GEAR ANALYSIS USING THE MSC/NASTRAN CYCLIC SYMMETRY APPROACH WITH ENHANCED GRAPHICS

by

G.R. Parker

Presented at

MSC/NASTRAN USER'S CONFERENCE

Pasadena, California

March 22-23, 1984

HUGHES HELICOPTERS, INC.
Culver City, California

GEAR ANALYSIS USING THE MSC/NASTRAN CYCLIC SYMMETRY APPROACH WITH ENHANCED GRAPHICS

G.R. Parker
Hughes Helicopters, Inc.
Culver City, California

Presented at

MSC/NASTRAN USER'S CONFERENCE
Pasadena, California

March 22-23, 1984

ABSTRACT

The application of the cyclic symmetry approach in MSC/NASTRAN is applied to the modal analysis of a large finite element model of a helicopter transmission gear. Solution sequence 48, cyclic modes, is used with "axi" type symmetry.

To enhance the post interactive graphics display, a modification was made to the graphics program to display assembled segment output deflections for any desired section, up to and including the full model. To verify the approach, a circular plate model was analyzed prior to application to the large gear model.

Results for both analyses are presented.

This technique was applied during the analysis of the Hughes AH-64A Apache Helicopter. The results show the obvious advantages offered by this method.

INTRODUCTION

During the past two years Hughes Helicopters, Incorporated (HHI) has been performing an extensive finite elements analysis of the AH-64A Helicopter.

The AH-64A Apache, shown in Fig. 1, is currently in the production phase for the U.S. Army. Results from the analysis formed a foundation for the work presented in this paper. Therefore, a brief overview of the prior work will be presented.

The Apache shown in Fig. 2 is a 4-bladed helicopter - approximately 50 feet long, 12 feet high, and having a 12-foot wing span. It can carry up to a maximum of four pylons which contain a variety of missiles and rockets. In addition, it houses a 30mm Chain Gun under its nose. Gross weight is approximately 15,000 pounds.

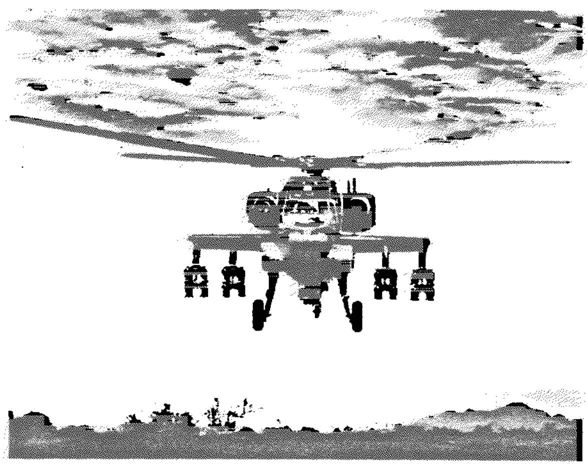


Fig. 1 - Hughes AH-64A Apache Helicopter

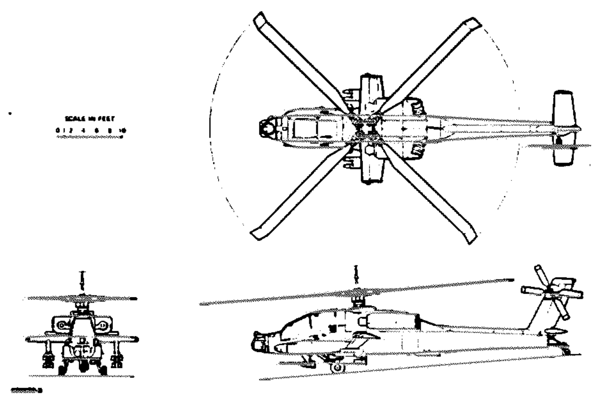


Fig. 2 - Views of the Apache

A dynamic analysis was performed using the NASTRAN model shown in Fig. 3. This model had 1,632 grid points, 4,357 structural elements, and 9,792 dynamic degrees-of-freedom (DOF).

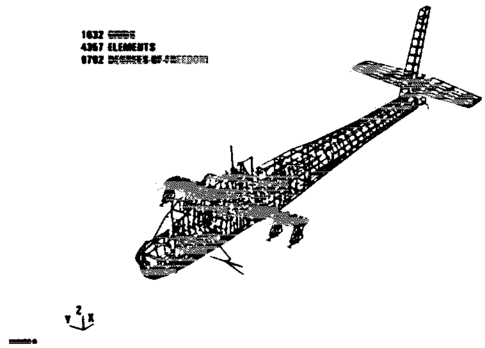


Fig. 3 - NASTRAN Model

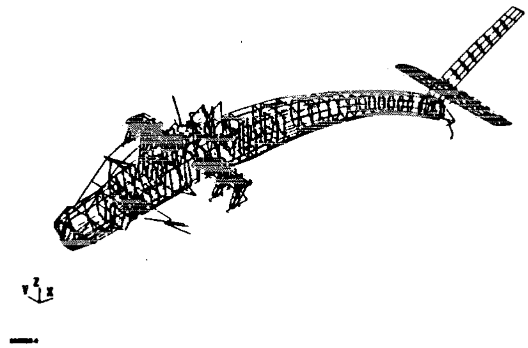


Fig. 4 - First Vertical Bending Mode (5.55 Hz)

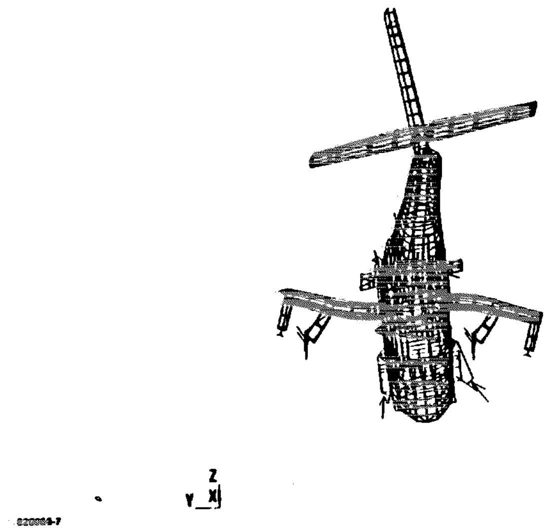


Fig. 5 - First Wing Antisymmetric Mode (5.40 Hz)

With the aid of some recent features in NASTRAN, namely, fast eigenvalue extraction routines, substructuring, and component mode synthesis, the scope of obtaining modal data has changed. We no longer have to use reduction techniques where the model is reduced to a small size with a loss of accuracy and fidelity. In addition, we can now divide the model into substructures, obtain the modes, and synthesize them to represent the whole structure economically.

Initial dynamic analyses of the Apache consisted of calculating modal data from the unreduced model shown in Fig. 3 utilizing generalized dynamic reduction (GDR). It quickly became apparent that the results from these large models presented solutions having high modal densities; i.e., many modes within a given frequency range. Thus, the ability to solve these large dynamic finite element problems had also increased the difficulty of modal identification. The work presented in Reference 1 was developed to provide an aid in mode identification.

Figs. 4 and 5 present some typical structural mode shapes which were identified using this aid, and show the detail now available. This is a vast improvement over earlier reduced "stick-type" dynamic models.

The next analysis step was to progress to a superelement model of the structure. The Apache was divided into 14 superelements and the component mode synthesis (CMS) approach was applied.

To illustrate this approach on a simple structure, the plate in Fig. 6 was divided into four superelements, numbers 10, 20, 30 and 40. Constrained normal modes were calculated for each superelement about the "heavy" boundary lines. The modes for each superelement were combined using generalized and discrete coordinates, from which free-free system modes were calculated for the full plate.

One of the system mode shapes is shown in Fig. 7, where the deflected shapes for each superelement were combined to present the deflected shape of the total structure.

The graphics program used for this display is called "FASTDRAW" (Reference 2), and was developed by the McDonnel Douglas Automation Company (MCAUTO). This program was modified to display the total deflected shape for a superelement analysis. Normally the system mode is

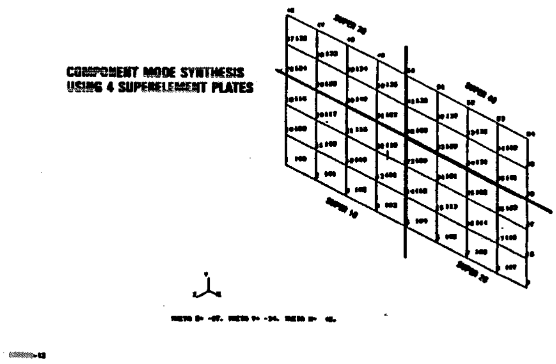


Fig. 6 - Component Mode Synthesis (CMS) Using Four Superelement Plates

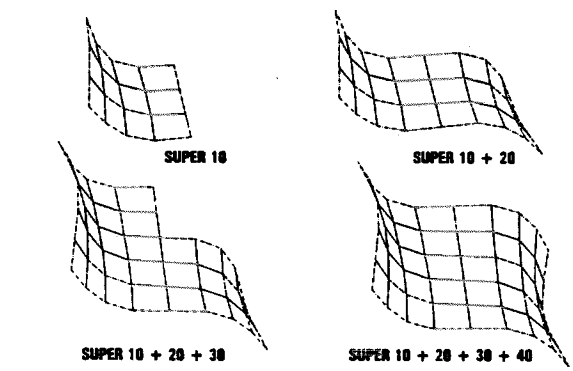


Fig. 7 - Assembled System Mode Using CMS

displayed for each individual superelement – but not assembled. Few graphics programs have this capability.

Therefore, in introducing the subject of cyclic symmetry with enhanced graphics, the previous experience in working with large finite element models, the associated data processing, and the use of interactive graphics, provided a foundation for this work.

BACKGROUND

Early this year, the dynamics section was asked to support the design of an intermediate stage helical gear.

The gear, shown by the cross-hatched section in Fig. 8 is located in the transmission of the Apache Helicopter shown earlier in Figs. 1 and 2. The following work has just been completed and the results are preliminary, but of interest in application.

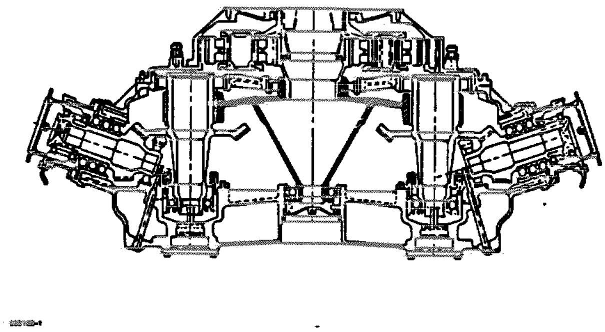


Fig. 8 - Intermediate Stage Helical Gear

The development procedure was to design the gear, build it, and test the product by acoustically exciting it to ensure that there were no responses near the gear mesh frequency – a function of the shaft speed and number of gear teeth.

The test procedure, as shown in Fig. 9, was very simple and consisted of setting the gear on a support, exciting the gear teeth with a siren, and monitoring the response.

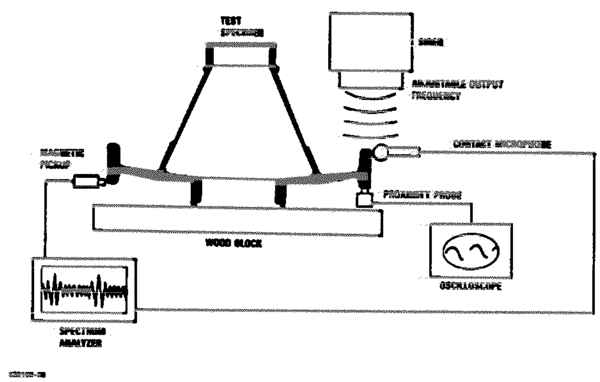


Fig. 9 - Test Schematic

Fig. 10 is a photo of the test set-up and a view of the actual gear being tested.

Fig. 11 shows a "sand pattern" resulting from sand type substances being sprinkled on the structure while it is excited at a constant input level and a frequency of one of it's structural modes.

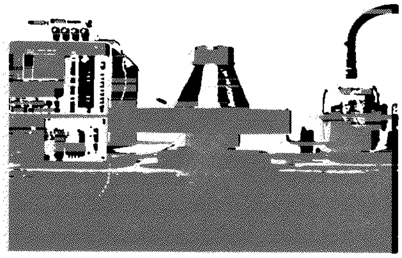


Fig. 10 - Resonance Test Setup

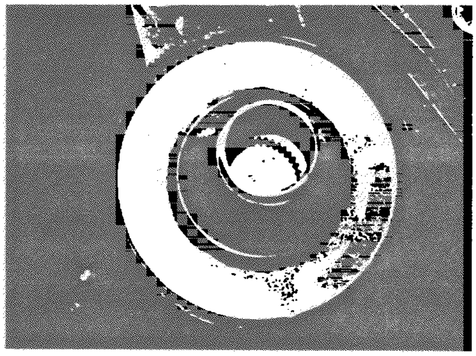


Fig. 11 - Sand Pattern of 8n Mode at 2600 Hz

The pattern is classified as an "8n" mode, where there are 8 radial node lines about the gear which indicate no motion on those lines.

Fig. 12 is a typical frequency response curve for a test specimen. The peaks were identified and labeled from the sand patterns. The "8n" mode is identified at 2600 Hz.

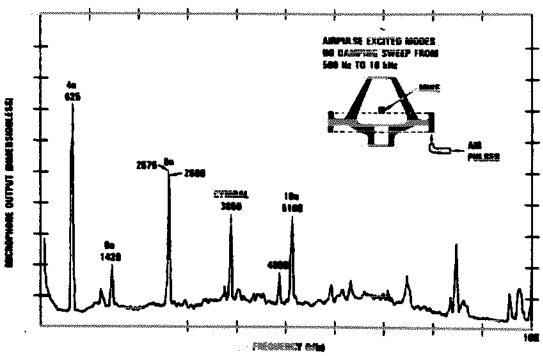


Fig. 12 - Response Curve

The task outlined for the NASTRAN analysis was to model the gear, duplicate the test results, and predict results for modified or other gear configurations. If successful, the analysis would greatly enhance the design procedure.

The first step in the analysis was to model the gear. This was performed with the aid of the "FASTDRAW" preprocessing program. Dimensions and angles were transformed from a production-type drawing as depicted in Fig. 13 to a graphics terminal screen as shown in Fig. 14. On the left, points and lines are keyed in to form boundaries and regions. On the right, arcs of circles are constructed between lines and points to form curved surfaces. Using construction methods such as these, the preprocessor becomes a powerful tool for the modeler.

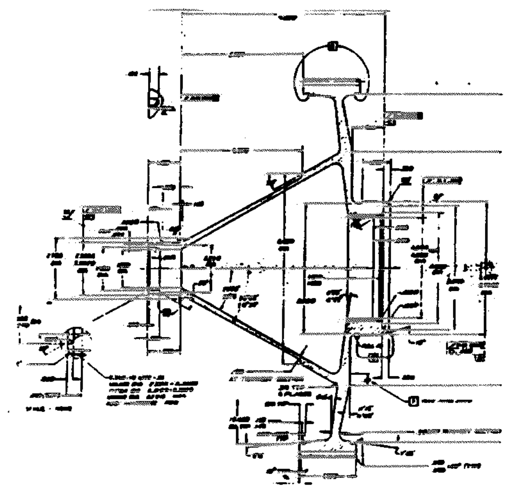


Fig. 13 - Production Drawing of Gear

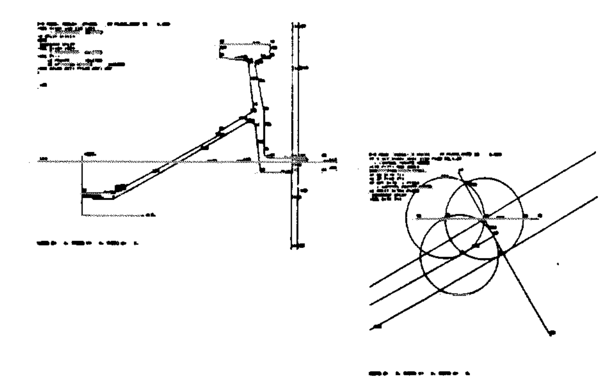


Fig. 14 - Preprocessing Interactive Graphics

Cursor operations allow the calculation of distances between points, lines, etc. for quick verification of the model to the drawing.

Fig. 15 shows a planer model being developed and divided into regions prior to meshing, using solid 8 noded brick elements. The planar model will then be 'poped' or 'swept' through a 5-degree segment to produce a 3-dimensional structure.

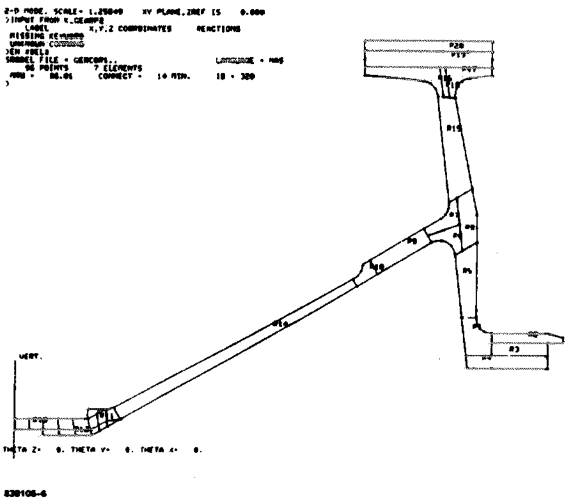


Fig. 15 - Planer Model

Fig. 16 shows a model which was 'poped' once to 5 degrees and repeated three more times to produce a four-layer model. One layer has 542 grid points and 189 elements.

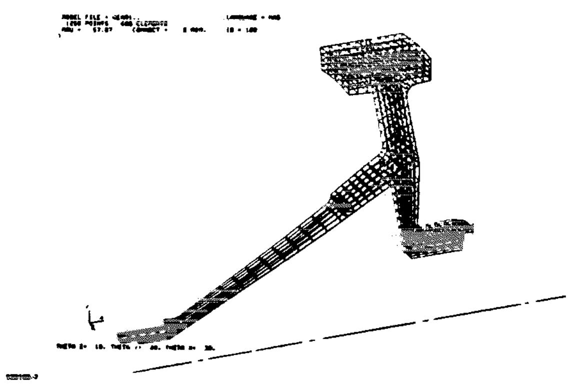


Fig. 16 - Three-Dimensional, Four Layered Solid Element Model

For efficiency, it was found best to use the axi-symmetry option in the cyclic symmetry analysis, where all grid points must lie on the boundary. Therefore, the one layer, 5 degree segment became the fundamental region. At this point, the mesh size was keyed to aspect ratios that should give accurate results.

The graphics 'window' option is shown in Fig. 17, which was used to provide detailed information on grids, elements, distances, etc.

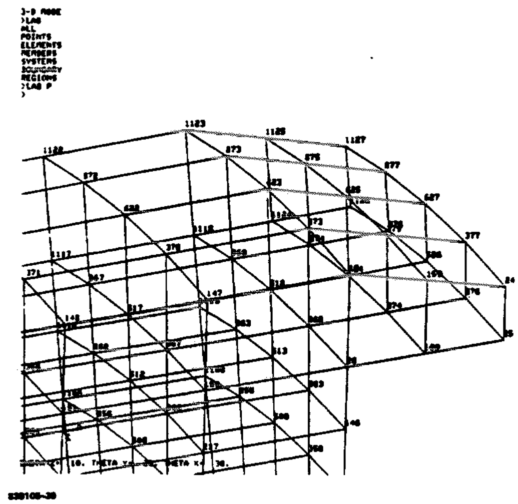


Fig. 17 - Graphics Window Option

Having completed the model constructions with the preprocessor, the one layer, 5 degree segment, shown in Fig. 18, was converted to a NASTRAN bulk data deck for use in the cyclic symmetry analysis.

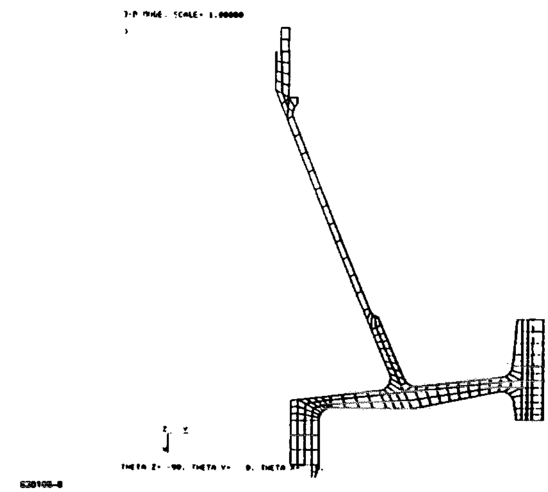


Fig. 18 - One Layer, Three-Dimensional Static Model

For a 5 degree model, the total gear would be divided into 72 segments. However, by using the cyclic symmetry approach, only the properties for one segment need to be used.

It can be seen from the models, that the helical gear teeth were not modeled. For this initial analysis work, the tooth section properties (i.e. area, E, and G) were modified to account for the mass and stiffness effects of this area. Modes and frequencies were calculated for the second through the tenth harmonic cases. Solution 48 (see Reference 3), the real eigenvalue analysis for cyclic symmetry problems was used to calculate the normal modes. This solution sequence is extremely easy to use, requiring only a few special cards. A parameter study was performed, where these properties were varied until a 'best fit' was obtained for all harmonics.

In cyclic symmetry, a fourth harmonic case will result in 8 radial nodal lines in the y-z plane as we saw in the test of the gear. A serious limitation is that for post-processing the output segment deflections cannot be shown assembled with existing graphics programs.

The deflected gear shape of segment 1 for the first mode of a fourth harmonic case is shown in Fig. 19. An arbitrary scale factor was used to set the relative deflections. Any requested individual segment can be output.

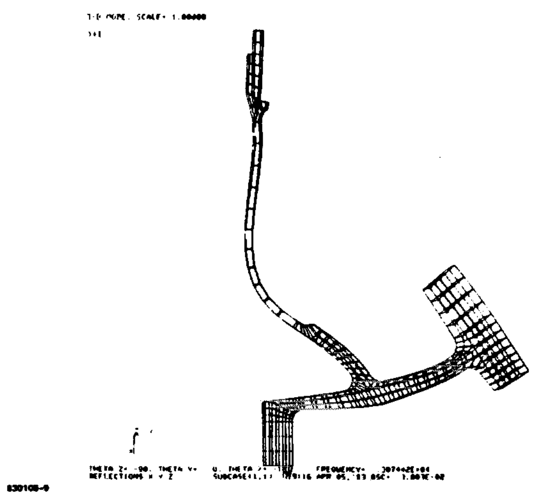


Fig. 19 - Deflected Shape for Mode 1, Segment 1

Fig. 20 shows this same mode shape with vectors referenced to the static shape - another graphics output option.

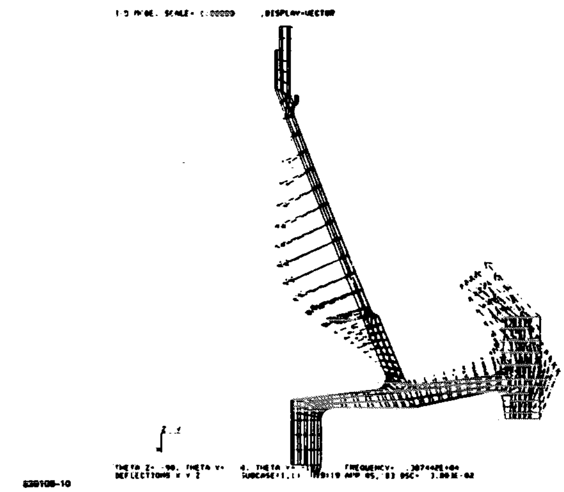


Fig. 20 - Vector Display for Mode 1, Segment 1

Again, Fig. 21 demonstrates the window option which can be used on the deflected shape for close examination.

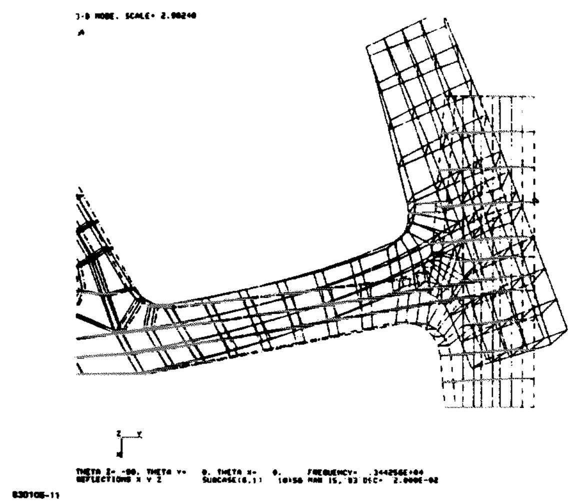


Fig. 21 - Window View - Deflected/Undeflected

In correlating the analysis results to the resonant frequency tests for various gear configurations, some discrepancies were found in the test data. Since a valid data base was required for our analysis, where the actual teeth had not been modeled and properties were set based on test data, it was decided to temporarily stop work on the gear analysis and proceed with the model of a structure for which we knew the results.

In addition, it was desired to pursue the capability of being able to display graphically the assembled segment outputs for a structure. This could be performed more economically on a smaller model.

A free-free circular plate was selected as a structure with which displacement patterns could be developed for a fourth harmonic case to duplicate the "8n" type nodal lines we had seen in the gear test.

Charts similar to the one shown in Fig. 22 provide theoretical frequency and mode shape descriptions for flat plates (Reference 4). The darkened plate for a free circumference give a matrix of frequencies for various combinations of nodal circles and nodal diameters.

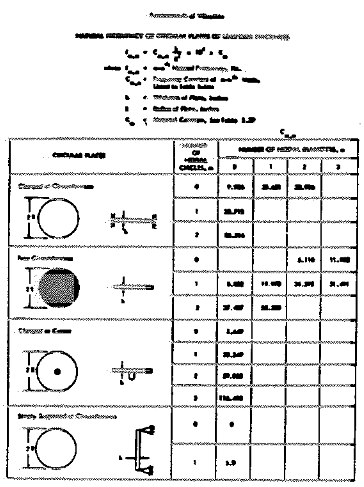


Fig. 22 - Plate Model Test Book Solution

The static circular plate model shown in Fig. 23 was developed again with the aid of the preprocessor of the FASTDRAW interactive graphics program. Note the darkened strip which will later be used as the model in a cyclic symmetry analysis to compare those results with this full plate model.

Fig. 24 shows the designated grid numbers for the plate, which contained 361 points and 360 elements.

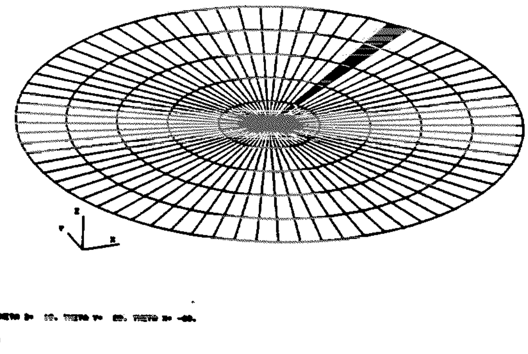


Fig. 23 - NASTRAN Static Plate Model

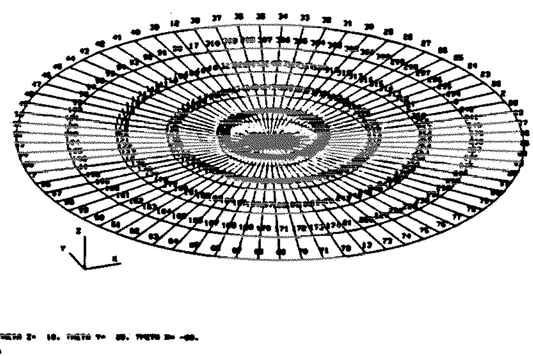


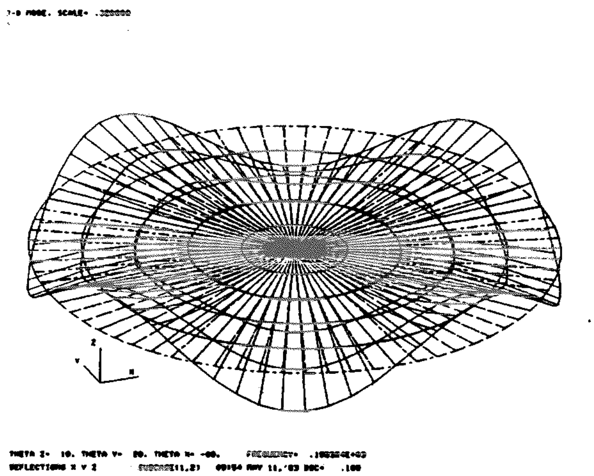
Fig. 24 - NASTRAN Plate Model Grid Points

Using the Solution 3 sequence for Normal Modes Analysis, modes and frequencies were calculated for the full plate model. Since the frequency of the fourth harmonic was known from the "textbook" values, the inverse power eigenvalue routine was used to calculate the modes within a small frequency range. These modes could then be evaluated to find the actual fourth harmonic modes. The Inverse Power Routine was extremely efficient for this type analysis.

Fig. 25 shows the deflected/undeflected shape for the first fourth harmonic plate mode.

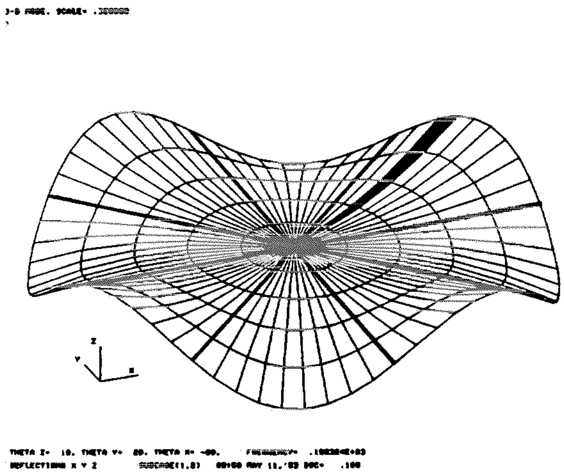
The deflected-shape-only plot of Fig. 26 may be clearer. One can see four circumferential sinewaves with 8 radial lines shown by the heavy lines every 45 degrees. A straight edge will verify no bending occurs along these lines.

The calculated frequency checks with textbook values, indicating that a fundamental fourth harmonic plate mode has been found.



630106-15

Fig. 25 - Plate Deflected/Undeflected Mode Shape

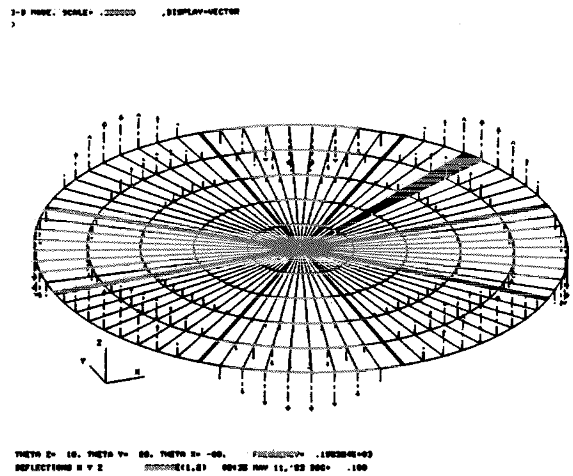


630106-16

Fig. 26 - NASTRAN Plate Model Deflected Shape

Again, observe the shaded strip for later comparisons with a cyclic symmetry analysis.

Fig. 27 shows a vector plot of the same mode for the full plate analysis. This display best shows the 8 nodal lines of zero displacements, emphasized by the heavy lines. Note that vectors repeat every 90 degrees as expected for a fourth harmonic, and vectors at 45 degrees are opposite in sign.

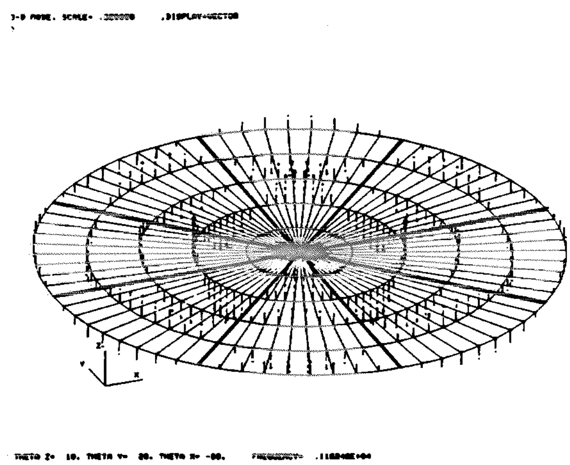


630106-17

Fig. 27 - NASTRAN Plate Model Vector Display

In Fig. 21 of the textbook solution, it can be seen that if the number of nodal diameters is held constant, the number of nodal circles will increase as the frequency is increased.

The vector display of Fig. 28 shows a higher frequency fourth harmonic mode, where the 8 diagonal nodal lines are still apparent, and two nodal circles will be formed as radial vectors cross in the two outer segments.



630106-18

Fig. 28 - NASTRAN Plate Model Fourth Harmonic, Third Mode, Vector Display

For the plate model, all elements are 2 inches long on the radial sides. Therefore element rings occur at 2, 4, 6, 8, and 10 inches for our model. From Reference 4, nodal circles for a fourth harmonic, third mode would occur at a radius of 9.25 and 6.05 inches. These values appear to agree very closely with the vector displacement of Fig. 28, and the deflected shape shown in Fig. 29, where again, the Z = 0 crossings occur in the two outer elements.

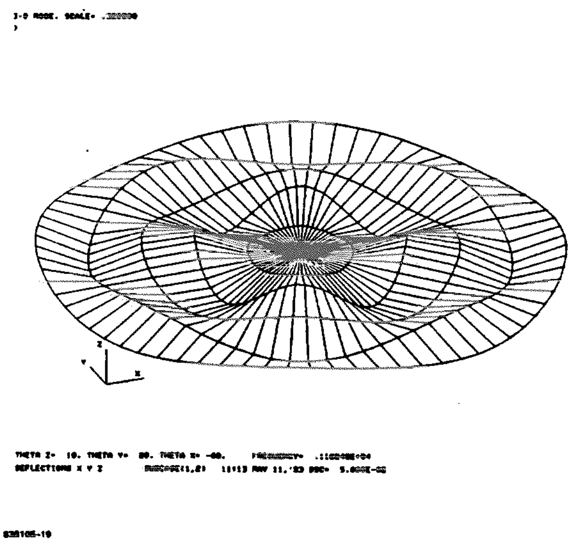


Fig. 29 - Fourth Harmonic, Third Mode Deflected Shape

With confidence that NASTRAN results agreed with "TEXTBOOK" solutions for a full plate, the remaining step was to apply the cyclic symmetry approach to the same problem.

A static model (see Fig. 30) was taken from a strip of the full plate model as shown earlier in Fig. 22. The fourth harmonic mode was calculated using the Cyclic Symmetry Solution Sequence 48. Output deflections for segments 1 and 2 were requested and are shown in Fig. 30. For current post-processing graphics, these deflected shapes can only be displayed one at a time, unassembled, which is a serious deficiency in understanding even as simple a structure as this.

Using a technique similar to that developed on the superelement analysis of the helicopter, the post-processing graphics program was again modified for this simple axi-symmetric case, to assemble as many output segments as desired - up to and including the whole structure.

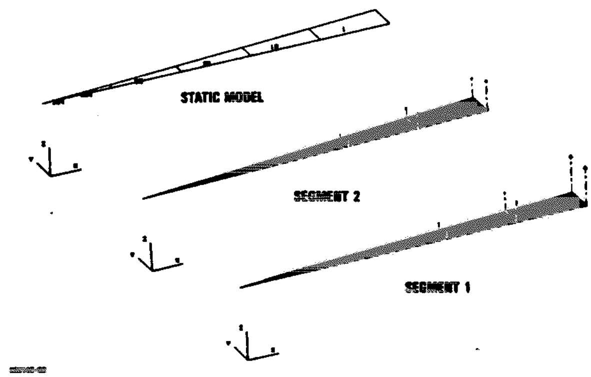


Fig. 30 - Cyclic Symmetry Approach

This procedure does require the creation of a static model file as large or larger than the assembled segments, and a correlation of grid point sequencing. Basically, the model file provides physical grid locations for the segments other than the reference grids for the initial fundamental region. In this case, where cylindrical coordinates were used, only the θ coordinates are incremented by 5 degrees for each segment while the "R" and "Z" locations remain constant. The creation of the model file is a simple task for the graphics preprocessor, while compatible grid points locations are created automatically in the "FASTDRAW" preprocessor program with a few special cards specified in the program documentation.

The modified program was checked out by assemblying segments which were output from the cyclic symmetry analysis of the plate strip. While 72 strips for the entire plate could have been assembled, it was decided to output only a quarter of the full plate, or 18 segments.

The static model file for this 18 segment assembly is illustrated in Fig. 31, where only the vector deflections for segment 1 are included.

Fig. 32 shows the assembled vector deflections for all 18 segments of the quarter plate. Segments 1 and 2 are highlighted, and segments 3 through 18 continue in a counter-clockwise direction.

Again, we note that the vectors are repeated every 90 degrees and are opposite at 45 degrees, as we saw in the full model of Fig. 28. The complete model could be assembled from the cyclic symmetry segments if desired.

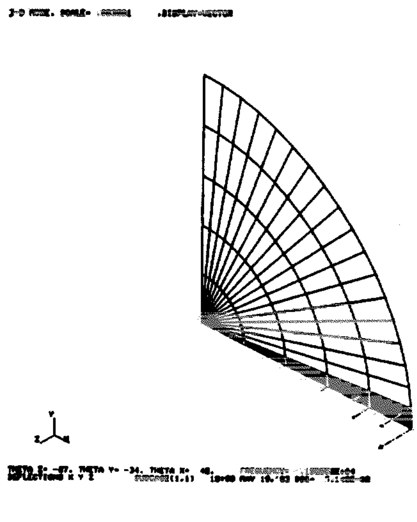


Fig. 31 - Segment 1 Deflections

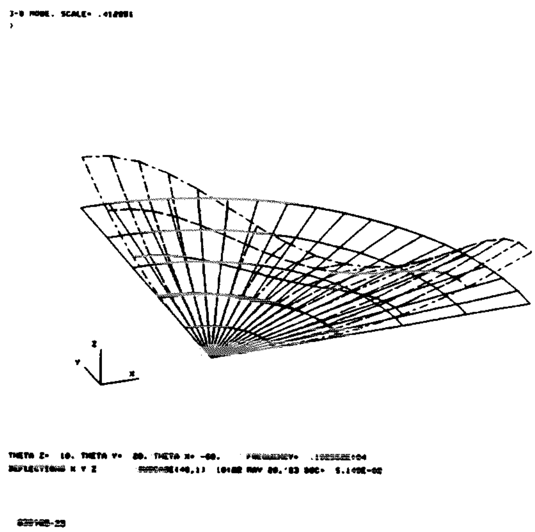


Fig. 33 - Assembled Deflected/Undeflected Shapes

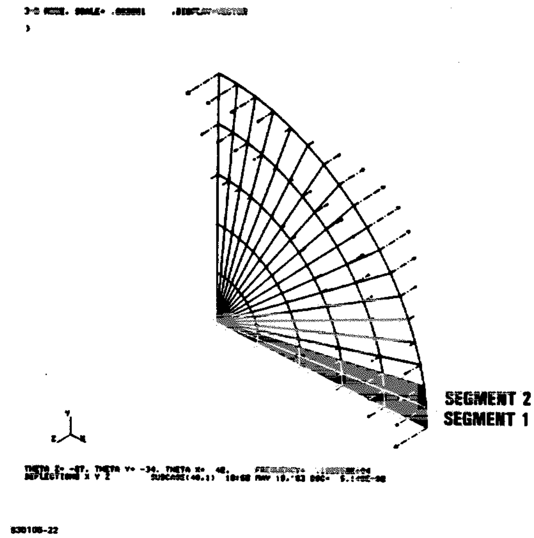


Fig. 32 - Quarter Plate Assembled Deflections

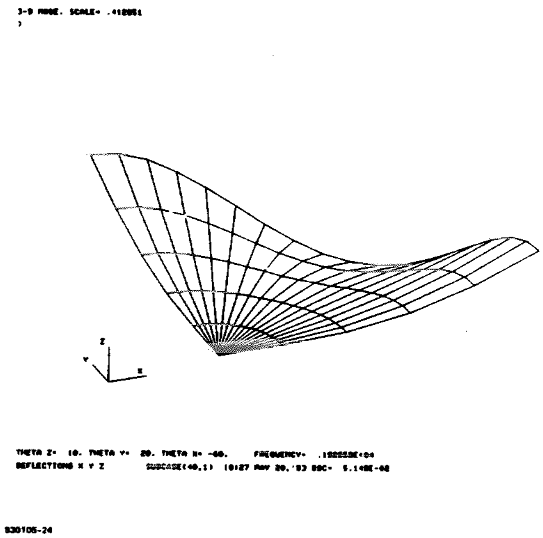


Fig. 34 - Assembled Deflected Shape

The deflected/undeflected results are shown in a rotated view in Fig. 33 for easier comparison to the full model results of Fig. 25.

Also, the deflected only shape of Fig. 34 can be directly compared to the full plate analysis of Fig. 26.

With good frequency and mode shape agreement, it was concluded that the cyclic symmetry approach was able to reproduce the full plate analysis and "TEXTBOOK" results.

With confidence gained from the plate analysis, we returned to the gear problem and applied the graphics assembly technique to a ten segment model.

Note, only one 5 degree segment was used in the NASTRAN cyclic symmetry analysis. However, output was requested for ten segments. NASTRAN outputs required for plotting are requested via an automated MCAUTO DMAP ALTER which uses the "OUTPUT2" module. A separate job step (NSPOST, Reference 2) processes and assembles the data for display in FASTDRAW.

Fig. 35 shows an outline option in FASTDRAW where the element visibility has been switched off, and only the outline of the elements are displayed.

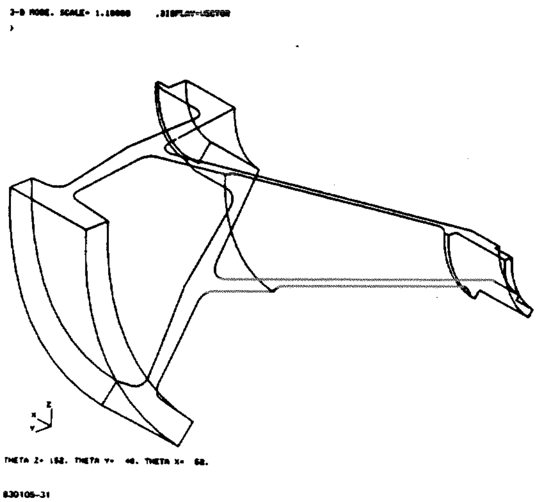


Fig. 35 - Ten Segment Static Model Outline

Fig. 36 shows the same outline with one layer of the ten segment model shown. This model contains approximately 3000 grid points and 2000 elements.

Output deflections for ten segments of the fourth harmonic, first mode were assembled and displayed in Fig. 37 in an outline option showing deflected/undeflected shapes. In this mode, the major displacements are in the tooth area.

Another option is shown in Fig. 38, where the static outline is displayed with the elements turned off, but with the resultant vectors displayed at all 3000 grids. Again, the vectors show the major displacements in the tooth area.

The final effort consisted of displaying an assembly of 18 segments which represented a 90 degree or quarter segment of the total gear.

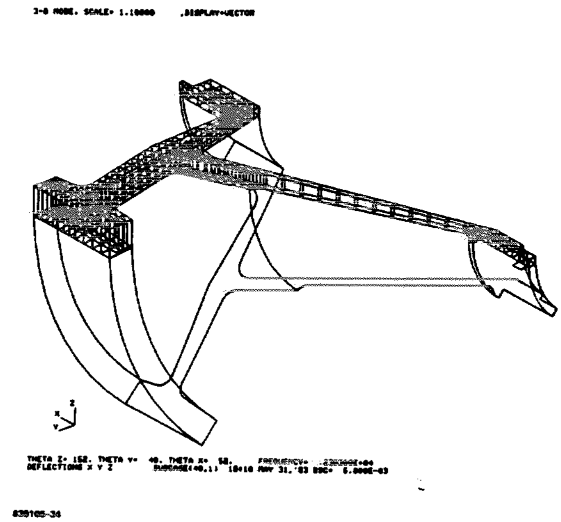


Fig. 36 - Ten Segment Static Model Outline

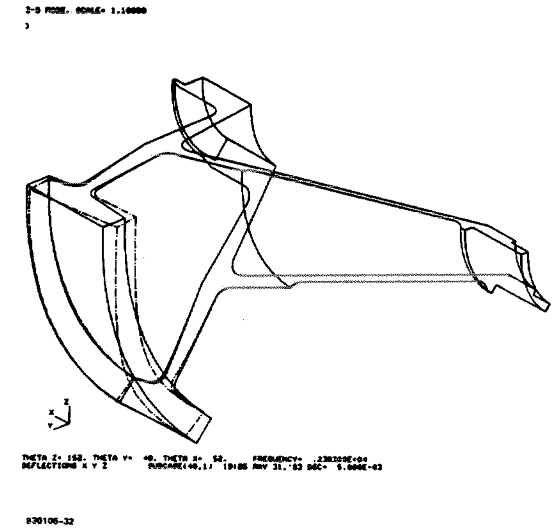


Fig. 37 - Ten Segment Outline Defl/Undefl

This model had approximately 5000 grid points and 3400 elements. The static model with a portion of the elements displayed is shown in Fig. 39.

In Fig. 40 a close up of the tooth area is shown for the 18 segment model, where output displacements for the fourth harmonic, first mode were displayed for only one edge of the gear face.

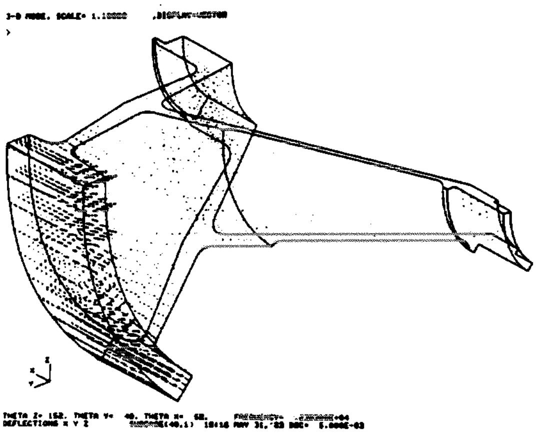


Fig. 38 - Ten Segment Outline/Vector Displacement

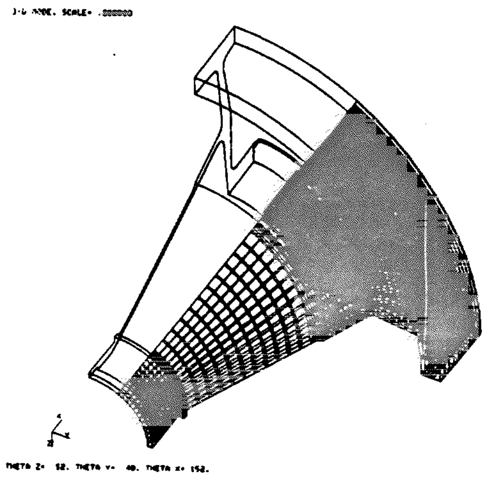


Fig. 39 - 18 Segment Static Model

Close inspection of this 90 degree segment shows vectors repeated every 90 degrees and opposite at 45 degrees. There are two nodal crossings which would produce 8 nodal lines on a full gear model, similar to what was shown in the sand patterns of the gear test shown in Fig. 11.

With these results, it is felt that the gear test results can be duplicated using the cyclic symmetry approach with the enhanced "FASTDRAW" graphics program.

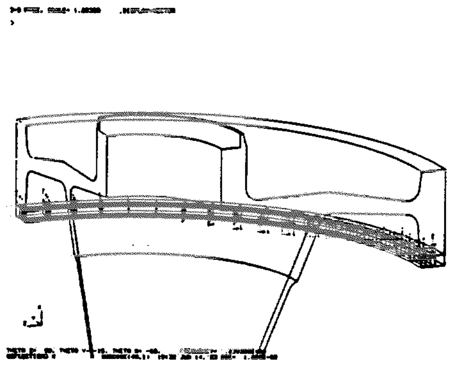


Fig. 40 - Fourth Harmonic Gear Face Displacements

SUMMARY

In summary, the cyclic symmetry approach has been applied to a large finite element model of an axi-symmetric structure. By using only a fundamental region, the approach has been found to be cost effective and efficient and it expands capabilities for increasing problem size. The use of pre and post interactive graphics has been illustrated in aiding in the creation of models and presenting results. A simple verifiable model was utilized to demonstrate the procedure and results. In addition a new graphics capability for assemblying cyclic symmetry segment outputs has been demonstrated.

ACKNOWLEDGMENT

The author wishes to thank the MSC and MCAUTO consultants, and the HHI stress group for their assistance in the publication of this paper.

REFERENCES

1. Parker, G.R. and J.J. Brown, "Kinetic Energy DMAP for Mode Identification," MSC/NASTRAN User's Conference Proceedings, Paper 8, March 1982.
2. MCAUTO FASTDRAW/3 Interactive Post-Processing Manual, McDonnell Douglas Automation Company.
3. NASTRAN Users and Programmers Manuals, MacNeal-Schwendler Corporation.
4. Leissa, A.W., "Vibration of Plates," NASA SP-160, 1969.