. The element matrices are transferred to correspond to the global coordinate system and corrections are made for blade #2 orientation.

Subroutine PRNT. This routine organizes the printing of the elements of the matrices as DMIG cards. It also deletes any elements having both real and imaginary parts with magnitudes below a certain value (CMIN).

Subroutine THEO returns the real and imaginary parts of the Theodorsen function which defines the phase of certain aeroelastic terms.

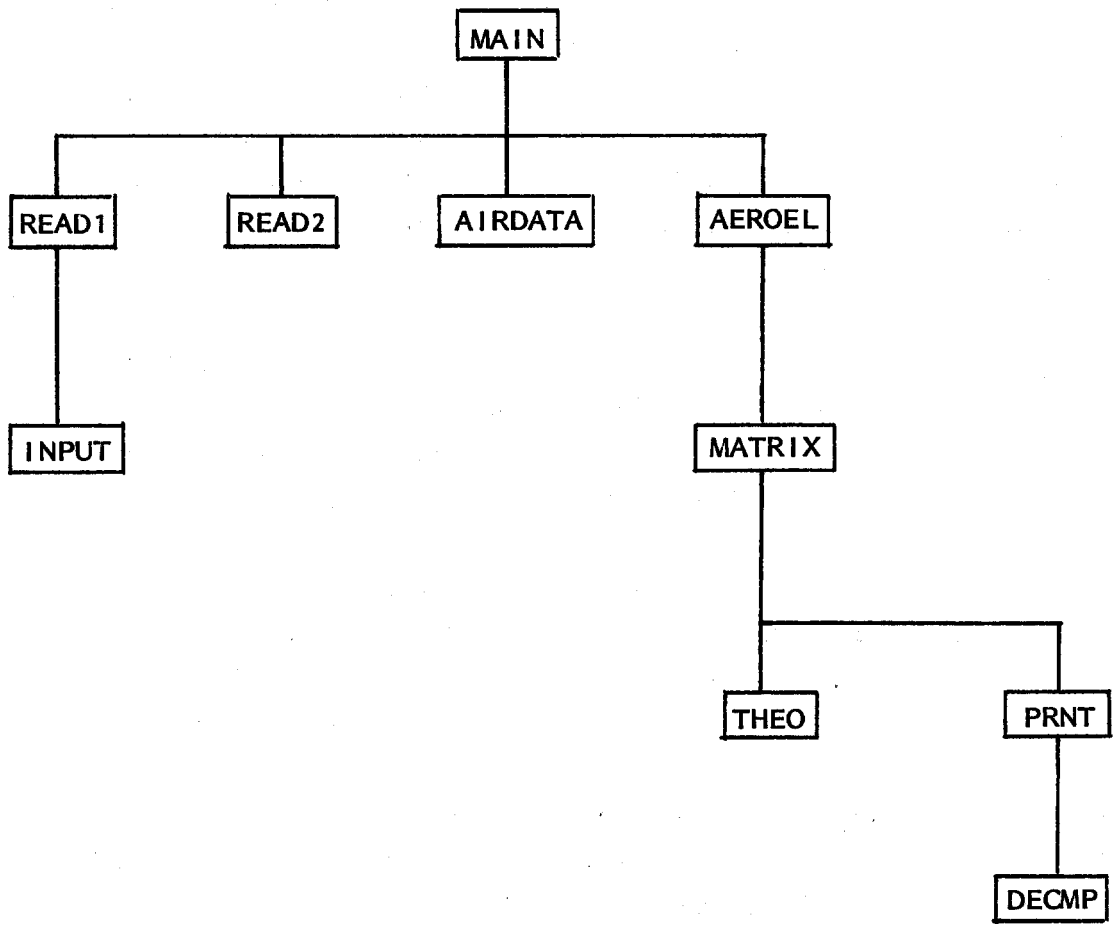


FIGURE B.1. Flowchart of Program AEROB5

```
      PROGRAM AEROB5
      WRITE(*,*)' enter input data file name'
      OPEN(1,FILE=' ')
      WRITE(*,*)' enter airfoil data file name'
      OPEN(2,FILE='AIR2.DAT')
      WRITE(*,*)' enter NASTRAN bulkdata filename'
      OPEN(5,FILE=' ')
      OPEN(6,FILE='AEROB.OUT')
      OPEN(4,FILE='DMIG.OUT')
      WRITE(6,111)
111   FORMAT(' AEROB5. AEROELASTIC TERMS INCLUDING APPARENT MASS AND
     1ALL',/,' ROTATING FRAME EFFECTS. D.J.MALCOLM MAY 88',/,' JULY 88
     2 : ZSET NODES USED AS APPROXIMATION. CORRECTIONS AUG88 ')
C
      CALL READ1
      CALL READ2
      CALL AIRDATA
      CALL AEROEL
      END
C
```

```
      SUBROUTINE AEROEL
C
C  organizes the preparation of aeroelastic stiffness, damping and mass terms
C  as DMIG cards
      CHARACTER*8 NAME,TYPE
      COMMON/ALPHA/TYPE(15),ITYPE(15),NZSET
      COMMON/BASIC/RPM,ARHO,NSECT,NFOIL,IROT,IZS,IMASS,AB,CMIN
      COMMON/BLADE/CH(15),R(50),Z(50),ICBEAM(50,2),NGRIDB,IZSET(50)
      COMMON/DMIG/SR1(6,6),SR2(6,6),SI1(6,6),SI2(6,6)
      COMMON/AERO/DEL,OMEGA,AIRHO,VR,EL,FLUT
      COMMON/COL/INDEX(50)
      OMEGA=RPM/9.549
      AIRHO=ARHO/386./1728.
      KTAB=5000
      WRITE(4,102)RPM,ARHO,FLUT,AB,CMIN,IROT,IMASS,IZS
102   FORMAT('$',/,'$ AEROELASTIC TERMS',/,'$ RPM=',F4.1,' ARHO=',F5.4,
     1' FLUT=',F4.1,' AB=',F3.1,' CMIN=', F4.1,' IROT=',I1,' IMASS=',I1,
     2' IZS=',I1)
C  loop on 2 blades
      DO 4 K=1,2
      IS=1
      IF(K.EQ.2) IS=-1
      WRITE(4,103)K
103   FORMAT('$',/,'$ BLADE NO',I2,/,'$')
C  loop on ZSET blade nodes (identical to full set if IZS=0)
        DO 1 L=2,NZSET-1
C  identify current and previous node IDs
        II=IZSET(L)-100+1
        IIM1=IZSET(L-1)-100+1
        IIP1=IZSET(L+1)-100+1
        ID=II+K*100-1
        IDM1=IIM1+K*100-1
        IDP1=IIP1+K*100-1
        IF(L.EQ.3) WRITE(4,100)
100     FORMAT('ECHOOFF')
C  loop on stiffness, damping & mass terms
          DO 1 JJ=1,3
          NAME='SOFTNING'
          IF(JJ.EQ.2) NAME='  CORIOL'
          IF(JJ.EQ.3) NAME='APRTMASS'
C  generate terms associated with preceding element
C
C  select blade type and airfoil type
          KS=ICBEAM(II,2)-100
          KA=ITYPE(KS)
C  define element slope and length
          DR=R(II)-R(IIM1)
          DZ=Z(II)-Z(IIM1)
          EL=SQRT(DR*DR+DZ*DZ)
          DEL=ATAN(DR/DZ)
          RMEAN=(R(II)+R(IIM1))/2.
C  define mean relative windspeed
          VR=OMEGA*RMEAN
C  basic aero terms
          CALL MATRIX(JJ,KS,KA,IS)
C  prepare and print current-preceding matrix terms
            DO 2 I=1,6
            DO 2 J=1,6
            SR2(I,J)=SR1(I,J)/2.
2           SI2(I,J)=SI1(I,J)/2.
```

```
              CALL PRNT(SR2,SI2,NAME,IDM1,ID,KTAB)
C  generate terms associated with next element
            KS=ICBEAM(IIP1,2)-100
            KA=ITYPE(KS)
C  element length and slope
            DR=R(IIP1)-R(II)
            DZ=Z(IIP1)-Z(II)
            EL=SQRT(DR*DR+DZ*DZ)
            DEL=ATAN(DR/DZ)
            RMEAN=(R(IIP1)+R(II))/2.
C   relative windspeed
            VR=OMEGA*RMEAN
C  basic aero terms
            CALL MATRIX(JJ,KS,KA,IS)
C  add terms to current-current matrix; prepare current-next terms
              DO 3 I=1,6
              DO 3 J=1,6
              SR1(I,J)=SR1(I,J)+SR2(I,J)*2.
              SI1(I,J)=SI1(I,J)+SI2(I,J)*2.
              SR2(I,J)=(SR1(I,J)-2*SR2(I,J))/2.
3             SI2(I,J)=(SI1(I,J)-2*SI2(I,J))/2.
C  print current-current terms
            CALL PRNT(SR1,SI1,NAME,ID,ID,KTAB)
C  print current-next terms
            CALL PRNT(SR2,SI2,NAME,IDP1,ID,KTAB)
1         CONTINUE
4       CONTINUE
      WRITE(4,101)
101   FORMAT('ECHOON')
      RETURN
      END
```

```
      SUBROUTINE AIRDATA
C
C  reads and stores the required airfoil datasets with corresponding Reynolds
C  numbers, static stall, and Cdmin. This information is used to calc lift
C  coefficient per radian. As an approximation this routine could be omitted
C  and  a value of 2.0*PI used.
      CHARACTER*8 TYPE,AA,NAME
      COMMON/ALPHA/TYPE(15),ITYPE(15),NZSET
      COMMON/BASIC/RPM,ARHO,NSECT,NFOIL,IROT,IZS,IMASS,AB,CMIN
      COMMON/BLADE/CH(15),R(50),Z(50),ICBEAM(50,2),NGRIDB,IZSET(50)
      COMMON/AIRFOIL/DSET(5,50,11),RE(5,5),AS(5,5),CDMIN(5,5),NRE(5)
      COMMON/STORE/TC(5),NA(5),DSET1(50,2),ANG(50)
C
C loop on no of airfoils.
      DO 9 I=1,NFOIL
C  search for airfoil name
      J1=0
11    J1=J1+1
      IF(J1.LE.NSECT) THEN
        IF(ITYPE(J1).NE.I) GO TO 11
        NAME=TYPE(J1)
      ELSE
        WRITE(6,*)' ERROR IN  READAIR'
        STOP
      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.NAME) 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
```

```
      SUBROUTINE DECMP(E,SE,NE,NN)
C decomposes vector E into exponential form
      CHARACTER SE(6)
      DIMENSION E(6),NE(6)
      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 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
```

```
      SUBROUTINE MATRIX(JJ,KS,KA,IS)
C
C  formulates the basic 6x6 matrices
      COMMON/BASIC/RPM,ARHO,NSECT,NFOIL,IROT,IZS,IMASS,AB,CMIN
      COMMON/DMIG/SR1(6,6),SR2(6,6),SI1(6,6),SI2(6,6)
      COMMON/AERO/DEL,OMEGA,AIRHO,VR,EL,FLUT
      COMMON/BLADE/CH(15),R(50),Z(50),ICBEAM(50,2),NGRIDB,IZSET(50)
      COMMON/AIRFOIL/DSET(5,50,11),RE(5,5),AS(5,5),CDMIN(5,5),NRE(5)
      DIMENSION XR(6),XI(6),RR(6,6)
C  zero matrices
        DO 1 I=1,6
          DO 1 J=1,6
          SR1(I,J)=0.0
1         SI1(I,J)=0.0
C  basic parameter values
      C=COS(DEL)
      S=SIN(DEL)
      B=CH(KS)/2.
      D1=B*(AB+.5)
      D2=B*(AB-.5)
      W=OMEGA*IROT
      BB=B*B*W*W/2./VR/VR
C  calc Theodorsen function (real and imaginary)
      CALL THEO(CR,CI,CH(KS))
C  basic matrix for stiffness terms
      IF(JJ.EQ.1) THEN
C  real part
        SR1(1,1)=C*C*BB/B
        SR1(1,2)=CR*W*C/VR
        SR1(1,3)=C*S*BB/B
        SR1(1,4)=-C*S*AB*BB
        SR1(1,5)=B*W*S/2./VR*(CR*(1.-2*AB)+1.)
        SR1(1,6)=+CR-AB*S*S*BB
        SR1(6,1)=-AB*BB*C*C
        SR1(6,2)=-D1*CR*W*C/VR
        SR1(6,3)=-AB*BB*C*S
        SR1(6,4)=-(AB*AB+.125)*BB*B*C*S
        SR1(6,5)=-B*W*S/2./VR*(CR*(1.-2.*AB)*D1+D2)
        SR1(6,6)=-(AB*AB+.125)*BB*B*S*S+CR*D1
C  imaginary part
        SI1(1,2)=CI*W*C/VR
        SI1(1,5)=B*W/2./VR*S*CI*(1.-2.*AB)
        SI1(1,6)=+CI
        SI1(6,2)=-D1*CI*W*C/VR
        SI1(6,5)=-B*W*S/2./VR*CI*(1.-2.*AB)*D1
        SI1(6,6)=CI*D1
C  damping matrix terms
      ELSEIF(JJ.EQ.2) THEN
        SR1(1,1)=-CR/VR
        SR1(1,2)=B*W*C/VR/VR
        SR1(1,5)=-AB*B*B*W*S/VR/VR
        SR1(1,6)=-B/2./VR*(CR*(1.-2.*AB)+1.)
        SR1(6,1)=D1*CR/VR
        SR1(6,2)=-AB*B*B*W*C/VR/VR
        SR1(6,5)=-(AB*AB+.125)*B**3*W*S/VR/VR
        SR1(6,6)=B/2./VR*(CR*(1.-2*AB)*D1+D2)
        SI1(1,1)=-CI/VR
        SI1(1,6)=-B/2./VR*CI*(1.-2.*AB)
        SI1(6,1)=D1*CI/VR
        SI1(6,6)=B/2./VR*CI*(1.-2.*AB)*D1
```

```
C  mass matrix terms (matrix is entirely real)
      ELSEIF(JJ.EQ.3) THEN
        SR1(1,1)=-B/2./VR/VR*IMASS
        SR1(1,6)=AB*B*B/2./VR/VR*IMASS
        SR1(6,1)=AB*B*B/2./VR/VR*IMASS
        SR1(6,6)=(AB*AB+.125)*B**3/2./VR/VR*IMASS
      ENDIF
C  calc Cl-angle relationship
      AL=(DSET(KA,2,2)-DSET(KA,1,2))/(DSET(KA,2,1)-DSET(KA,1,1))*57.3
C  combine with element length, chord, air density
      AL=AL*B*AIRHO*EL*VR*VR/3.
C  prepare orientation transformation
        DO 2 I=1,6
          DO 2 J=1,6
2         RR(I,J)=0.0
      RR(1,1)=C*IS
      RR(1,3)=S*IS
      RR(2,2)=1.*IS
      RR(3,1)=-S
      RR(3,3)=C
      RR(4,4)=C*IS
      RR(4,6)=S*IS
      RR(5,5)=1.*IS
      RR(6,4)=-S
      RR(6,6)=C
C  calc X=SxR(T)
        DO 4 I=1,6
          DO 6 J=1,6
          XR(J)=0.
          XI(J)=0.
            DO 6 K=1,6
            XR(J)=XR(J)+SR1(I,K)*RR(J,K)
6           XI(J)=XI(J)+SI1(I,K)*RR(J,K)
          DO 4 J=1,6
          SR1(I,J)=XR(J)
4         SI1(I,J)=XI(J)
C  calc S=RxX x common parameters
        DO 5 J=1,6
          DO 7 I=1,6
          XR(I)=0.
          XI(I)=0.
            DO 7 K=1,6
            XR(I)=XR(I)+SR1(K,J)*RR(I,K)
7           XI(I)=XI(I)+SI1(K,J)*RR(I,K)
C  introduce -ve sign to convert from RHS to LHS of equations
          DO 5 I=1,6
          SR1(I,J)=-XR(I)*AL
5         SI1(I,J)=-XI(I)*AL
      RETURN
      END
```

```
      SUBROUTINE PRNT(AR,AI,NAME,ID1,ID2,KTAB)
C
C  prints DMIG cards (real and imaginary parts)
      CHARACTER SCR(6),SCI(6)
      CHARACTER*8 NAME
      COMMON/BASIC/RPM,ARHO,NSECT,NFOIL,IROT,IZS,IMASS,AB,CMIN
      DIMENSION AR(6,6),AI(6,6),VR(6),VI(6),IC(6),NCR(6),NCI(6)
C  loop on columns
        DO 1 J=1,6
C  check for terms above minimum and reorganize
        NI=0
          DO 2 I=1,6
          IF(ABS(AR(I,J)).GE.CMIN.OR.ABS(AI(I,J)).GE.CMIN) THEN
            NI=NI+1
            VR(NI)=AR(I,J)
            VI(NI)=AI(I,J)
            IC(NI)=I
          ENDIF
2         CONTINUE
C  reformat output in exponential form
        CALL DECMP(VR,SCR,NCR,NI)
        CALL DECMP(VI,SCI,NCI,NI)
C  write NASTRAN DMIG cards
        IF(NI.GE.1) THEN
          IF(NI.EQ.1) THEN
            WRITE(4,100)NAME,ID1,J,ID2,IC(1),VR(1),SCR(1),NCR(1),VI(1),
     1                  SCI(1),NCI(1)
100         FORMAT('DMIG    ',A8,2I8,8X,2I8,2(F6.4,A1,I1))
          ELSE
            KTAB=KTAB+1
            WRITE(4,101)NAME,ID1,J,ID2,IC(1),VR(1),SCR(1),NCR(1),VI(1),
     1                  SCI(1),NCI(1),KTAB
101         FORMAT('DMIG    ',A8,2I8,8X,2I8,2(F6.4,A1,I1),'+TAB',I4)
          ENDIF
C  continuation cards
          II=2
3         IF(NI-II.GE.2) THEN
            WRITE(4,102)KTAB,(ID2,IC(L),VR(L),SCR(L),NCR(L),VI(L),SCI(L)
     1                  ,NCI(L),L=II,II+1),KTAB+1
102         FORMAT('+TAB',I4,2(2I8,2(F6.4,A1,I1)),'+TAB',I4)
            II=II+2
            KTAB=KTAB+1
            GO TO 3
          ELSEIF(NI-II.EQ.1) THEN
            WRITE(4,103)KTAB,(ID2,IC(L),VR(L),SCR(L),NCR(L),VI(L),SCI(L)
     1                  ,NCI(L),L=II,II+1)
103         FORMAT('+TAB',I4,2(2I8,2(F6.4,A1,I1)))
          ELSEIF(NI-II.EQ.0) THEN
            WRITE(4,104)KTAB,(ID2,IC(L),VR(L),SCR(L),NCR(L),VI(L),SCI(L)
     1                  ,NCI(L),L=II,II)
104         FORMAT('+TAB',I4,2I8,2(F6.4,A1,I1))
          ENDIF
        ENDIF
1       CONTINUE
      RETURN
      END
```

```
      SUBROUTINE READ1
C
C  reads in some basic data from unit #1 and writes to unit #6
      CHARACTER*3 BB, AROT, AMASS, AZS
      CHARACTER*8 TYPE
      COMMON/BASIC/RPM, ARHO, NSECT, NFOIL, IROT, IZS, IMASS, AB, CMIN
      COMMON/ALPHA/TYPE(15), ITYPE(15), NZSET
      COMMON/BLADE/CH(15), R(50), Z(50), ICBEAM(50,2), NGRIDB, IZSET(50)
      COMMON/AERO/DEL, OMEGA, AIRHO, VR, EL, FLUT
      CALL INPUT(1)
      READ(1,*) RPM, ARHO, FLUT, AB, CMIN, NSECT
      CALL INPUT(1)
      READ(1,100) AROT
100   FORMAT(A3)
      IROT=0
      IF(AROT.EQ.'YES') IROT=1
      CALL INPUT(1)
      READ(1,100) AMASS
      IMASS=0
      IF(AMASS.EQ.'YES') IMASS=1
      CALL INPUT(1)
      READ(1,100) AZS
      IZS=0
      IF(AZS.EQ.'YES')  IZS=1
      WRITE(6,109) RPM, RPM/9.549
      WRITE(6,112) ARHO
      WRITE(6,113) FLUT
      WRITE(6,114) AB
      WRITE(6,115) AROT
      WRITE(6,116) AMASS
      WRITE(6,143) AZS
      WRITE(6,117) CMIN
109   FORMAT('  ROTOR SPEED                    =',F6.1,'  RPM   =',F5.3,'  RAD/S'
     1)
112   FORMAT('  AIR DENSITY                    =',F6.4,'  LB/FT3')
113   FORMAT('  FLUTTER FREQUENCY              =',F6.3,'  HZ')
114   FORMAT('  C OF TWIST TO MID CHORD        =',F6.3,'  *CHORD/2')
115   FORMAT('  ROTATIONAL TERMS INCLUDED          ',A3)
116   FORMAT('  APPARENT MASS INCLUDED             ',A3)
117   FORMAT('  MIN VALUE IN OUTPUT            =',F6.1)
143   FORMAT('  ZSET USED?                         ',A3)
C  read data on airfoil names, chords
      CALL INPUT(1)
      WRITE(6,105)
105   FORMAT(/,'SECTION# FOIL# FOIL-TYPE   CHORD(IN)    ')
      K=0
        DO 2 I=1,NSECT
        READ(1,138) II, TYPE(I), CH(I)
138     FORMAT(I4, A8, F10.2)
        J=0
5       J=J+1
        IF(J.LT.I) THEN
          IF(TYPE(I).NE.TYPE(J)) GO TO 5
          ITYPE(I)=ITYPE(J)
        ELSE
          K=K+1
          ITYPE(I)=K
        ENDIF
2       CONTINUE
      NFOIL=K
      WRITE(6,137)(I, ITYPE(I), TYPE(I), CH(I), I=1,NSECT)
137   FORMAT(2I6, 2X, A8, F8.2)
      RETURN
      END
```

```
      SUBROUTINE READ2
C
C reads required NASTRAN data and writes to unit #6
      CHARACTER*8 TYPE
      CHARACTER*5 BB
      CHARACTER*4 AA
      COMMON/BASIC/RPM, ARHO, NSECT, NFOIL, IROT, IZS, IMASS, AB, CMIN
      COMMON/ALPHA/TYPE(15), ITYPE(15), NZSET
      COMMON/BLADE/CH(15), R(50), Z(50), ICBEAM(50,2), NGRIDB, IZSET(50)
      COMMON/COL/INDEX(50)
      NGRIDB=0
      NCBEAM=0
1     READ(5,100) AA
100   FORMAT(A4,3A8)
      IF(AA.EQ.'GRID') THEN
        BACKSPACE 5
        READ(5,101) II, RR, ZZ
101     FORMAT(8X,I8,8X,F8.2,8X,F8.2)
        IF(II.GE.100.AND.II.LT.200) THEN
C  blade #1 coordinates
          NGRIDB=NGRIDB+1
          INDEX(NGRIDB)=II
          R(NGRIDB)=RR
          Z(NGRIDB)=ZZ
        ENDIF
      ELSEIF(AA.EQ.'CBEA') THEN
        BACKSPACE 5
        READ(5,102) IB, IP
102     FORMAT(8X,2I8)
        IF(IB.GE.100.AND.IB.LT.200) THEN
C  blade #1 elements
          NCBEAM=NCBEAM+1
          ICBEAM(NCBEAM,1)=IB
          ICBEAM(NCBEAM,2)=IP
        ENDIF
C  read ZSET nodes for blade #1
      ELSEIF(AA.EQ.'$ZSE') THEN
        BACKSPACE 5
        READ(5,107)(IZSET(I), I=1,20)
107     FORMAT(5X,20I4)
        NZSET=0
2       NZSET=NZSET+1
        IF(IZSET(NZSET+1).GT.0) THEN
          GO TO 2
        ENDIF
      ENDIF
      IF(AA.NE.'ENDD') GO TO 1
      WRITE(6,106) NGRIDB
106   FORMAT(/,' # OF NODES ON BLADE        =',I6)
C  if ZSET not used then replace with complete set of blade nodes
      IF(IZS.EQ.0) THEN
        NZSET=NGRIDB
          DO 5 I=1,NGRIDB
5         IZSET(I)=I+100-1
      ELSE
        WRITE(6,108)(IZSET(I), I=1,NZSET)
108     FORMAT(/,' ZSET=',20I4)
      ENDIF
      RETURN
      END
```

```
      SUBROUTINE THEO(CR,CI,CH)
C  calcs the real and imaginary parts of the current Theodorsen function
C  (see Lobitz+Ashwill paper - with sign correction)
      COMMON/AERO/DEL,OMEGA,AIRHO,VR,EL,FLUT
      A1=0.165
      A2=0.0455
      A3=0.335
      B=CH/2.
      AK=FLUT*6.283*B/VR
      C1=AK*AK+A2*A2
      C2=AK*AK+0.09
      CR=1.-A1*AK*AK/C1 - A3*AK*AK/C2
      CI=-A1*A2*AK/C1 - A3*0.3*AK/C2
      RETURN
      END
```

EXAMPLE OF AN INPUT FILE FOR PROGRAM AEROB5

```
$ AEROBSL.DAT data for SNL 34M ROTOR  . AEROB program.
$   RPM   ARHO   FLUT  AB  CMIN  NSECT (free format)
   37.5  0.0766  4.0  -.2   0.1    9
$ rotational terms included? (A3 format)
YES
$ apparent mass terms included? (A3 format)
NO
$ ZSET used? "YES/NO" free format
YES
$   I  ,TYPE(I), CH(I) in  format (I4,A8,F10.2)
   1NACA0021 48.0
   2NACA0021 48.0
   3NACA0021 48.0
   4NACA0021 48.0
   5SNLA1850 42.0
   6SNLA1850 42.0
   7SNLA1850 42.0
   8SNLA1850 36.0
   9SNLA1850 36.0
```

APPENDIX C

LISTING OF NASTRAN BULKDATA FOR SNL 34-M

```
$
BEGIN BULK
$ D MALCOLM VERSION OF ATEST.DAT.  MODIFIED TO "11-87 MODEL" MARCH'88
$ PBEAM STRESS RECOVERY MODIFIED 18 MARCH 88.  LOCAL COORDS MODIFIED
$ COLUMN CONNECTIONS
CBEAM       1      10       1       2    1.00
CBEAM       2      10       2       3    1.00
CBEAM       3      10       3       4    1.00
CBEAM       4      20       4       5    1.00
CBEAM       5      30       5       6    1.00
CBEAM       6      30       6       7    1.00
CBEAM       7      30       7       8    1.00
CBEAM       8      30       8       9    1.00
CBEAM       9      30       9      10    1.00
CBEAM      10      30      10      11    1.00
CBEAM      11      30      11      12    1.00
CBEAM      12      30      12      13    1.00
CBEAM      13      30      13      14    1.00
CBEAM      14      30      14      15    1.00
CBEAM      15      30      15      16    1.00
CBEAM      16      30      16      17    1.00
CBEAM      17      30      17      18    1.00
CBEAM      18      30      18      19    1.00
CBEAM      19      30      19      20    1.00
CBEAM      20      30      20      21    1.00
CBEAM      21      30      21      22    1.00
CBEAM      22      30      22      23    1.00
CBEAM      23      40      23      24    1.00
CBEAM      24      50      24      25    1.00
CBEAM      25      50      25      26    1.00
$ BLADE 1 CONNECTIONS
CBEAM     100      60      24     100    1.00    0.00    1.00
CBEAM     101     101     100     101    1.00    0.00    0.00
CBEAM     102     101     101     102    1.00    0.00    0.00
CBEAM     103     102     102     103    1.00    0.00    0.00
CBEAM     104     103     103     104    1.00    0.00    0.00
CBEAM     105     103     104     105    1.00    0.00    0.00
CBEAM     106     103     105     106    1.00    0.00    0.00
CBEAM     107     103     106     107    1.00    0.00    0.00
CBEAM     108     104     107     108    1.00    0.00    0.00
CBEAM     109     105     108     109    1.00    0.00    0.00
CBEAM     110     106     109     110    1.00    0.00    0.00
CBEAM     111     106     110     111    1.00    0.00    0.00
CBEAM     112     106     111     112    1.00    0.00    0.00
CBEAM     113     106     112     113    1.00    0.00    0.00
CBEAM     114     106     113     114    1.00    0.00    0.00
CBEAM     115     107     114     115    1.00    0.00    0.00
CBEAM     116     108     115     116    1.00    0.00    0.00
CBEAM     117     109     116     117    1.00    0.00    0.00
CBEAM     118     109     117     118    1.00    0.00    0.00
CBEAM     119     109     118     119    1.00    0.00    0.00
CBEAM     120     109     119     120    1.00    0.00    0.00
CBEAM     121     109     120     121    1.00    0.00    0.00
CBEAM     122     109     121     122    1.00    0.00    0.00
CBEAM     123     109     122     123    1.00    0.00    0.00
CBEAM     124     109     123     124    1.00    0.00    0.00
CBEAM     125     109     124     125    1.00    0.00    0.00
CBEAM     126     109     125     126    1.00    0.00    0.00
CBEAM     127     108     126     127    1.00    0.00    0.00
CBEAM     128     107     127     128    1.00    0.00    0.00
```

```
CBEAM        129     106     128     129     1.00     0.00     0.00
CBEAM        130     106     129     130     1.00     0.00     0.00
CBEAM        131     106     130     131     1.00     0.00     0.00
CBEAM        132     106     131     132     1.00     0.00     0.00
CBEAM        133     106     132     133     1.00     0.00     0.00
CBEAM        134     105     133     134     1.00     0.00     0.00
CBEAM        135     104     134     135     1.00     0.00     0.00
CBEAM        136     103     135     136     1.00     0.00     0.00
CBEAM        137     103     136     137     1.00     0.00     0.00
CBEAM        138     103     137     138     1.00     0.00     0.00
CBEAM        139     103     138     139     1.00     0.00     0.00
CBEAM        140     102     139     140     1.00     0.00     0.00
CBEAM        141     101     140     141     1.00     0.00     0.00
CBEAM        142     101     141     142     1.00     0.00     0.00
CBEAM        143      60     142       4     1.00     0.00    -1.00
$ BLADE 1 STRUTS
CBEAM       1000     250      23    1000     1.00     0.00     1.00
CBEAM       1001     260    1000     102     1.00     0.00     1.00
CBEAM       1002     250       5    1001     1.00     0.00    -1.00
CBEAM       1003     260    1001     140     1.00     0.00    -1.00
$ BLADE 2 CONNECTIONS
CBEAM        200      60      24     200    -1.00     -.00     1.00
CBEAM        201     101     200     201    -1.00     -.00     0.00
CBEAM        202     101     201     202    -1.00     -.00     0.00
CBEAM        203     102     202     203    -1.00     -.00     0.00
CBEAM        204     103     203     204    -1.00     -.00     0.00
CBEAM        205     103     204     205    -1.00     -.00     0.00
CBEAM        206     103     205     206    -1.00     -.00     0.00
CBEAM        207     103     206     207    -1.00     -.00     0.00
CBEAM        208     104     207     208    -1.00     -.00     0.00
CBEAM        209     105     208     209    -1.00     -.00     0.00
CBEAM        210     106     209     210    -1.00     -.00     0.00
CBEAM        211     106     210     211    -1.00     -.00     0.00
CBEAM        212     106     211     212    -1.00     -.00     0.00
CBEAM        213     106     212     213    -1.00     -.00     0.00
CBEAM        214     106     213     214    -1.00     -.00     0.00
CBEAM        215     107     214     215    -1.00     -.00     0.00
CBEAM        216     108     215     216    -1.00     -.00     0.00
CBEAM        217     109     216     217    -1.00     -.00     0.00
CBEAM        218     109     217     218    -1.00     -.00     0.00
CBEAM        219     109     218     219    -1.00     -.00     0.00
CBEAM        220     109     219     220    -1.00     -.00     0.00
CBEAM        221     109     220     221    -1.00     -.00     0.00
CBEAM        222     109     221     222    -1.00     -.00     0.00
CBEAM        223     109     222     223    -1.00     -.00     0.00
CBEAM        224     109     223     224    -1.00     -.00     0.00
CBEAM        225     109     224     225    -1.00     -.00     0.00
CBEAM        226     109     225     226    -1.00     -.00     0.00
CBEAM        227     108     226     227    -1.00     -.00     0.00
CBEAM        228     107     227     228    -1.00     -.00     0.00
CBEAM        229     106     228     229    -1.00     -.00     0.00
CBEAM        230     106     229     230    -1.00     -.00     0.00
CBEAM        231     106     230     231    -1.00     -.00     0.00
CBEAM        232     106     231     232    -1.00     -.00     0.00
CBEAM        233     106     232     233    -1.00     -.00     0.00
CBEAM        234     105     233     234    -1.00     -.00     0.00
CBEAM        235     104     234     235    -1.00     -.00     0.00
CBEAM        236     103     235     236    -1.00     -.00     0.00
CBEAM        237     103     236     237    -1.00     -.00     0.00
CBEAM        238     103     237     238    -1.00     -.00     0.00
```

```
CBEAM        239     103     238     239   -1.00    -.00    0.00
CBEAM        240     102     239     240   -1.00    -.00    0.00
CBEAM        241     101     240     241   -1.00    -.00    0.00
CBEAM        242     101     241     242   -1.00    -.00    0.00
CBEAM        243      60     242       4   -1.00    -.00    1.00
$ BLADE 2 STRUTS
CBEAM       2000     250      23    2000   -1.00    -.00    1.00
CBEAM       2001     260    2000     202   -1.00    -.00    1.00
CBEAM       2002     250       5    2001   -1.00    -.00   -1.00
CBEAM       2003     260    2001     240   -1.00    -.00   -1.00
$ LOWER RESTRAINTS
GRID       15000            1.000   0.000   0.000           123456
CELAS2     10000.300E+07      1       1   15000       1
CELAS2     10001.300E+07      1       2   15000       2
CELAS2     10002.200E+08      1       6   15000       6
CDAMP2      9000  1.0E07       1       6   15000       6
$ UPPER RESTRAINTS
GRID       15003                        1768.98           123456
CELAS2     10003.480E+05     26       1   15003       1
CELAS2     10004.480E+05     26       2   15003       2
$ CONCENTRATED MASSES
CONM2       5000       2        6100.00
CONM2       5001       4       10084.00
CONM2       5002      11        2910.00
CONM2       5003      17        2910.00
CONM2       5004      23        9200.00
CONM2       5005      26       25300.00
CONM2       5006     101         459.00
CONM2       5007     141         856.00
CONM2       5008     201         459.00
CONM2       5009     241         856.00
$
EIGR    21      MGIV                          22                        +BC
+BC     MAX
EIGC,11,HESS,MAX,,,,,,+EIGC1
+EIGC1,0.,10.7,0.,13.2,3.,1,12
$
FORCE,103,   26,0,.320E+06,0.,0.,-1.
GRAV         101          386.40     0.0     0.0    -1.0
LOAD,100,1.,1.,101,1.,102,1.,103
RFORCE       102                    0.625     0.0     0.0     1.0       2
$ COLUMN POINTS
GRID           1          0.000   0.000   0.000                3          1.00
GRID           2          0.000   0.000  33.667                          1.00
GRID           3          0.000   0.000  67.333                        120.00
GRID           4          0.000   0.000 101.000
GRID           5          0.000   0.000 151.000
GRID           6          0.000   0.000 234.332
GRID           7          0.000   0.000 317.665
GRID           8          0.000   0.000 400.997
GRID           9          0.000   0.000 484.329
GRID          10          0.000   0.000 567.662
GRID          11          0.000   0.000 650.994
GRID          12          0.000   0.000 734.327
GRID          13          0.000   0.000 817.659
GRID          14          0.000   0.000 900.991
GRID          15          0.000   0.000 984.324
GRID          16          0.000   0.0001067.660
GRID          17          0.000   0.0001150.990
GRID          18          0.000   0.0001234.320
```

```
GRID          19          0.000   0.0001317.650
GRID          20          0.000   0.0001400.990
GRID          21          0.000   0.0001484.320
GRID          22          0.000   0.0001567.650
GRID          23          0.000   0.0001650.980
GRID          24          0.000   0.0001700.980
GRID          25          0.000   0.0001734.980                    120.00
GRID          26          0.000   0.0001768.980
$ BLADE 1 POINTS
GRID         100         36.000   0.0001700.980
GRID         101         69.762   0.0001676.000
GRID         102        103.524   0.0001651.010
GRID         103        135.678   0.0001627.220
GRID         104        189.519   0.0001587.380
GRID         105        243.360   0.0001547.540
GRID         106        297.201   0.0001507.700
GRID         107        351.042   0.0001467.860
GRID         108        375.158   0.0001450.020
GRID         109        396.961   0.0001429.410
GRID         110        431.132   0.0001395.770
GRID         111        463.908   0.0001360.780
GRID         112        495.236   0.0001324.480
GRID         113        525.063   0.0001286.940
GRID         114        553.340   0.0001248.210
GRID         115        570.536   0.0001223.630
GRID         116        584.366   0.0001197.010
GRID         117        611.392   0.0001138.270
GRID         118        632.674   0.0001077.210
GRID         119        648.016   0.0001014.400
GRID         120        657.278   0.000 950.410
GRID         121        660.375   0.000 885.826
GRID         122        656.320   0.000 811.952
GRID         123        644.205   0.000 738.966
GRID         124        624.175   0.000 667.744
GRID         125        596.470   0.000 599.142
GRID         126        561.424   0.000 533.985
GRID         127        545.786   0.000 508.382
GRID         128        526.981   0.000 485.008
GRID         129        496.172   0.000 448.271
GRID         130        463.897   0.000 412.815
GRID         131        430.208   0.000 378.699
GRID         132        395.161   0.000 345.980
GRID         133        358.814   0.000 314.712
GRID         134        335.678   0.000 295.613
GRID         135        310.518   0.000 279.274
GRID         136        267.887   0.000 251.590
GRID         137        225.257   0.000 223.905
GRID         138        182.626   0.000 196.220
GRID         139        139.995   0.000 168.535
GRID         140        106.448   0.000 146.750
GRID         141         71.224   0.000 123.875
GRID         142         36.000   0.000 101.000
$ BLADE 1 STRUTS
GRID        1000         60.000   0.0001650.980
GRID        1001         60.000   0.000 151.000
$ BLADE 2 GRID POINTS
GRID         200        -36.000   -.0001700.980
GRID         201        -69.762   -.0001676.000
GRID         202       -103.524   -.0001651.010
GRID         203       -135.678   -.0001627.220
```

```
GRID          204          -189.519    -.0001587.380
GRID          205          -243.360    -.0001547.540
GRID          206          -297.201    -.0001507.700
GRID          207          -351.042    -.0001467.860
GRID          208          -375.158    -.0001450.020
GRID          209          -396.961    -.0001429.410
GRID          210          -431.132    -.0001395.770
GRID          211          -463.908    -.0001360.780
GRID          212          -495.236    -.0001324.480
GRID          213          -525.063    -.0001286.940
GRID          214          -553.340    -.0001248.210
GRID          215          -570.536    -.0001223.630
GRID          216          -584.366    -.0001197.010
GRID          217          -611.392    -.0001138.270
GRID          218          -632.674    -.0001077.210
GRID          219          -648.016    -.0001014.400
GRID          220          -657.278    -.000 950.410
GRID          221          -660.375    -.000 885.826
GRID          222          -656.320    -.000 811.952
GRID          223          -644.205    -.000 738.966
GRID          224          -624.175    -.000 667.744
GRID          225          -596.470    -.000 599.142
GRID          226          -561.424    -.000 533.985
GRID          227          -545.786    -.000 508.382
GRID          228          -526.981    -.000 485.008
GRID          229          -496.172    -.000 448.271
GRID          230          -463.897    -.000 412.815
GRID          231          -430.208    -.000 378.699
GRID          232          -395.161    -.000 345.980
GRID          233          -358.814    -.000 314.712
GRID          234          -335.678    -.000 295.613
GRID          235          -310.518    -.000 279.274
GRID          236          -267.887    -.000 251.590
GRID          237          -225.257    -.000 223.905
GRID          238          -182.626    -.000 196.220
GRID          239          -139.995    -.000 168.535
GRID          240          -106.448    -.000 146.750
GRID          241           -71.224    -.000 123.875
GRID          242           -36.000    -.000 101.000
$ BLADE 2 STRUTS
GRID         2000           -60.000    -.0001650.980
GRID         2001           -60.000    -.000 151.000
$ MATERIAL PROPERTIES
MAT1           10.290E+08.110E+08          .284E+00
MAT1           20.100E+08.400E+07          .978E-01
$
PBEAM          10       10.352E+03.352E+05.352E+05          .704E+05          +ESP0001
+ESP0001  16.000    0.000 -16.000    0.000    0.000 -16.000    0.000  16.000+PBE1001
+PBE1001    YESA      1.0
PBEAM          20       10.491E+03.240E+06.240E+06          .480E+06          +ESP0002
+ESP0002  32.500    0.000 -32.500    0.000    0.000 -32.500    0.000  32.500+PBE1002
+PBE1002    YESA      1.0
PBEAM          30       20.188E+03.335E+06.335E+06          .670E+06          +ESP0003
+ESP0003  60.000    0.000 -60.000    0.000    0.000 -60.000    0.000  60.000+PBE1003
+PBE1003    YESA      1.0
PBEAM          40       10.491E+03.240E+06.240E+06          .480E+06          +ESP0004
+ESP0004  32.500    0.000 -32.500    0.000    0.000 -32.500    0.000  32.500+PBE1004
+PBE1004    YESA      1.0
PBEAM          50       10.352E+03.352E+05.352E+05          .704E+05          +ESP0005
+ESP0005  16.000    0.000 -16.000    0.000    0.000 -16.000    0.000  16.000+PBE1005
```

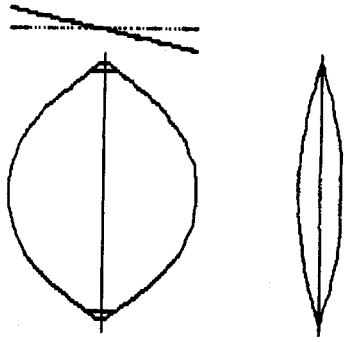
```
+PBE1005     YESA      1.0
PBEAM          60      10.100E+02.400E+05.800E+05          .400E+05
PBEAM         101      20.200E+03.400E+05.400E+05          .100E+05          +ESP0007
+ESP0007    5.145    0.000   -5.145    0.000    0.000 -22.900    0.000   26.100+PBE1007
+PBE1007     YESA      1.0
PBEAM         102      20.100E+03.100E+04.200E+05          .200E+04    11.30+ESP0008
+ESP0008    5.040    0.000   -5.040    0.000    0.000 -22.500    0.000   25.500+PBE1008
+PBE1008     YESA      1.0
PBEAM         103      20.574E+02.583E+03.945E+04          .143E+04     0.92+ESP0009
+ESP0009    5.040    7.100   -5.040    7.100   -0.737  21.700   -0.250 -25.700+PBE1009
+PBE1009     YESA     0.25                                                      +PBE1091
+PBE1091     YESA     0.50                                                      +PBE1092
+PBE1092     YESA     0.75                                                      +PBE1093
+PBE1093     YESA     1.00
PBEAM         104      20.847E+02.884E+03.150E+05          .220E+04     3.81+ESP0010
+ESP0010    5.145    0.000   -5.145    0.000    0.000 -22.400    0.000   26.600+PBE1010
+PBE1010     YESA      1.0
PBEAM         105      20.564E+02.321E+03.732E+04          .830E+03     3.50+ESP0011
+ESP0011    3.870    0.000   -3.870    0.000    0.000 -20.200    0.000   22.800+PBE1011
+PBE1011     YESA      1.0
PBEAM         106      20.327E+02.184E+03.398E+04          .478E+03     0.82+ESP0012
+ESP0012    3.780    2.100   -3.780    2.100   -0.375  19.400   -0.188 -21.800+PBE1012
+PBE1012     YESA     0.25                                                      +PBE1121
+PBE1121     YESA     0.40                                                      +PBE1122
+PBE1122     YESA     0.75                                                      +PBE1123
+PBE1123     YESA     1.00
PBEAM         107      20.564E+02.321E+03.732E+04          .830E+03     2.65+ESP0013
+ESP0013    3.870    0.000   -3.870    0.000    0.000 -20.200    0.000   22.800+PBE1013
+PBE1013     YESA      1.0
PBEAM         108      20.462E+02.195E+03.446E+04          .509E+03     2.17+ESP0014
+ESP0014    3.330    0.000   -3.330    0.000    0.000 -17.400    0.000   19.600+PBE1014
+PBE1014     YESA      1.0
PBEAM         109      20.260E+02.112E+03.236E+04          .296E+03     0.44+ESP0015
+ESP0015    3.240    1.600   -3.240    1.600   -0.375  16.700   -.2510 -18.600+PBE1015
+PBE1015     YESA      0.5                                                       +PBE1151
+PBE1151     YESA      1.0
PBEAM         250      10.100E+02.252E+06.504E+06          .252E+06
PBEAM         260      10.450E+02.200E+04.200E+05          .200E+04          +ESP0026
+ESP0026    1.050    0.000   -1.050    0.000    0.000 -21.000    0.000   21.000+PBE1026
+PBE1026     YESA      1.0
$ MASTER DEGREES OF FREEDOM FOR EIGENVALUE EXTRACTION
$ASET1,12,5,9,14,19,23,26
$ASET1,123,108,115,121,127,134
$ASET1,123,208,215,221,227,234
$
$ REDUCED SET FOR AERODYNAMIC CALCULATIONS (TRES4)
$ZSET 102 105 108 111 113 115 117 119 120 121 122 123 125 127 129 131 134 137 140
$ REDUCED SET FOR AEROELASTIC CALCULATIONS (AEROB5)
$ZSET 102 105 108 111 115 118 121 124 127 131 134 137 140
$
PARAM    WTMASS   .002588
PARAM    MAXRATIO 9.E12
$PARAM,LMODES,22
$PARAM,DDRMM,-1
$PARAM,G,0.04
$PARAM,MODACC,+1
$  ROTATING FRAME EFFECTS
$
PARAM    OMEGA      3.9270
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     1       3     0
DMIG    SOFTNING    4     1             4     1  .1E-09
DMIG    CORIOL      0     1       3     0
DMIG    CORIOL      4     1             4     2  .1E-09
DMIG    CORIOL      4     2             4     1  .1E-09
$
ENDDATA
```

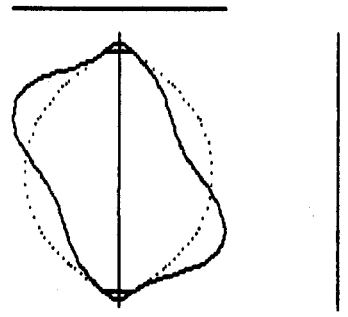
APPENDIX D

MODES OF VIBRATION OF STATIONARY SNL 34-M ROTOR

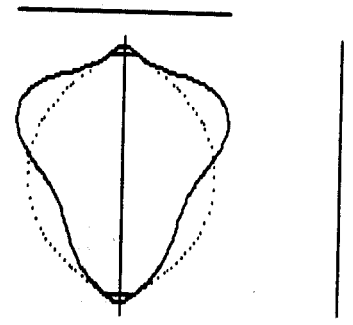
SNL34m REAL MODES 0RPM



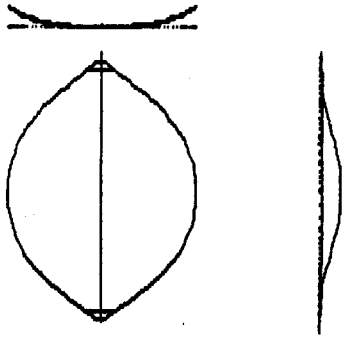
MODE#1 1P FREQ=0.22 Hz



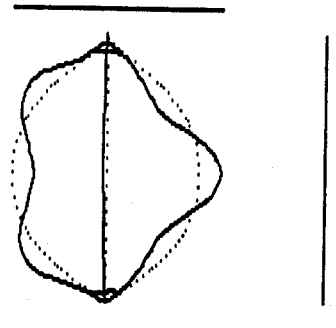
MODE#2 1FA FREQ=1.05 Hz



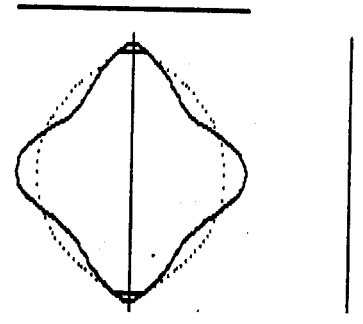
MODE#3 1FS FREQ=1.05 Hz



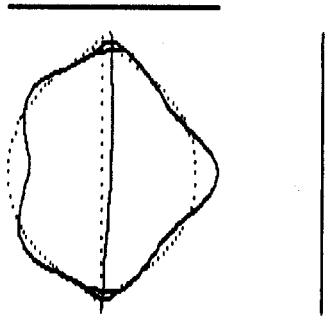
MODE#4 1B FREQ=1.70 Hz



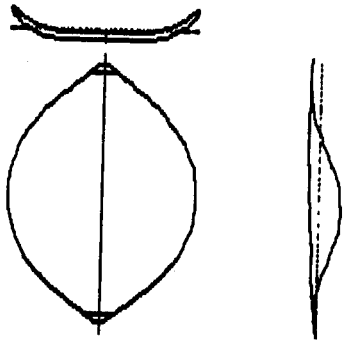
MODE#5 2FA FREQ=2.05 Hz



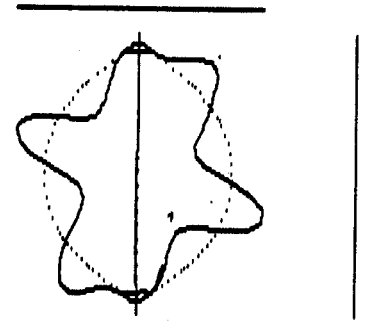
MODE#6 2FS FREQ=2.12 Hz



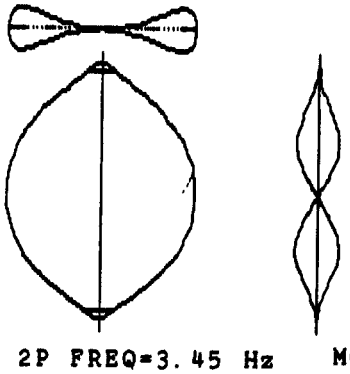
MODE#7 1TI FREQ=2.41 Hz



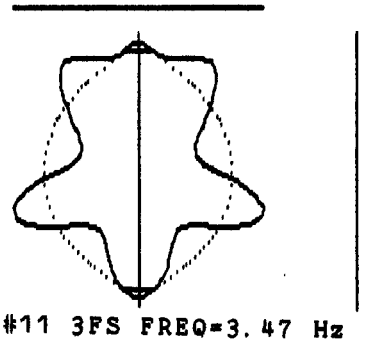
MODE#8 1TO FREQ=2.54 Hz



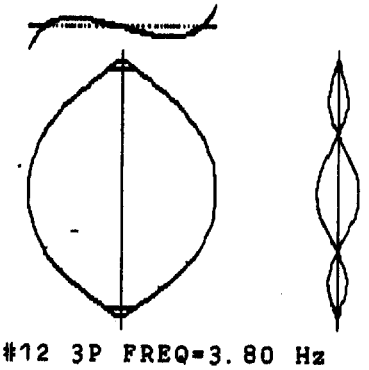
MODE#9 3FA FREQ=3.54 Hz



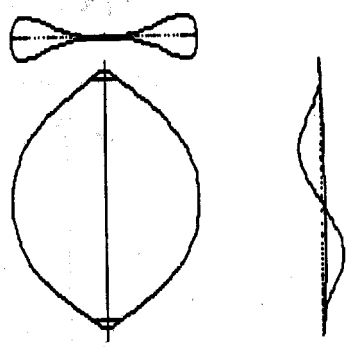
MODE#10 2P FREQ=3.45 Hz



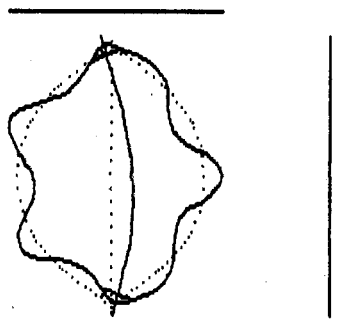
MODE#11 3FS FREQ=3.47 Hz



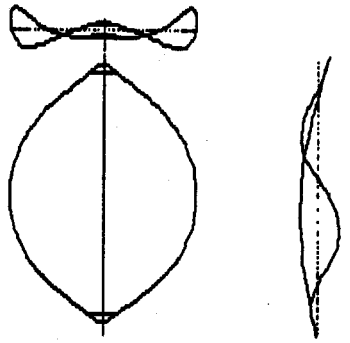
MODE#12 3P FREQ=3.80 Hz



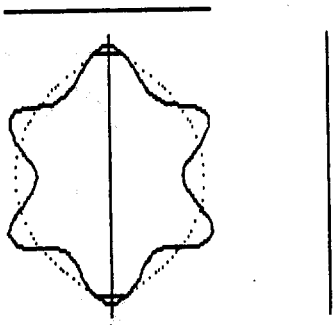
MODE#13 2B FREQ=3.82 Hz



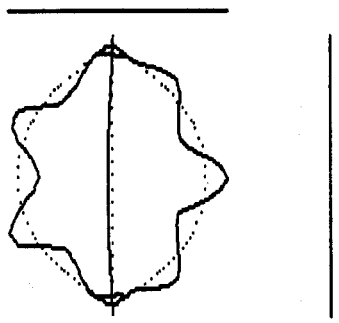
MODE#14 2TI FREQ=4.16 Hz



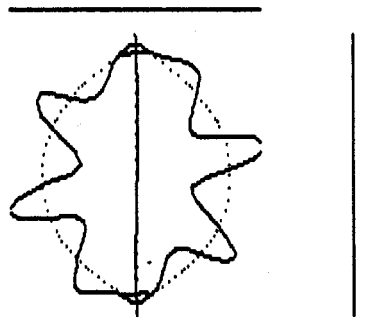
MODE#15 2TO FREQ=4.42 Hz



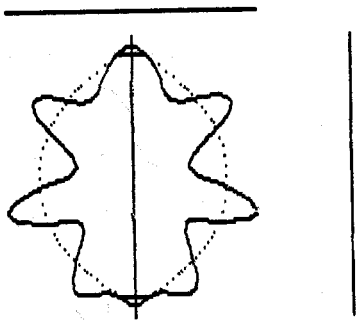
MODE#16 4FS FREQ=5.11 Hz



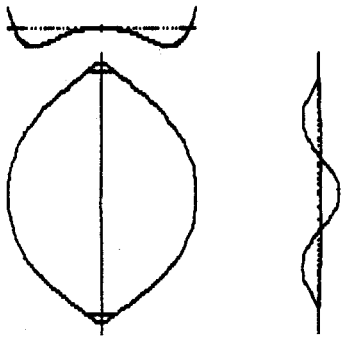
MODE#17 4FA FREQ=5.22 Hz



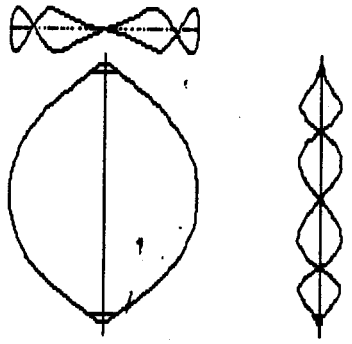
MODE#18 5FA FREQ=7.59 Hz



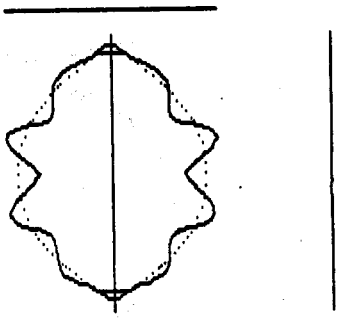
MODE#19 5FS FREQ=7.63 Hz



MODE#20 3B FREQ=7.76 Hz



MODE#21 4P FREQ=11.02 Hz



MODE#22 6FS FREQ=11.39 Hz

DISTRIBUTION:

Advanced Alternative Energy
Solutions
Attn: Ugur Ortabasi
5673 W. Las Positas Boulevard
Suite 205
P.O. Box 5246
Pleasanton, CA

Alcoa Technical Center (5)
Aluminum Company of America
Attn: D. K. Ai
J. T. Huang
J. R. Jombock
M. Klingensmith
J. L. Prohaska
Alcoa Center, PA 15069

Alternative Sources of Energy
Attn: L. Stoiaken
Milaca, MN 56353

Amarillo College
Attn: E. Gilmore
Amarillo, TX 79100

The American Wind Energy Association
1730 N. Lynn Street, #610
Arlington, VA 22209

Roger J. Austin
Hydro-LIFT Systems
125 Catron Drive
Reno, NV 89512

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

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

Bechtel Group, Inc.
Attn: B. Lessley
P.O. Box 3965
San Francisco, CA 94119

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

Ir. Jos Beurskens
Programme Manager for
Renewable Energies
Netherlands Energy Research
Foundation ECN
Westerduinweg 3
P.O. Box 1
1755 ZG Petten (NH)
The Netherlands

Bonneville Power Administration
Attn: N. Butler
P.O. Box 3621
Portland, OR 97208

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

Monique Carpentier
Energy, Mines and Resources
Renewable Energy Branch
460 O'Connor St.
Ottawa, Ontario
CANADA K1A 0E4

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

W. H. Cherry
4547 Province Line Road
Princeton, NJ 08540

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

Commonwealth Electric Co.
Attn: D. W. Dunham
Box 368
Vineyard Haven, MA 02568

M. M. Curvin
11169 Loop Road
Soddy Daisy, TN 37379

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

Department of Economic Planning and Development
Barrett Building
Attn: G. N. Monsson
Cheyenne, WY 82002

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

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

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

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

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

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

Electric Power Research Institute
Attn: J. R. Birk
E. A. DeMeo
3412 Hillview Avenue
Palo Alto, CA 94304

George Elliot, Manager
National Wind Turbine Centre
Department of Trade and Industry
National Engineering Laboratory
East Kilbride
Glasgow G75 OQU
Scotland

John Ereaux
RR No. 2
Woodbridge, Ontario L4L 1A6
CANADA

Dr. Norman E. Farb
10705 Providence Drive
Villa Park, CA 92667

FloWind Corporation
Attn: L. Schienbein
1183 Quarry Lane
Pleasanton, CA 94566

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

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

Dr. I. J. Graham
Southern University
Dept. of Mechanical Engineering
P.O. Box 9445
Baton Rouge, LA 70813-9445

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

Helion, Inc.
Attn: J. Park, President
Box 445
Brownsville, CA 95919

Indal Technologies, Inc.
Attn: V. Lacey
3570 Hawkestone Road
Mississauga, Ontario
CANADA L5C 2V8

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

Iowa State University
Agricultural Engineering
Attn: L. H. Soderholm
Room 213
Ames, IA 50010

K. Jackson
Dynamic Design
123 C Street
Davis, CA 95616

M. Jackson
McAllester Financial
1816 Summit
W. Lafayette, IN 47906

Leif G. Johansen
Vice President of Operations
Cannon Energy Corporation
P.O. Box 1457
Tehachapi, CA 93561

KW Control Systems, Inc.
Attn: R. H. Klein
RD#4, Box 914C
South Plank Road
Middletown, NY 10940

Kaiser Aluminum and Chemical
Sales, Inc.
Attn: A. A. Hagman
14200 Cottage Grove Avenue
Dolton, IL 60419

Kaiser Aluminum and Chemical
Sales, Inc.
Attn: D. D. Doerr
6177 Sunol Blvd.
P.O. Box 877
Pleasanton, CA 94566

Kansas State University
Electrical Engineering Department
Attn: Dr. G. L. Johnson
Manhattan, KS 66506

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

Kinetics Group, Inc.
Attn: J. Sladky, Jr.
P.O. Box 1071
Mercer Island, WA 98040

L. K. Liljergren
120 East Penn Street
San Dimas, CA 71773

L. Liljidahl
Building 005, Room 304
Barc-West
Beltsville, MD 20705

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

David Malcolm
Lavalin Engineers, Inc.
Atria North - Phase 2
2235 Sheppard Avenue East
Willowdale, Ontario M25 5A6
CANADA

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

H. S. Matsuda
Composite Materials Laboratory
Pioneering R&D Laboratories
Toray Industries, Inc.
Sonoyama, Otsu, Shiga, JAPAN 520

Brian McNiff
Engineering Consulting Services
55 Brattle Street
So. Berwick, ME 03908

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

Alan H. Miller
10013 Tepopa Drive
Oakdale, CA 95361

Napier College of Commerce
and Technology
Tutor Librarian,
Technology Faculty
Colinton Road
Edinburgh, EH10 5DT
ENGLAND

National Rural Electric
Cooperative Assn.
Attn: Wilson Prichett, III
1800 Massachusetts Avenue, NW
Washington, DC 20036

Natural Power, Inc.
Attn: Leander Nichols
New Boston, NH 03070

New Mexico Engineering
Research Institute (2)
Attn: G. G. Leigh
D. Morrison
Campus P.O. Box 25
Albuquerque, NM 87131

Ohio State University
Aeronautical & Astronautical Dept.
Attn: Professor G. Gregorek
2300 West Case Road
Columbus, OH 43220

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

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

Debby Oscar
Massachusetts Institute of
Technology
77 Massachusetts Ave.
Room 1-303
Cambridge, MA 02139

Pacific Gas & Electric Co.
Attn: T. Hillesland
J. J. Iannucci
W. J. Steeley
3400 Crow Canyon Road
San Ramon, CA 94583

Ion Paraschivoiu
Dept. of Mechanical Engineering
Ecole Polytecnique
CP 6079
Succursale A
Montreal, Quebec
CANADA H3C 3A7

Jacques Plante
Shawinigan Consultants, Inc.
620 Dorchester Blvd. West
Montreal, Quebec
CANADA H3B 1N8

Public Service Co. of New Hampshire
Attn: D. L. C. Frederick
1000 Elm Street
Manchester, NH 03105

Public Service Co. of New Mexico
Attn: M. Lechner
P.O. Box 2267
Albuquerque, NM 87103

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

R. Rangi (2)
Low Speed Aerodynamics Laboratory
NRC-National Aeronautical
Establishment
Montreal Road
Ottawa, Ontario, K1A 0R6
CANADA

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

Mr. Bent Rasmussen
Overgade 14
DK-7000 Fredericia
DENMARK

Markus G. Real, President
Alpha Real Ag
Feldeggstrasse 89
CH 8008 Zurich
Switzerland

The Resources Agency
Department of Water Resources
Energy Division
Attn: R. G. Ferreira
P.O. Box 388
Sacramento, CA 95802

Reynolds Metals Company
Mill Products Division
Attn: G. E. Lennox
6601 West Broad Street
Richmond, VA 23261

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

Riso National Laboratory
Attn: Troels Friis Pedersen
Helge Petersen
Peter Hauge Madsen
Postbox 49
DK-4000 Roskilde
DENMARK

H. M. Romanowitz, P. E.
Oak Creek Energy Systems, Inc.
P.O. Box 469
Tehachapi, CA 93561

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

Gwen Schreiner
Librarian
National Atomic Museum
Albuquerque, NM 87185

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

Mr. Farrell Smith Seiler, Editor
Wind Energy News Service
P.O. Box 4008
St. Johnsbury, VT 05819

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

Kent Smith
Instituto Technologico Costa Rica
Apartado 159 Cartago
COSTA RICA

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

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

Peter South
ADECON
6535 Millcreek Dr., Unit 67
Mississauga, Ontario
CANADA L5N 2M2

Southern California Edison
Research & Development Dept.
Room 497
Attn: R. L. Scheffler
P.O. Box 800
Rosemead, CA 91770

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

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

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

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

Walter V. Thompson
410 Ericwood Court
Manteca, CA 95336

K. J. Touryan
P.O. Box 713
Indian Hills, CO 80454

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

J. M. Turner Technologies, Inc.
Attn: Eric N. Hinrichsen
P.O. Box 1058
Schenectady, NY 12301-1058

US WindPower
Attn: W. E. Holley
G. M. McNerney
Suite 3050
400 West Cummings Park
Woburn, MA 01803

USDA
Agricultural Research Service
Southwest Great Plains Research
Center
Attn: Dr. R. N. Clark
Bushland, TX 79012

United Engineers and
Constructors, Inc.
Attn: A. J. Karalis
P.O. Box 8223
Philadelphia, PA 19101

Universal Data Systems
Attn: C. W. Dodd
5000 Bradford Drive
Huntsville, AL 35805

University of California
Institute of Geophysics
and Planetary Physics
Attn: Dr. P. J. Baum
Riverside, CA 92521

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

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

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

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

The University of Tennessee
Dept. of Electrical Engineering
Attn: T. W. Reddoch
Knoxville, TN 37916

W. A. Vachon
W. A. Vachon & Associates
P.O. Box 149
Manchester, MA 01944

Dirk Vandenberghe
State Univ. of Ghent
St. Pietersniewstraat 41
9000 Ghent
BELGIUM

Washington & Lee University
Attn: Dr. R. E. Akins
P.O. Box 735
Lexington, VA 24450

Washington State University
Dept. of Electrical Engineering
Attn: F. K. Bechtel
Pullman, WA 99163

West Texas State University
Government Depository Library
Number 613
Canyon, TX 79015

West Texas State University
Department of Physics
Attn: V. Nelson
P.O. Box 248
Canyon, TX 79016

West Virginia University
Dept. of Aero Engineering
Attn: R. Walters
1062 Kountz Avenue
Morgantown, WV 26505

D. Westlind
Central Lincoln People's
Utility District
2129 North Coast Highway
Newport, OR 97365-1795

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

Wind Power Digest
Attn: Michael Evans
P.O. Box 700
Bascom, OH 44809

400	R. C. Maydew
1520	L. W. Davison
1522	R. C. Reuter, Jr.
1522	D. W. Lobitz
1522	E. D. Reedy
1523	J. H. Biffle
1524	C. R. Dohrmann
1524	D. R. Martinez
1550	C. W. Peterson
1552	J. H. Strickland
1556	G. F. Homicz
3141	S. A. Landenberger (5)
3151	W. I. Klein (3)
3154-1	C. L. Ward (8) For DOE/OSTI (Unlimited Release)
3161	P. S. Wilson
6000	D. L. Hartley
6200	V. L. Dugan
6220	D. G. Schueler
6225	H. M. Dodd (50)
6225	T. D. Ashwill
6225	D. E. Berg
6225	T. C. Bryant
6225	M. E. Ralph
6225	D. C. Reda
6225	M. A. Rumsey
6225	L. L. Schluter
6225	W. A. Stephenson
6225	H. J. Sutherland
6225	P. S. Veers
7544	D. O. Smallwood
7544	T. G. Carne
7544	J. Lauffer
8524	J. R. Wackerly

8232-2/069847
00000001 -
8232-2/069847
00000001 -
8232-2/069847
00000001 -

8524
8524-2