ROTOR DYNAMIC ANALYSIS WITH MSC/NASTRAN VIA THE IMPORTANT MODES METHOD

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ABSTRACT

This paper describes an MSC/NASTRAN solution procedure by which the problem size of a free or forced complex modes rotor dynamics analysis may be substantially reduced with minimal loss of accuracy. Strain and kinetic energies in the system normal modes are calculated for user-designated groups of elements within the engine. Then, the "importance" of each mode is assessed based on whether or not the elements in the rotors contain a preselected small percentage of energy relative to the entire system energy content. The complex eigenvalue solutions are then formulated containing only these "important" normal modes. It is predicted that these modes which are judged to be active based on energy content will be affected by gyroscopic moments and rotor unbalance loads.

DMAP alters were written for inclusion in Solutions 63, 70 and 71. The DMAP alters for Solution 63 direct that mass, eigenvalue, eigenvector and strain energy data be output into binary files for subsequent processing. The alters for Solution 70 and 71 use DMI entries in the bulk data to choose which of the normal modes are to be used in the complex solution and to direct that the above data be output for further processing. Post-processing programs were created to calculate the desired strain and kinetic energies, to tabulate the energies by engine component, and to prepare data for subsequent graphical presentation.

INTRODUCTION

Control of engine system vibration and maneuver deflections is a major design requirement for aircraft engines. Three-dimensional rotor analyses of installed engines are desirable when the dynamic behavior involves participation of non-axisymmetric stator frames or engine mounts with stiffnesses different in the horizontal direction than in the vertical direction. Usually, the size of the model required to describe the engine accurately for stiffness and mass determination is quite large, and the computer run for the model is expensive. For instance, a recently created three-dimensional model contained 5190 normal mode degrees of freedom after completion of the real eigenvalue solution using standard problem size reduction techniques (Guyan and generalized dynamic reduction).

The difficulty of large problem size is compounded because gyroscopic moments [Reference 1] in the rotor, and material and viscous damping must be included to obtain an accurate prediction of system dynamic behavior. This necessitates the determination of complex eigenvalues (via Solution 67) which is not practical for a problem of this size.

Modal truncation is a common procedure for problem size reduction. This is a scheme whereby modes above a selected frequency (perhaps 1.3 times the highest possible excitation frequency) are truncated and the problem reformulated in the remaining set of normal modes. By use of the parameter cards LMODES, HFREQ and LFREQ, MSC/NASTRAN permits either the selection of the number of lowest modes to be used or the frequency range of the modes to be included.

Modal truncation was unacceptable, however, for the 5190 degrees of freedom problem because the number of modes in the operating range was still too large to handle. An assessment of the normal mode shapes for the frequencies in the operating range revealed that many modes involved case ovalization, local "panel" movement, etc., and as such are not "important" for rotor dynamics analyses.

This paper describes a technique by which problem size of a free or forced complex modes rotor dynamics analysis may be substantially reduced with minimal loss of accuracy. The strain and kinetic energies in the system normal modes are calculated for user-designated groupings of finite elements corresponding to major modules of the engine. These groupings are designated in input to a post-processing program and are independent of the superelement layout in the MSC/NASTRAN model.

The importance of each mode is assessed based on whether or not the elements in the rotors contain a preselected small percentage of energy relative to the entire system energy content. The complex eigenvalue solutions are then formulated containing only the normal modes affected by gyroscopic moments and rotor unbalance loads.

The problem that is described in this paper was chosen for the express purpose of demonstrating the method. The criterion employed in this problem is to include only those normal modes in the complex analyses for which the strain or kinetic energy of rotor components is 1% or more of the system total. The method is sufficiently general that other selection criteria could be used. For instance, the user could select modal displacements at selected points of unbalance in addition to rotor energy. Also, the percentage of energy criteria could be changed depending upon the problem size that is tolerable.

METHODOLOGY

Figure 1 shows the logic flow diagram for this modal reduction technique. The flow diagram shows the MSC/NASTRAN runs (for which DMAP Alters are required) and several post-processing FORTRAN programs.

The following steps are included in the procedure:

1. DMAP alters are added to the MSC/NASTRAN input at two locations:

(a) Within the normal modes solution to output binary files containing mass, eigenvalue solution and strain energy data.
(b) Within the complex modes solution to
    (1) Perform selective modal reduction of the eigenvalue and eigenvector matrices,
    (2) Output binary files of eigenvectors and eigenvalues,
    (3) Calculate strain energies and output the values onto binary files.

2. The NOTRAN (MSC/NASTRAN Output TRANslator) program reads the binary output files written by MSC/NASTRAN, and reformulates this data from "internal" sequence into an "external" format (input element and grid ID's). Data from several superelements are combined into one continuous output file.

3. The NIMMP63 (MSC/NASTRAN IMPortant Modes from Solution 63) program calculates energy content (MSC/NASTRAN-calculated strain energy and NIMMP63-calculated kinetic energy) by engine component groupings (e.g. fan frame, compressor casing, high pressure turbine, etc.) from the MSC/NASTRAN output that is collected by NOTRAN. The output from NIMMP63 is a tabulation that gives the percentage of strain and kinetic energies in each of the designated engine component groupings. If the percentage of both strain and kinetic energy in the rotors is small for a particular natural frequency, it is assumed that the mode will be unaffected by gyroscopic moments or is unexcitable by rotor unbalance loadings, and may be deleted from subsequent complex eigenvalue analyses without loss of accuracy. The remaining normal modes are the generalized degrees of freedom designated as "important" for the accuracy of the solution.

4. The SOL70I computer program was written to assist in the preparation of two groups of MSC/NASTRAN bulk data cards. The first group includes the gyroscopic moment terms that are added to the B (damping) matrix in the general equations of motion [Reference 2]. These terms are accessed via the B2PP directive in the case control deck. The second group contains the modal

selection input expected by the DMAP alters. The modes are selected by the user based on Solution 63 output that has been processed by NIMMP63.

5. The NIMMP70 program calculates element kinetic energy and energy content by component grouping from the MSC/NASTRAN output that is collected by NOTRAN.

RESULTS

The model, which was developed expressly to demonstrate the method, is shown in Figure 2. The initial model has approximately 1150 physical degrees of freedom and, although not as detailed as an actual design evaluation model would be, is sufficiently complicated to simulate an analysis of a turbo-fan engine without excessive computer run times and cost.

Generalized dynamic reduction was used to reduce the analysis size to approximately 500 degrees of freedom; the 500 degree of freedom model was used to develop base case results.

The "important modes" model was formulated using 19 normal modes as generalized degrees of freedom. The modes selected were those that were indicated as involving high pressure (HP) or low pressure (LP) rotor activity based on their strain or kinetic energy content at speeds within the operating range of the engine.

Figures 3 through 5 illustrate the type of data generated by the reduced size model. Figures 3 and 4 show whirl speed plots (also called Campbell diagrams) referenced to the low and high pressure rotors for the demonstration model. Figure 5 is response amplitude plotted versus low pressure rotor speed for a 100 gm-in fan unbalance loading.

An assessment of the accuracy of results was made to evaluate the acceptability of this technique. The relatively small size of the sample model (at least as compared to an actual engine evaluation) permitted the development of solutions using all modes of vibration for the base case complex modes analysis. Table 1 provides a summary of data take from three runs:

1. A normal modes analysis (Solution 63).
2. A direct complex eigenvalue analysis (Solution 67) with material damping and gyroscopic moments included for LP/HP rotor speeds of 1000/3000 RPM.
3. A modal complex eigenvalue analysis (Solution 70) with

material damping and gyroscopic moments included for the same rotor speeds but only with important modes as generalized coordinates.

The normal modes data for this model indicate that the energy content for rotor elements is very small for a number of modes. Based on this observation, these modes were deleted from the Solution 70 run as indicated. The objective of this Table is to show that modes with little or no rotor involvement as indicated by small energy content in the normal modes analysis ("unimportant modes") can be deleted from the generalized coordinates for the complex eigenvalue analysis without affecting the results for the retained (important) modes .

The small differences between frequencies for Solutions 63 and 67 for Rotor Active "No" (i.e. the unimportant modes as predicted by small rotor energy content in Solution 63) verify the prediction made with the Solution 63 results that these modes would be unaffected by including gyroscopic moment terms in the equations of motion.

Table 2 provides data for a comparison between Solution 67 results with LP/HP rotor speeds of 1000/3000 RPM and Solution 70 runs with LP/HP rotor speeds of 1000/3000 and 4500/12500 RPM.

CONCLUSIONS

There is good agreement for the model studied between Solution 67 results (baseline) and Solution 70 results in which the unimportant modes have been eliminated. Similar data were developed to compare Solution 71 results with Solution 68 results with similar excellent agreement. (These data are not included here for reasons of brevity.) It is concluded from these observation that the procedure described in Figure 1 offers a useful method for performing rotor dynamics analysis. The one percent energy content criterion as used in this example for selection of important modes is acceptable but may prove to be overly restrictive and be relaxed as experience with the procedure is gained.

REFERENCES

1. Green, R. B., "Gyroscopic Effects on the Critical Speeds of Flexible Rotors," ASME Journal of Applied Mechanics, Vol. 15, p. 369, (1948).

2. MSC/NASTRAN Handbook for Dynamic Analysis, The MacNeal-Schwendler Corporation, Los Angeles, CA, (1983).

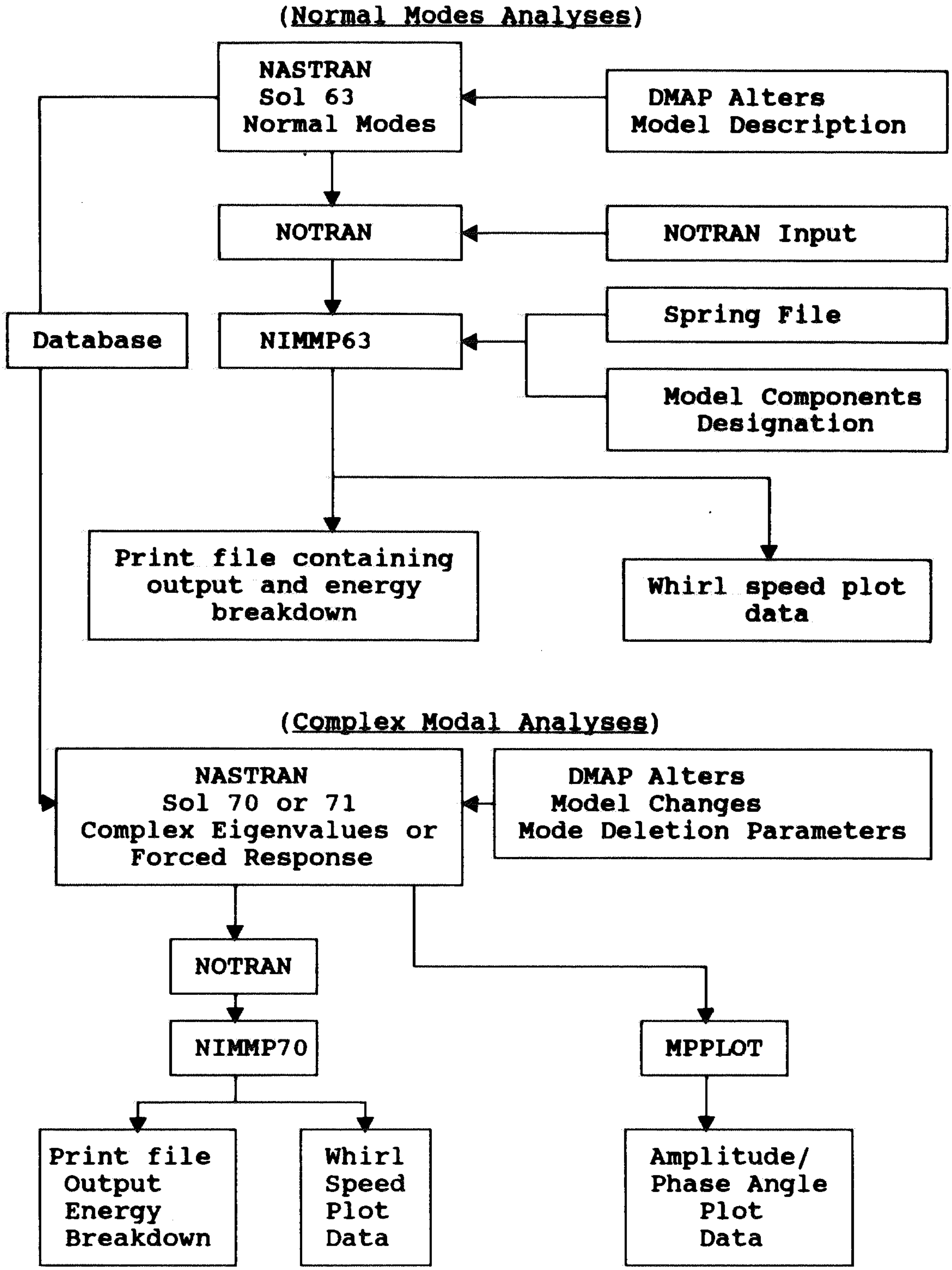

FIGURE 1 - THREE-DIMENSIONAL ROTOR DYNAMICS AND ANALYSIS STEPS

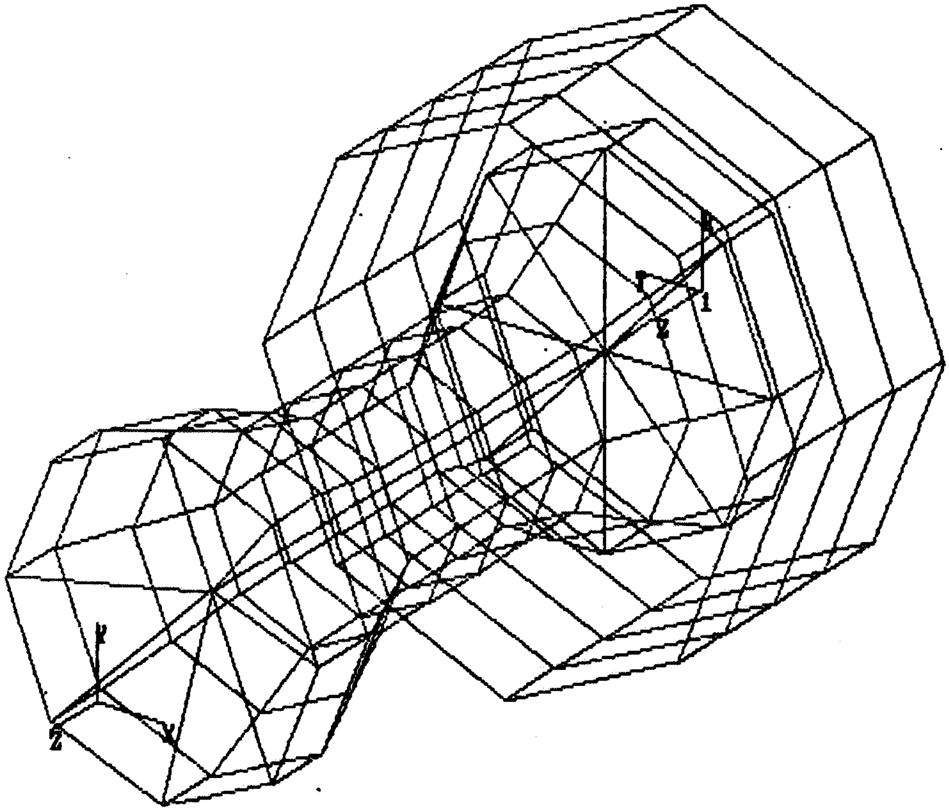

FIGURE 2 - PROGRAM DEMONSTRATION MSC/NASTRAN MODEL

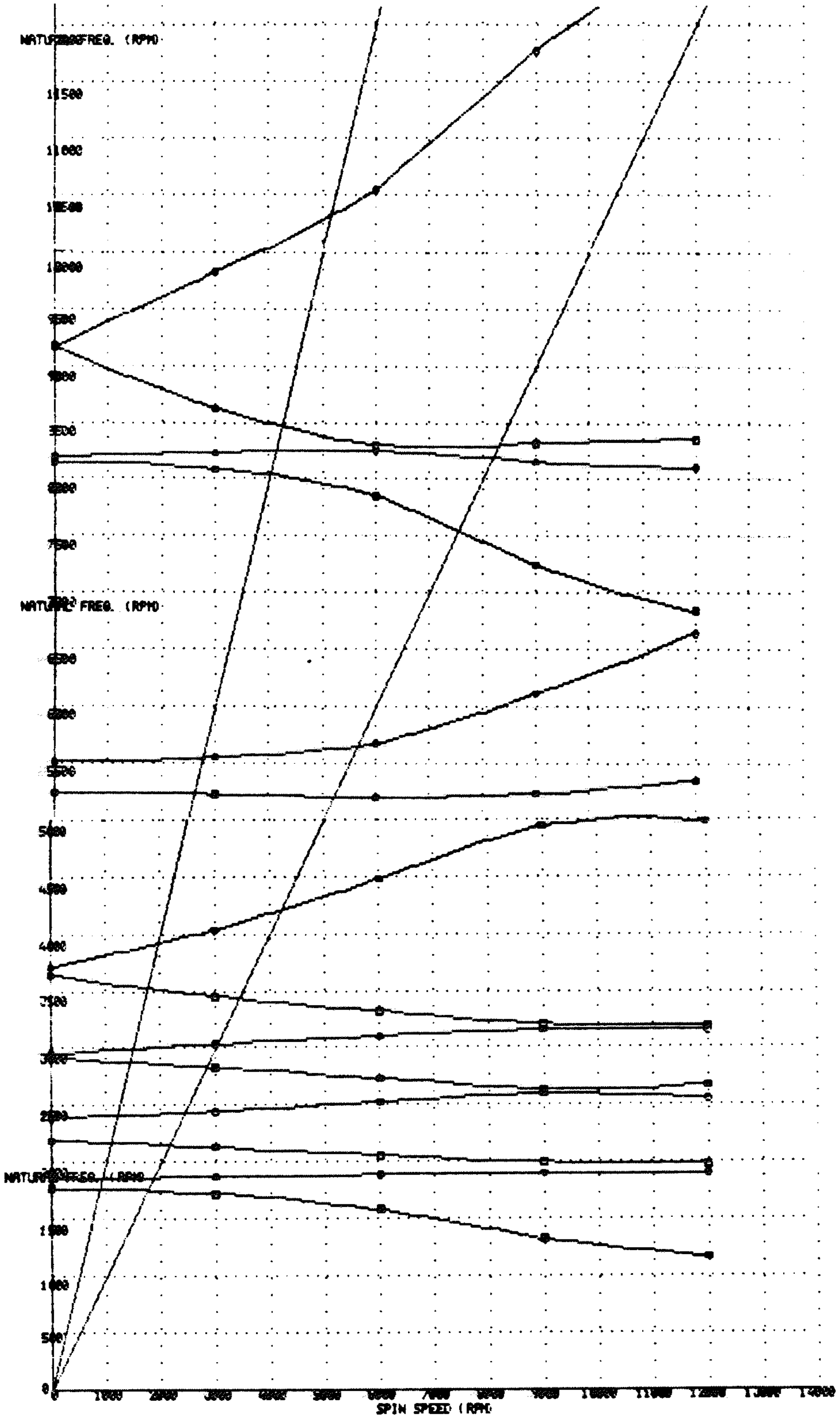

FIGURE 3 - CAMPBELL DIAGRAM REFERENCED TO HP ROTOR

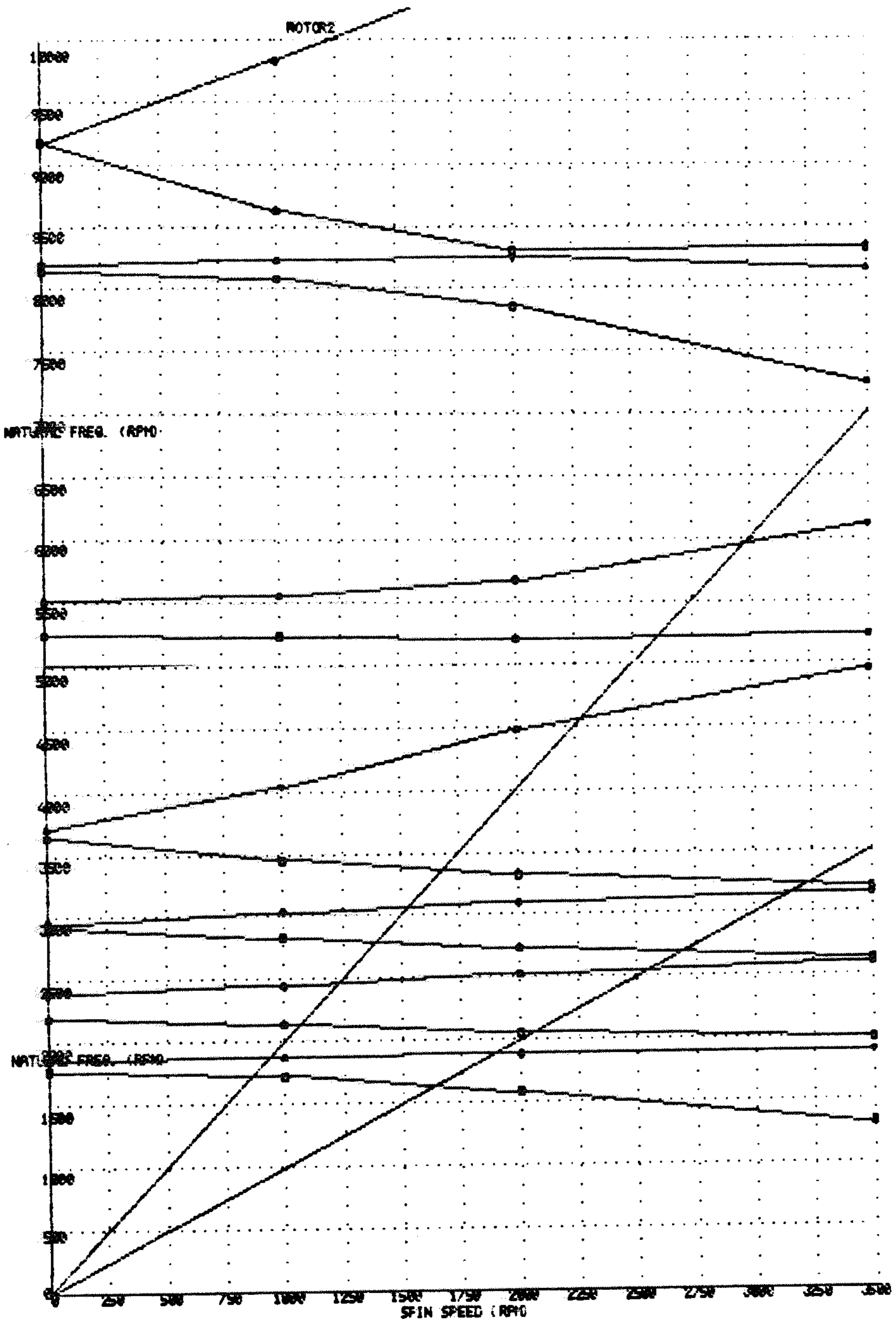

FIGURE 4 - CAMPBELL DIAGRAM REFERENCED TO LP ROTOR

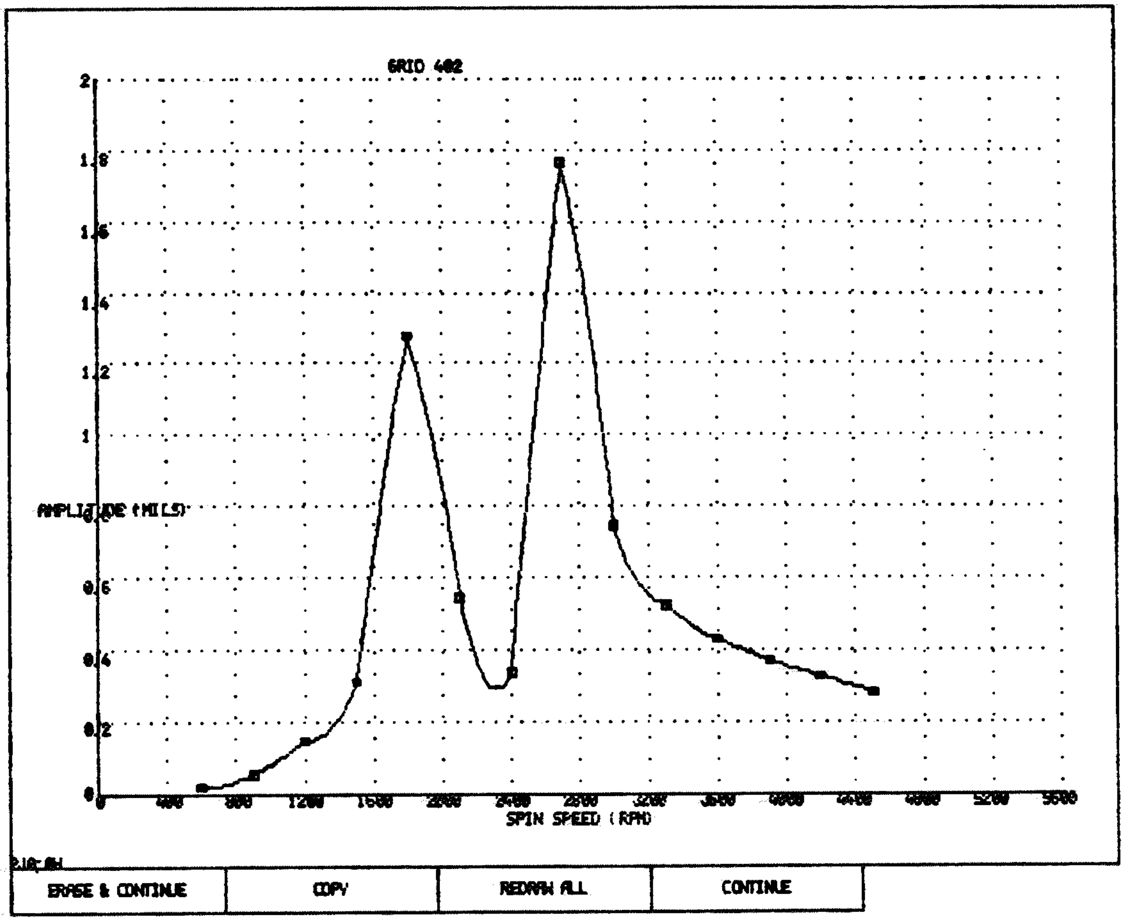

FIGURE 5 - RESPONSE AMPLITUDE FOR 100 GM-IN UNBALANCE

TABLE 1 FREQUENCIES FOR THREE SOLUTION TYPES

Frequencies in radians/second

Rotor Speeds in RPM (HP/LP)			None	1000/3000	1000/3000
Sol 63 Mode No.	Rotor Active	% Energy in Rotor	Sol 63 Frequencies	Baseline Sol 67 Frequencies	Modes Removed Sol 70 Frequencies
1	No	0.2	1.337275E02	1.338020E02	
2	Yes	90.4	1.857094E02	1.801891E02	1.801940E02
3	Yes	91.2	1.946524E02	1.960071E02	1.960082E02
4	Yes	97.9	2.294582E02	2.231259E02	2.231590E02
5	No	0.3	2.489047E02	2.490471E02	
6	Yes	96.1	2.503991E02	2.561518E02	2.561699E02
7	No	0.1	2.524745E02	2.526157E02	
10	No	0.1	2.856489E02	2.703219E02	
11	Yes	97.4	3.057553E02	2.965035E02	2.965046E02
12	Yes	97.3	3.099390E02	3.176280E02	3.177222E02
18	Yes	91.9	3.811256E02	3.609919E02	3.609790E02
19	Yes	91.2	3.884914E02	4.224918E02	4.224667E02
26	Yes	93.9	5.495437E02	5.481274E02	5.481272E02
27	Yes	78.4	5.773789E02	5.817490E02	5.817408E02
32	Yes	15.5	8.525498E02	8.466332E02	8.466325E02
33	Yes	30.9	8.581851E02	8.616168E02	8.616174E02
34	Yes	95.6	9.598007E02	9.028885E02	9.028870E02
35	Yes	95.5	9.598689E02	1.028179E03	1.028177E03
46	Yes	6.1	1.569888E03	1.655639E03	1.655599E03
47	Yes	45.9	1.689112E03	1.674025E03	1.674019E03
48	Yes	46.0	1.709518E03	1.707907E03	1.707904E03
49	Yes	99.0	1.767097E03	1.735437E03	1.735422E03
50	Yes	98.4	1.767322E03	1.812235E03	1.818790E03

The designation "Rotor Active Yes" indicates that it was predicted, based upon an evaluation of rotor element strain and kinetic energies from the normal modes analysis, that the rotor would be responsive for this mode to gyroscopic moments and rotor unbalance loadings. The mode therefore needs to be included as a generalized coordinate in the modal rotor dynamics analysis. "Rotor Active No" indicates that it was predicted that the mode would not be responsive and needs not be included in the modal analysis.

Solution 63 results and Solution 67 results should be the same for the modes indicated "No", and different for those modes indicated "Yes". The agreement of the results for Solutions 67 and Solution 70 with "Rotor Active Yes" demonstrates the validity of reducing problem size via the important modes method for rotor dynamic analyses.

TABLE 2 FREQUENCIES FOR SOLUTIONS 67 AND 70

Frequencies in radians/second

Rotor Speeds RPM		1000/3000	1000/3000	4500/12000 (HP/LP)
Sol 67 Mode No.	Rotor Active	Baseline Sol 67 Frequencies	Modes Removed Sol 70 Frequencies	Modes Removed Sol 70 Frequencies
2	Yes	1.801891E02	1.801940E02	1.226158E02
3	Yes	1.960071E02	1.960082E02	1.993978E02
4	Yes	2.231259E02	2.231590E02	2.074528E02
6	Yes	2.561518E02	2.561699E02	2.675352E02
11	Yes	2.965035E02	2.965046E02	2.796130E02
12	Yes	3.176280E02	3.177222E02	3.296641E02
18	Yes	3.609919E02	3.609790E02	3.342639E02
19	Yes	4.224918E02	4.224667E02	5.211521E02
26	Yes	5.481274E02	5.481272E02	5.602191E02
27	Yes	5.817490E02	5.817408E02	6.957375E02
32	Yes	8.466332E02	8.466325E02	7.169649E02
33	Yes	8.616168E02	8.616174E02	8.490428E02
34	Yes	9.028885E02	9.028870E02	8.748251E02
35	Yes	1.028179E03	1.028177E03	1.328892E03
46	Yes	1.655639E03	1.655599E03	1.519360E03
47	Yes	1.674025E03	1.674019E03	1.533869E03
48	Yes	1.707907E03	1.707904E03	1.673560E03
49	Yes	1.735437E03	1.735422E03	1.791311E03
50	Yes	1.812235E03	1.818790E03	1.812237E03
51	No	1.818700E03	1.818790E03	1.818790E03
52	No	1.819988E03	1.819988E03	1.819989E03
53	No	1.827498E03	1.827498E03	1.827582E03
54	No	1.831018E03	1.831018E03	1.831140E03
55	No	1.833544E03	1.833542E03	1.833542E03
56	No	1.856605E03	1.856605E03	1.856605E03

As before, the designation "Rotor Active Yes" indicates that it was predicted that the rotor would be responsive for this mode to gyroscopic moments and rotor unbalance loadings, and that the mode needs to be included as a generalized coordinate in the modal rotor dynamics analysis. "Rotor Active No" indicates that it was predicted that the mode would not be responsive and needs not be included in the modal analysis.

For responsive modes, it was predicted that frequencies for complex eigenvalue analyses would vary for different rotor spin speeds. For nonresponsive modes (Rotor Active No), it was predicted that the frequencies would not vary. These predictions are verified with the results contained in this table.