# A NASTRAN PRIMER FOR THE ANALYSIS OF ROTATING FLEXIBLE BLADES

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## SUMMARY

This primer provides documentation for using MSC NASTRAN in analyzing rotating flexible blades. The analysis of these blades includes geometrically nonlinear (large displacement) analysis under centrifugal loading, and frequency and mode shape (normal modes) determination. The geometrically nonlinear analysis using NASTRAN Solution sequence 64 is discussed along with the determination of frequencies and mode shapes using Solution Sequence 63. A sample problem with the complete NASTRAN input data is included. Items unique to rotating blade analyses, such as setting angle and centrifugal softening effects are emphasized.

## 1.0 INTRODUCTION

The purpose of this primer is to document the use of MSC NASTRAN in analyzing rotating flexible blades. The analysis of rotating flexible blades such as compressor and turboprop blades, often requires complex procedures including geometrically nonlinear (large displacement) analysis and frequency and mode shape determination. The objective in performing such analyses includes the prediction of steady state deflections and stresses under centrifugal forces, the generation of data for constructing Campbell diagrams (plots of frequency versus rotational speed), and the provision of modal data for use in flutter calculations. In performing these analyses, and in modeling the complex geometries and material properties of the blades (fig. 1), finite element (F.E.)

computer programs typically are used. NASTRAN is particularly well-suited because of its ability to compute steady-state displacements from its geometrically nonlinear analysis capabilities, and then, to use those results for a subsequent normal modes analyses.

The computation of steady-state displacements, frequencies, and modes shapes of flexible rotating blades requires that two NASTRAN Solution sequences be run. First, a large displacement analysis is run using NASTRAN Solution Sequence 64. This solution sequence performs large displacement analysis on the rotating blade, computes steady-state displacements and stresses (due to the rotational effects), and then stores the blade's final stiffness and mass matrix in a database. Experience has shown (ref. 2) that a large displacement analysis is required because the blades are relatively flexible and normally deflect considerably under the centrifugal forces (fig. 2).

Following the large displacement analysis, the frequencies and mode shapes are computed using Solution Sequence 63. (A typical plot demonstrating the variation in natural frequencies with rotational speed is shown in fig. 3.) This solution sequence computes the modal parameters from the final mass and stiffness matrices which were computed during the Solution 64 run. The structural property matrices that correspond to the blade in its deformed position must be used so that the effects of centrifugal stiffening, and other elements which will be discussed, are included in the normal modes analysis.

## 2.0 DESCRIPTION OF SAMPLE PROBLEM

The sample problem in figure 4 is provided in order to demonstrate the procedures required for large displacement and normal modes analyses. All of the requirements for these analyses are exhibited in this sample problem even though this problem does not have the mesh complexity required of typical flexible blades. The mesh used in this sample problem is for demonstration purposes and is over simplified compared to typical analyses. Although there are no aerodynamic loads included in this problem, they can be included, and would be combined with the centrifugal loads for computing the steady-state displacements.

The sample problem consists of a rotating, swept back, flat plate. The plate is modeled with three plate elements (CQUAD4) connected by 8 grid points. The grid points are defined in a local rectangular coordinate system, which is rotated 30° from the axis of rotation in the X/Y.

## 3.0 GEOMETRICALLY NONLINEAR ANALYSIS/MSC NASTRAN SOLUTION 64

This section provides a discussion regarding the construction of the Solution 64 input data deck. The sample data deck is comprised of four components; the CRAY Job Control Language, the NASTRAN Executive, the Case Control, and Bulk Data, and is included in appendix A of reference 10.

### 3.1 CRAY Job Control Language

The CRAY Job Control Language for submitting jobs to the CRAY (at NASA Lewis Research Center) and running NASTRAN is given at the beginning of the data deck. The amount of time and memory indicated on the "JOB" card is based on the number of degrees of freedom used for the model and the number of iterations (section 3.3) specified for the nonlinear analysis. Faster turnaround time on the computer is accomplished when these allocations are minimized.

On the "NASTRAN" card (see ref. 3 for a complete description), a temporary database named "BLADE" is specified. This database is used for storing the mass and stiffness matrices for subsequent use in the Solution 63 normal modes analysis.

### 3.2 Solution 64 Executive

Solution 64 is well suited to the large steady-state displacement analysis of rotating structures except for the fact that coriolis forces and centrifugal softening terms (see appendix C of ref. 10 for a derivation of centrifugal softening) are not automatically included. Since the coriolis forces are velocity related, they do not have any influence on the large displacement analysis and do not need to be accounted for. Furthermore, from previous studies it has been determined that coriolis forces have negligible effects on thin, flexible blade frequencies (ref. 4), so they normally do not need to be included in the Solution 63 analysis. However, the centrifugal softening terms do need to be included in the analysis and must be added via DMAP (Direct Matrix) programming.

The centrifugal softening terms ($-w^2M$) are added to the global stiffness matrix for all grid points for the translational degrees of freedom in the direction of the two axes perpendicular to the axis of rotation. The softening terms are input into the Solution 64 analysis using the NASTRAN DMAP included with the sample problem given in reference 10.

## 3.3 Solution 64 Case Control

The cards in the CASE CONTROL Deck are used to specify the problem titles, the type of printed output, and the number of iterations that are to be carried out in the large displacement analysis.

For the sample problem the applied forces at all of the grid points (OLOAD=ALL), and the resulting displacements (DISP=ALL) and reactions (SPCFO=ALL), are printed in the last three iterations. It is recommended that displacements and reactions be printed in at least the last few of iterations so that convergence can be monitored. It may be desirable to print displacements in the first iteration so that the nonlinearity of the blade's response can be assessed. Acceptable convergence is achieved when both the displacement changes between iterations and the force unbalance between the applied centrifugal forces and the internal element forces are small. The force unbalance at each of the unconstrained grid points is printed along with the reactions at the constrained points by using the command "SPCFO=ALL".

There are eight iterations, or "subcases," specified for this sample problem. In the first subcase a linear analysis is performed. In the second subcase, the displacements from the first subcase are used to form a differential stiffness matrix which is then used to compute a new set of displacements. In subsequent subcases the differential stiffness matrix is updated using the resultant displacements and a new set of displacements is computed. (Details of the theory underlying the iterative procedure and results for a flexible turboprop blade are provided in (refs. 2 and 5).)

When actual blades having large numbers of degrees of freedom are analyzed the cost of running a large number of iterations can be significant. To minimize the CPU time and cost, the number of iterations should be kept to a minimum. The best way to optimize the number of iterations is to specify a minimum number of iterations, and then if the solution has not converged, use NASTRAN "restart" (ref. 6) to resume the analysis.

## 3.4 Solution 64 Bulk Data Deck

The primary function of the bulk data deck is to describe the blade geometry, boundary conditions, material properties, and loads. Details of blade modeling techniques and the bulk data cards required for the model description are presented in (ref. 1), and in the NASTRAN User's Manual (ref. 6). In addition to describing the model, the bulk data deck is used to specify the rotational speed (RFORCE and PARAM RPM), and the matrix "K1" which is used for inputting the softening terms.

NASTRAN automatically computes a centrifugal force field whenever an "RFORCE" card is used to specify a rotational speed. The centrifugal force field is computed by using the blade's geometrical and mass properties defined in the bulk data deck, and the rotational speed specified on the "RFORCE" card. The rotational speed is also included on a parameter card, "PARAM RPM." This card is used by the DMAP Alters for computing the value $-w^2$ for the centrifugal softening terms.

Several issues which concern the blade model and are addressed in (refs. 1 and 7), are discussed below as they are relevant to the large displacement analysis of flexible blades. The first issue concerns the method of formulation for the element mass matrices. Most of the elements available in NASTRAN permit the user to utilize a lumped or consistent mass matrix, but since the formulation for the centrifugal softening terms, and the centrifugal force field, is based on a lumped mass representation, a lumped mass matrix should also be used for the elements. Furthermore, no clear advantages have been found for utilizing a consistent mass formulation. A lumped mass matrix is computed by default in NASTRAN.

The next issue regards the lack of stiffness in the in-plane, normal rotation for plate and shell elements. This condition can present problems when adjacent elements lie in the same plane (coplanar). Since the elements have zero computed stiffness in the normal rotation, and the elements are coplanar, the accumulated rotational stiffness may end up being very close to zero. When this occurs the stiffness matrix becomes singular and the analysis fails. To circumvent this problem, these "small" rotational stiffnesses can be constrained with SPC's. This solution is sensible since the normal rotational stiffness usually is relatively stiff, thus it is reasonable to fully constrain the rotation. For nonlinear problems this approach is not feasible because the large displacements may deflect the elements such that elements that start out noncoplanar become coplanar. When this happens, singularities that did not exist in earlier iterations arise, and the solution fails in the resultant iteration. A feature in NASTRAN for overcoming this problem is the K6ROT parameter. This parameter adds artificial rotational stiffness at the element level so that even if elements are coplanar, the global stiffness matrix will not have any singularities. The effect of adding this rotational stiffness produces results similar to when the rotation is fully constrained with SPC's (see ref. 1 for details of comparison). The advantage of using the K6ROT parameter over using SPC's is that it is difficult to determine beforehand where SPC constraints are required.

The final issue concerns the constraint at the base of the blade model. For most blade analyses performed thus far, the base of the blade has been fully constrained. In reference 7, it was shown that base flexibility can have a significant effect on steady-state displacements, frequencies, and mode shapes. Therefore, whenever there is information on the blade's base support flexibility, it should be incorporated into the blade model.

## 4.0 NORMAL MODES ANALYSIS/MSC NASTRAN SOLUTION 63

The NASTRAN Solution 63 data deck for the normal modes analysis is given in appendix B of reference 10. This data deck uses the identical model description that was used in the Solution 64 deck. The Solution 63 deck was created by duplicating all of data cards used in the Solution 64 deck for defining the blade model, removing the cards associated with the large displacement analysis, and then adding the necessary cards for the Solution 63 normal modes analysis. It should be noted the "NASTRAN" command accesses the same database that was used in the Solution 64 run.

## 5.0 CHANGES IN ROTATIONAL SPEED

To obtain the steady state displacements, frequencies, and modes shapes when the blade is spinning at a new speed, both the large displacement and normal modes analyses must be rerun. The large displacement analysis (Solution 64) needs to be rerun because the steady-state position of the blade changes with rotational speed. Furthermore, updated mass and stiffness matrices, which reflect the effects of the current rotational speed, need to be transferred to the normal modes analysis performed in Solution 63. The effect of rotational speed on blade frequencies for a typical blade was shown in figure 3.

In the Solution 64 run the rotational speed is altered by changing the speed on the RFORCE and PARAM RPM cards. In addition to changing the blade's speed, the blade's angle of attack normally has to be adjusted when the blade is operating at a new rotational speed. Once the correct angle of attack is determined, either the axis that the blade is rotating about must be changed or the blade itself must be rotated. Due to the way the centrifugal softening terms are applied it is simpler to rotate the blade than to change the axis of rotation. To implement a change in the angle of attack, the entire blade can be rotated by defining the blade's geometry in a new coordinate system. This method of rotating the blade is convenient because the coordinates of the blade on the "GRID" cards do not have to be changed. Instead, the coordinate system in which the blade is described is rotated.

## 6.0 COMBINED SOLUTION 64/SOLUTION 63 ANALYSIS

A combined large displacement, frequency, and mode shape analysis can be performed in the Solution 64 Sequence. This analysis is completed by adding NASTRAN DMAP Alters to the Solution 64 data deck (see appendix D of ref. 10). The function of these DMAP alters is to access the eigenvalue extraction routines that solve for the frequencies and mode shapes. The alters are setup so that the final mass and stiffness matrices generated in the large displacement analysis are used. The advantages of utilizing the combined analysis capability are reduced CPU, faster turnaround time, and reduced quantities of output listings. In general, the CPU time can be reduced by one half.

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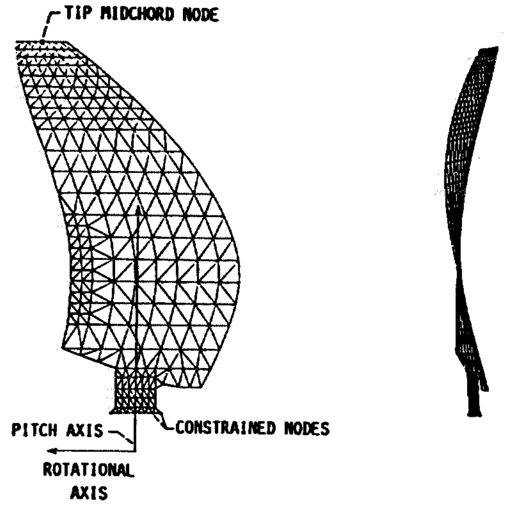

FIGURE 1. - TYPICAL FLEXIBLE BLADE FINITE ELEMENT MODEL.

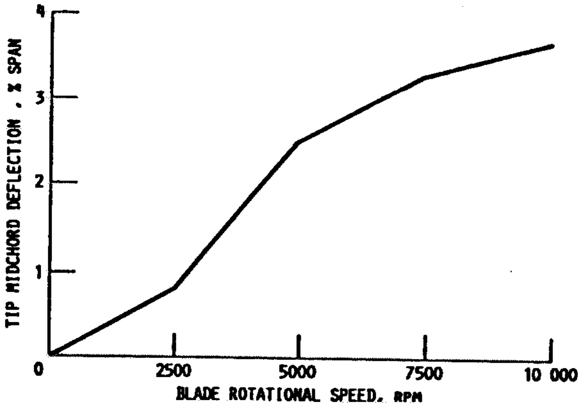

FIGURE 2. - TYPICAL NONLINEAR DEFLECTION CURVE FOR FLEXIBLE BLADE.

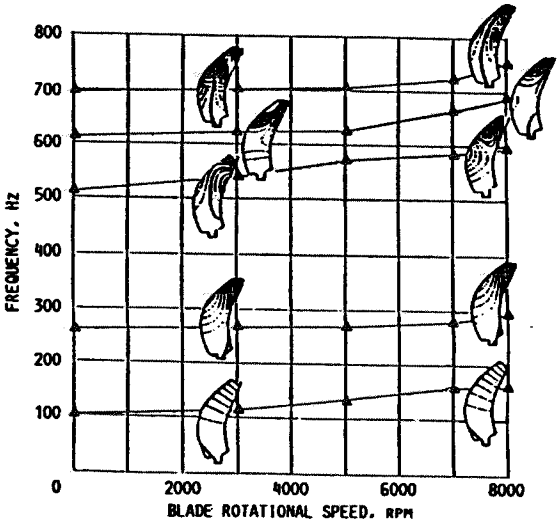

FIGURE 3. - TYPICAL FLEXIBLE BLADE CAMPBELL DIAGRAM.

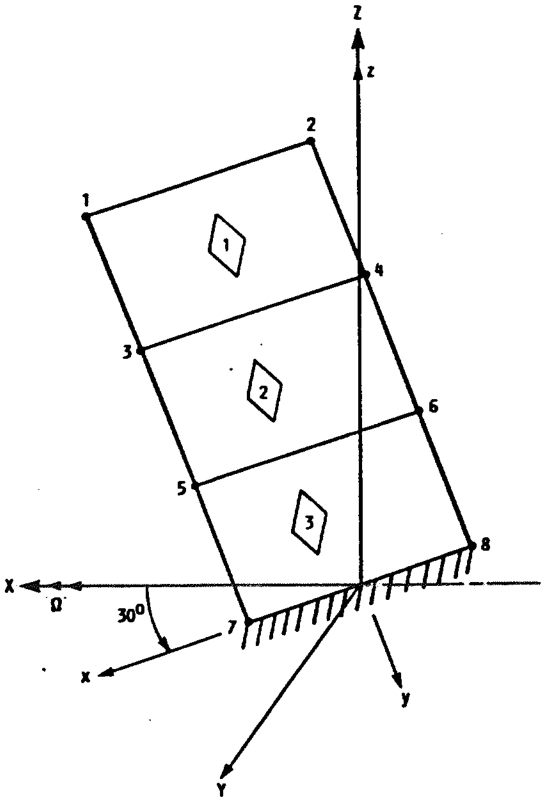

FIGURE 4. - DEMONSTRATION PROBLEM FINITE ELEMENT MODEL.