ABSTRACT

The increased capabilities of modern computers and commercial analysis codes have made possible the complex and detailed analysis required to develop efficient and reliable turbine components subject to extreme mechanical and thermal loading. The major problems associated with utilizing this technology are concentrated in three areas:

- Generating efficient finite element models of complicated turbine structures.
- Organizing and condensing, into a manageable unit, the information resulting from detailed analyses.
- Ability for rapid modification and iteration based on the results obtained.

This paper describes an ongoing project at AVCO Lycoming which incorporates MSC/NASTRAN into an integrated turbine analysis system utilizing computer graphics. The initial phase of this work included software development to utilize MSC/NASTRAN's capability to output any user selected information involved in the course of an analysis to a data file. Geometry connectivity, displacement and stress output to tape, can be accessed and displayed by this software, allowing the engineer to interrogate in great detail complicated 3-dimensional structure models in a brief interactive graphics terminal session.

A case study is presented which illustrates the payoff associated with these methods.

INTRODUCTION

Modern computerized structural analysis systems, such as MSC/NASTRAN, have had widespread acceptance in the gas turbine industry. The actual realization of their full utility to produce turbine hardware of greater efficiency and reliability, however, does not depend on this analysis capability alone. Effective design of complicated structures using the proven capabilities of the various commercial codes must also incorporate the following interactive computer capabilities as an integral part of the analysis process.

1. Finite element model generation.
2. Display, summation and interrogation of the results of an analysis.
3. Modification for re-analysis.

The schematic diagram shown in Figure 1 represents the logical design process utilizing these key ingredients. It is presented to emphasize the importance of each step in the design and optimization process accompanying much of the hardware development in the gas turbine industry. In the event that any of these aides are not available, the process will not be nearly as effective. As the complexity of computer programs and engine components increases, extensive graphics capability becomes essential, rather than just a convenience. Interactive geometry definition, modification and enhancement enables the user to rapidly create a mathematical model with considerable detail. Subsequent analysis provides the analyst with unprecedented insight into the behavior of the component under various loading conditions and applications. However, the ability to generate refined models which can be quickly modified and re-analyzed for component optimization, while very essential, results in an overwhelming amount of information which must be examined by the analyst. Postprocessing of this structural analysis data using computer graphics and data management techniques is an approach to resolving this problem.

Software which transfers MSC/NASTRAN analysis data and produces on-line contour plots at a graphics display has been developed. Interrogation routines which provide information regarding local properties, displacements, stresses and temperatures are also included. This enables one to make full use of the data resulting from a detailed stress or vibration analysis during a brief interactive session. In addition, it allows the participants to iterate on the design until all criteria are satisfied. This type of system facilitates the investigation of alternative concepts, parametric studies/tradeoffs and variance analyses (i.e., tolerance influences, low material properties, hot spots, etc.).

The system described above has been utilized in the design of a high performance centrifugal impeller subjected to centrifugal loading Three-dimensional isoparametric elements were used to model the disc and airfoil geometry. Although numerous iterations were necessary to produce the desired structural, dynamic and aerodynamic configuration, the time frame in which this was accomplished was well within schedule.

For all the requirements outlined above, it is becoming increasingly evident that the integration of interactive graphics with state-of-the-art finite element codes, and an engineering data management system can produce the desired results.

INTERACTIVE GRAPHICS SOFTWARE DEVELOPMENT

A project which incorporates MSC/NASTRAN into an integrated turbine analysis system utilizing computer graphics is in progress at AVCO Lycoming. The initial phase of this work included software development to utilize MSC/NASTRAN's capability to output user selected information involved in the course of an analysis to a user file. For the purpose of performing a detailed review of a finite element analysis by interactively interrogating the results at a computer graphics display, it was necessary to obtain in the output file the following data from the NASTRAN analysis:

1. Grid point geometry (GPDT)
2. Element connection arrays (ECT)
3. Grid point deflections (OUGV1)
4. Element stresses at all grid points (OES1)

These tables are shown in the DMAP listing, in Figure 2, for a static analysis in rigid format 24. The ALTER used to print these tables and also to output them to a user file is shown in Figure 3. It should be noted that this part of the project is very straightforward due to the "OUTPUT2" capability built into NASTRAN.

Using the documentation provided by MSC, software was developed to read this user tape and make its contents available to our own application programs. A program was developed to process this information and display it on a graphics terminal. The fortran program is executed on an IBM 370/3033 under TSO, using a TEKTRONIX 4014 and PLOT10 display primitives.

The three major functions that this software can perform are projection of any three dimensional finite element model made up of brick elements, stress contour plotting, and stress interrogation capability. The three dimensional projection feature is used for orientation purposes. The engineer can display the entire structure or any subset of elements selected at any scale or viewpoint. All information about the model is available in this mode. For instance, an area of interest in the structure can be isolated from the rest, windowed, and tumbled until the particular view which reveals the desired perspective is obtained. Node and element numbers can be displayed as desired. Still more detailed information can be extracted by selecting an individual node point with the cross hair cursor, at which time the software responds by displaying the node point coordinates, the elements connected to this grid point, and the grid point temperature. This capability of interactively viewing and interrogating a three dimensional model has made the handling of five or six thousand card image bulk data decks with confidence and speed a routine matter. This facility represents an order of magnitude improvement over the process of plotting on paper a three dimensional continuum model with grid point numbers displayed. The problem with batch plotting of 3-D continuum models on paper is that there is just too much data to be observed in any one view. With each new orientation of an element subset, some area becomes clear while another obscured. Information can be extracted only by continuous scaling, rotating, and windowing in an interactive fashion until a correct view is obtained.

The stress display option allows the NASTRAN user to easily handle the other end of the information problem associated with the refined analysis of complex three dimensional structures. The output from such analyses when printed on paper tends to overwhelm the user for days in an attempt to extract any useful information regarding the response of the structure, problem areas, improvement strategy, etc. Also the confidence level in the solution is strengthened with the ability to observe that stress distributions are relatively smooth and continous, where they should be, and can be interpreted as axial pull, hoop stress, or other gross behavior. Only by standing back and viewing stress summaries which present this information in a concise manner can such huge volumes of data be utilized effectively in a timeframe which can impact the design.

With the stress display option developed at Lycoming, the structure can be partitioned into element sets and isolated for display. All the standard scaling and windowing techniques described above are available. In addition any stress value such as x-normal, Y-Z shear, or VonMises effective stress, can be displayed using isostress contour lines. (Figure 4) The cross hair cursor can then be used to select nodes for displaying actual numerical stress values. Utilizing the software in this mode gives the operator the essential diagnostic capability mentioned above in a brief interactive session.

The final and equally important aspect of the total design process is the ability to iterate on a solution. After the engineer has made an accurate, refined, and correct model, executed the analysis, reviewed the results in great detail, found problem areas, formulated a strategy to modify the structure to produce improvements in the structural response or efficiency, he must now alter the model accordingly and do it all over again. In short, he needs a timely way to modify the structure in order to effectively complete all steps in the optimization cycle. This particular step may require input from other disciplines because structural modification often carries with it corresponding penalties in aerodynamics, performance and weight.

The vehicle for this rapid exchange of data requires considerable interactive graphics capability and a data management system for data transfer, presentation and permanent storage. The integrated turbine analysis project at AVCO Lycoming is aimed at achieving this goal.

CASE STUDY

Incorporation of interactive graphics and MSC/NASTRAN for component analysis can significantly reduce the total time and cost of a task from the levels required in a non-interactive mode. This savings was clearly realized during design and analysis of a high performance centrifugal impeller. The following is a description of the procedure utilized to obtain an optimum aerodynamic and structural configuration using the techniques discussed previously.

The cross section of a Lycoming gas turbine engine is shown in Figure 5. The component circled in this figure is a centrifugal impeller, or sometimes referred to as a centrifugal inducer-impeller. Its basic function as last rotating member in the compressor is to further compress the air that enters it axially and direct it into the diffuser's radial inlet. It has long been known that the performance of such a component could be greatly improved if its outer radius, at flow exit, could be increased without suffering the detrimental effects of the corresponding increased tip speeds. This could be accomplished by the "leanback" configuration illustrated in Figure 6. This approach, however, is hampered by the structural limitations of the "leaned" non-radial blade in a strong centrifugal force field. The blade must respond with a bending stress distribution in order to remain in equilibrium.

In the pre-processing mode, the initial finite element model of the impeller was generated using a specialized mesh generator. The primary input consisted of aerodynamic streamline definition tables which are passed to the display program. At the graphics terminal, the engineer incorporated the structural geometry, in this case a disc, to the initial aerodynamic geometry. Having created the total drawing the data was transferred to a mesh generator, and the finite element model returned to the screen. The model was then displayed in various orientations, nodal points and elements modified as needed, and files recycled to generate a corrected model. This sequence was repeated until the geometry was completely checked, and a NASTRAN deck created and submitted for execution.

Twenty-noded isoparametric brick elements were used to model the disc and airfoil geometry. The total model, shown in Figure 7, consisted of a single vane and corresponding disc wedge, containing 561 elements and 3738 grid points. Symmetry in geometry and loading made it possible to simulate the entire structure using a single wedge segment and applying multi-point constraint equations between corresponding grid points on either side of the disc. These equations were generated along with the geometry data by the specialized mesh generator. The impeller mesh generator was used to make a three dimensional brick model by taking the 2-D mesh nodal geometry and connectivity and mapping it onto 3-D space using the streamline coordinates R, Θ, Z and thickness data to produce one layer of bricks in the blade part of the structure and three layers of bricks in the disc part.

The model was then displayed and interrogated for correctness and used to extract other information such as which nodes to use for S.P.C.'s to eliminate rigid body motion and hence create a stable model for analysis. This viewing capability also allowed all participants to visualize the actual part for the first time, instead of just a series of numbers or a two dimensional drawing. It is important to note that the disc and blade and not just the blade are included in this model. This was done because the deflection of the disc under load significantly affects the elastic response of the blade.

The results from the analysis of this baseline design where output to a 1600 BPI, 8 track magnetic tape and later loaded onto a direct access file as desired for post-processing. Interactive interrogation of this model revealed high bending stress in the "leanedback" exit area of the impeller at the base of the blade. The resulting stress output from a single static run contained on the order to 250,000 words of stress data. This is clearly in excess of what can be reviewed by an individual from conventional printer output, with any semblance of confidence. A subsequent dynamic analysis of just the blade, supported at the base, revealed a fundamental frequency which would have to be doubled in order to put it outside the range of a known source of excitation.

The objective of the analysis was to configure a geometry which would satisfy aerodynamic, structural and vibratory requirements. By manipulating the impeller blade thickness distribution, stress levels were driven to an acceptable level at the critical flow exit location. Additional geometry changes were required to satisfy criteria regarding the dynamic characteristics of the blade. By varying the thickness of the airfoil, natural frequencies of concern were raised above known sources of excitation.

Thickness modification was accomplished by developing a special graphic application program to manipulate the aerodynamic streamline definition tables used as input to the three dimensional impeller mesh generator. This program displayed this data in four windows, an instruction tutorial and a message area as shown in figure 8. The windows displayed the following information.

1. The R versus Z view of the streamlines.

2. The thickness versus length of any streamline selected as the operational streamline.

3. The Θ coordinate versus length of any streamline selected as the operational streamline.

4. A cross-sectional slice through the impeller blade at any selected location.

Windows 2 through 4 displayed the unmodified impeller blade data as dotted lines and the modified shape as solid lines allowing the user to immediately examine the modifications in blade geometry caused by his interactive commands. In the first window, portions of the blade could be selected and modification schemes applied. Subsequent repainting of the display produced "feedback" in the form of streamline thickness, Θ orientation and blade cross-section in the other windows. This gave the user virtually unlimited control of the impeller blade shape in a very convenient and useable form. This aerodynamic data was then re-input to the impeller mesh generator and a modified 3-D model submitted for analysis. Furthermore, this altered streamline data was made available to the aerodynamics group for input to their various analysis programs to assess the impact of this modification on overall performance.

Several modifications were required and accomplished during the impeller analysis. The final geometry represents a judicious compromise between features chosen for aerodynamic, structural and vibratory reasons.

CONCLUSION

The design of advanced turbomachinery is a highly specialized and difficult task. Obtaining an acceptable design configuration within a reasonable time frame requires the involvement of numerous engineering disciplines having the ability to make continuous iterations and improvements based on detailed analysis. To facilitate this task, a project which incorporates interactive graphics and engineering data management techniques into an analytical tool for all engineering disciplines has been initiated at AVCO Lycoming. The initial phase of this project has been to demonstrate the optimization of stress and vibration considerations without sacrifice of aerodynamic performance in the design of an advanced centrifugal impeller; however, to obtain the maximum return from such a system, incorporation of other disciplines (heat transfer, materials, etc.) must also be accomplished.

Such a system reduces the risk of costly redesign programs, by providing the capability for a more thorough and precise investigation of the structural integrity of all components early in the design stage. This approach also creates the means for quick response to contract proposals with efficient interdisciplinary analyses. The development cost for a system with these capabilities is clearly not insignificant; however preliminary estimates based on Lycoming computer utilization have shown a positive return on investment can be achieved in a short period of time.

This project required the incorporation of MSC/NASTRAN into an interactive graphics environment. On-line geometry definition, modification and enhancement has enabled the user to rapidly create a refined mathematical model. Interactive programs which allow the user to display analysis results through the use of contour plots and interrogation routines have been developed and checked out in a production environment. The payoff associated with these methods is typified by the detailed case study provided in this paper for the design of a high performance centrifugal impeller.

Software development to extend these capabilities to other technical disciplines and applications is scheduled as part of an overall objective of an integrated turbine analysis system at Lycoming.

ACKNOWLEDGEMENT

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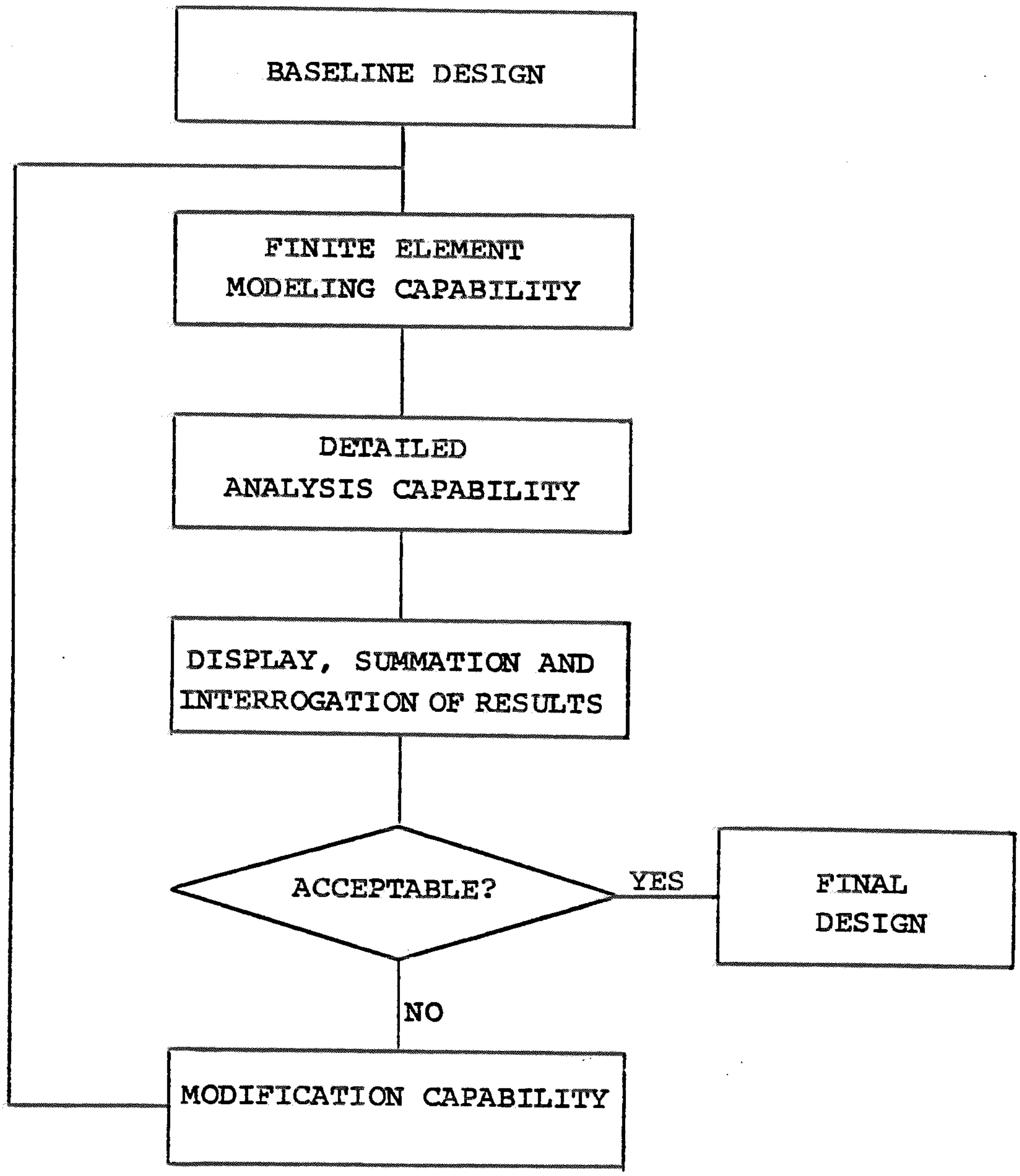


FIGURE 1. COMPUTER AIDED DESIGN AND ANALYSIS

```
   N A S T R A N   S O U R C E   P R O G R A M   C O M P L I C A T I O

DMAP-DMAP INSTRUCTION
 NO.
  1    BEGIN     NO. 24 STATIC AND INERTIA RELIEF ANALYSIS 11 AUGT 197
  .
  .
  9    GP1       GEOM1,GEOM2,/GPL,EQEXIN,GPDT,CSTM,BGPDT,...
                 NOGPDT $
  .
  .
 11    GP2       GEOM2,EQEXIN/ECT $
  .
  .
176    SDR2      CASECC,CSTM,MPT,DIT,EQEXIN,SIL,ETT,EDT,...
                 XYCDB/OPG1,OQG1,OUGV1,OES1,OEF1,PUGV1/...
  .
  .
188    OUTPUT2   GPDT,ECT,OUGV1,OES1,//0/8 $
188    TABPT     GPDT,ECT,OUGV1,OES1// $
  .
  .
214    END       $
```

FIGURE 2. DMAP LISTING SHOWING OUTPUT TABLES

NASTRAN JCL

```
//CLEAN    EXEC PURGE,PACK=MSNAST
//UTIL01.SYSIN DD *
  SCRATCH PURGE,VOL=3330=MSNAST,DSNAME=CHECK.POINT.RESTART
  SCRATCH PURGE,VOL=3330=MSNAST,DSNAME=DICTION.ARY
/*
//NASTRAN EXEC MSNAST,DB01=IMPEL2,DB1DISP=NEW,D1=50,
//         NEWGEN2=G0048V00,CPOINT=CYEST,
//         SPACK=MSNAST,DPACK=MSNAST,XUN=3330,PUNCH=PUNCH,
//         W1=25,W2=10,R=1024K,T=30,USER=USERT
```

NASTRAN EXECUTIVE CONTROL DECK ECHO

```
ID IMPEL2,NASTRAN
APP DISP
SOL 24
$    OUTPUT TO POSTPROCESSING TAPE
ALTER 188
OUTPUT2   GPDT,ECT,OUGV1,OES1,//0/8   $
TABPT   GPDT,ECT,OUGV1,OES1//   $
ENDALTER
$
DIAG 8,13,14
CHKPNT=YES
TIME 30
CEND
```

FIGURE 3. ALTER FOR OUTPUT TABLES

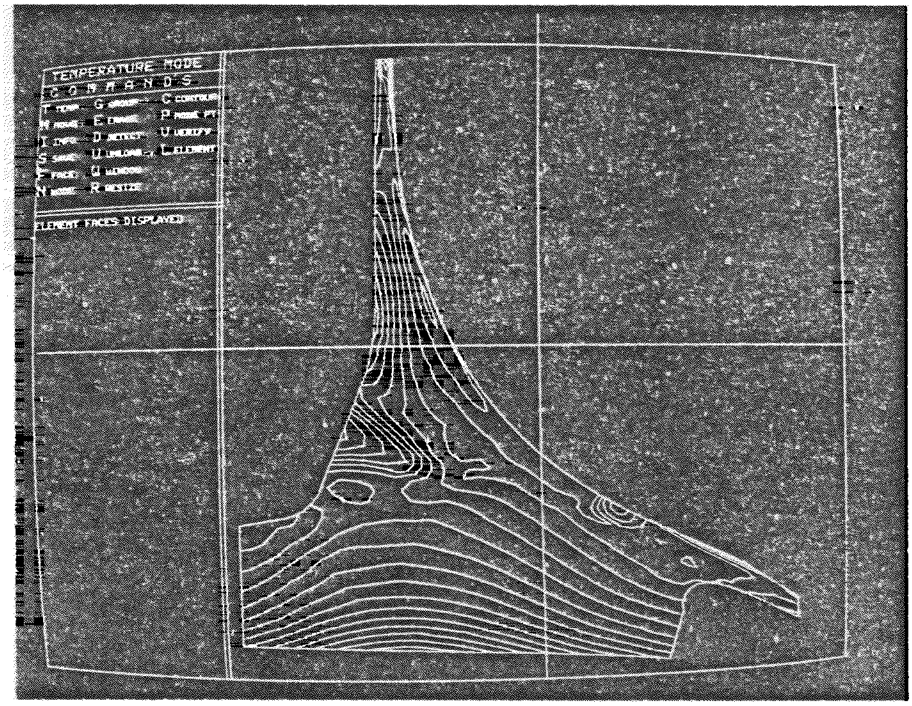
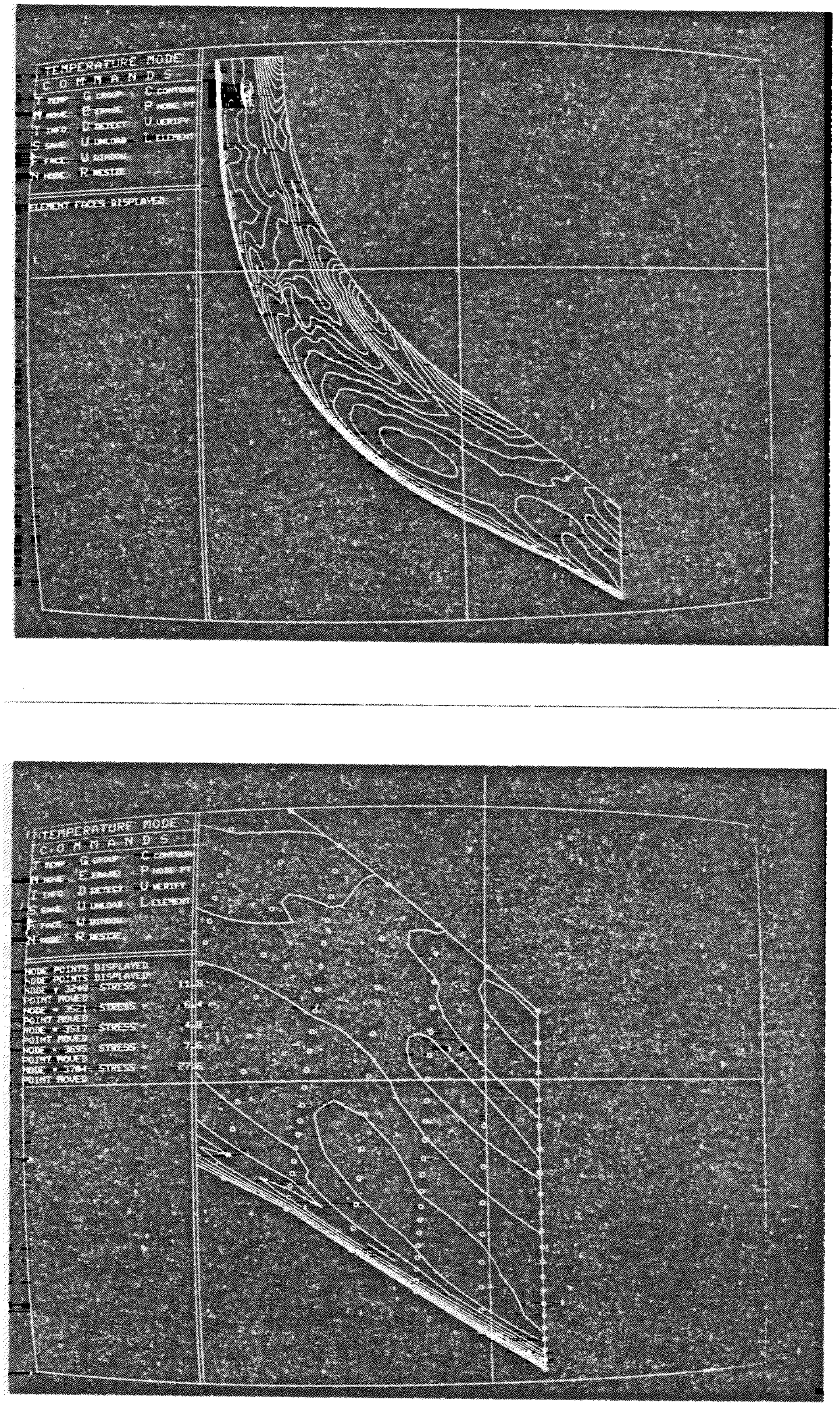


FIGURE 4-A. ISO-STRESS CONTOUR PLOTS



```
ELEMENT FACES DISPLAYED
```

```
NODE POINTS DISPLAYED
NODE POINTS DISPLAYED
NODE # 3249  STRESS =     11.8
POINT MOVED
NODE # 3521  STRESS =      6.4
POINT MOVED
NODE # 3517  STRESS =      4.8
POINT MOVED
NODE # 3695  STRESS =      7.6
POINT MOVED
NODE # 1784  STRESS =     27.6
POINT MOVED
```

FIGURE 4-B. ISO-STRESS CONTOUR PLOTS

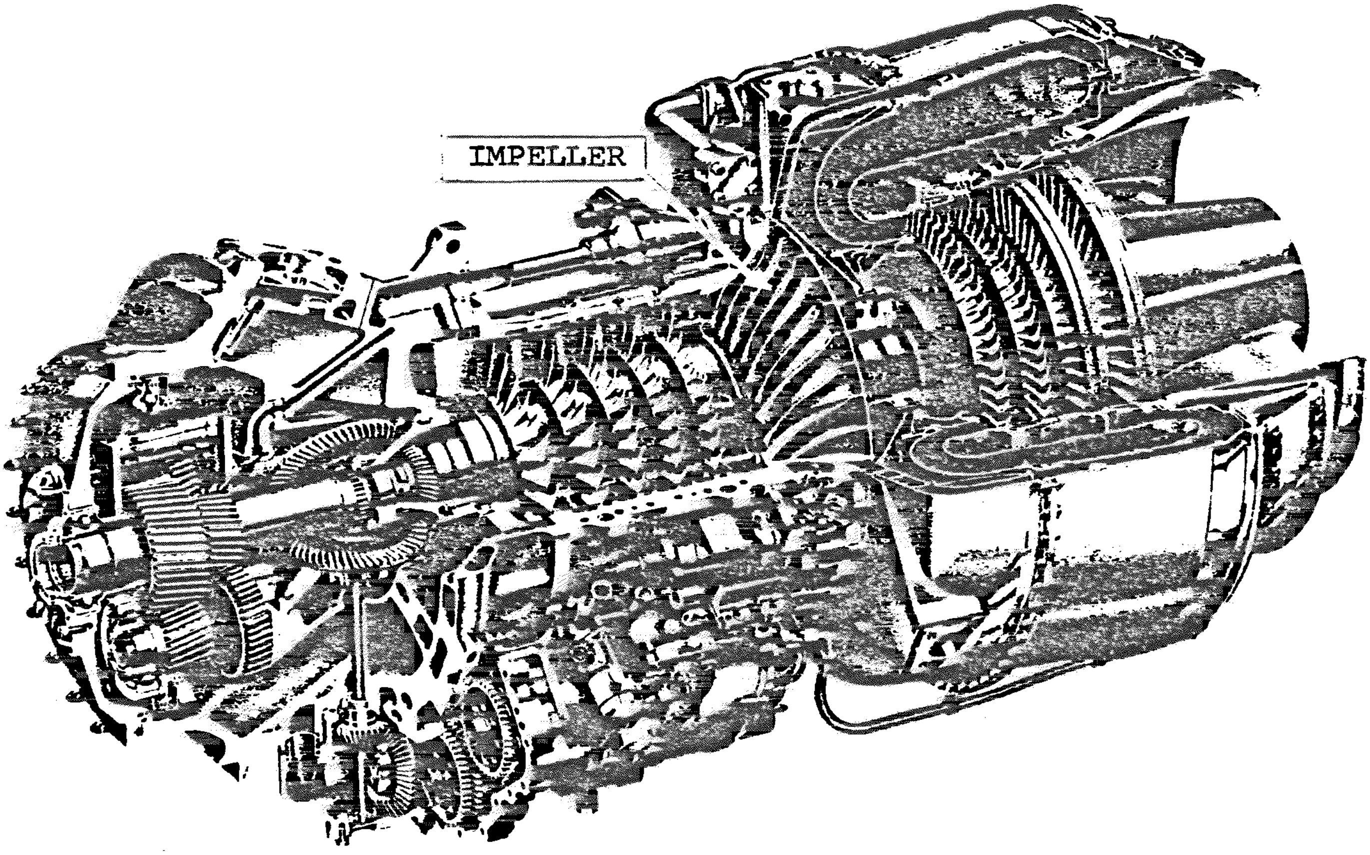


FIGURE 5. AVCO LYCOMING GAS TURBINE ENGINE

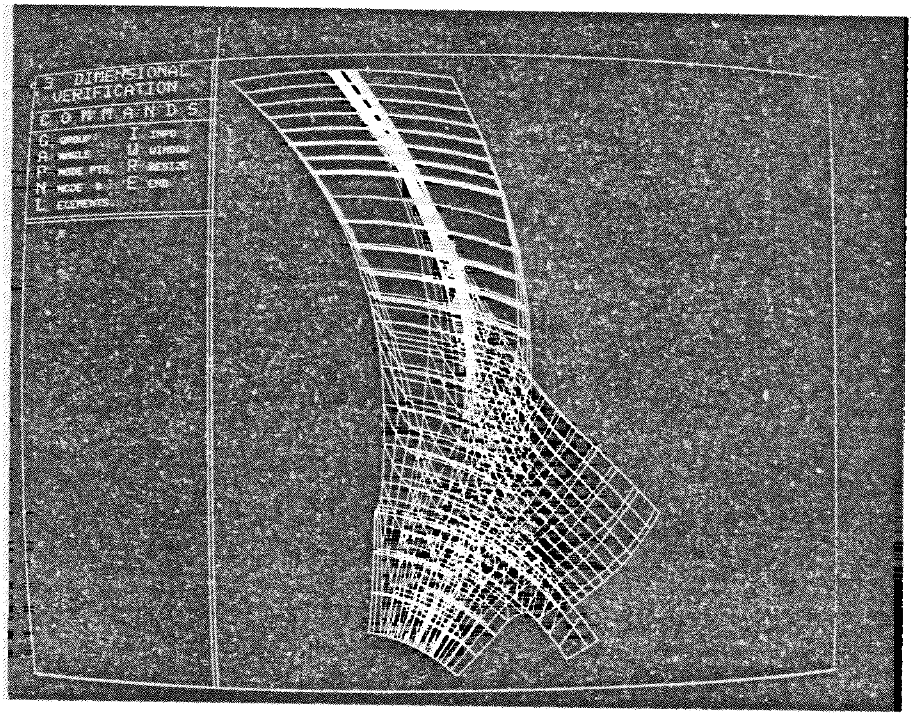


FIGURE 6. "LEANBACK" IMPELLER CONFIGURATION

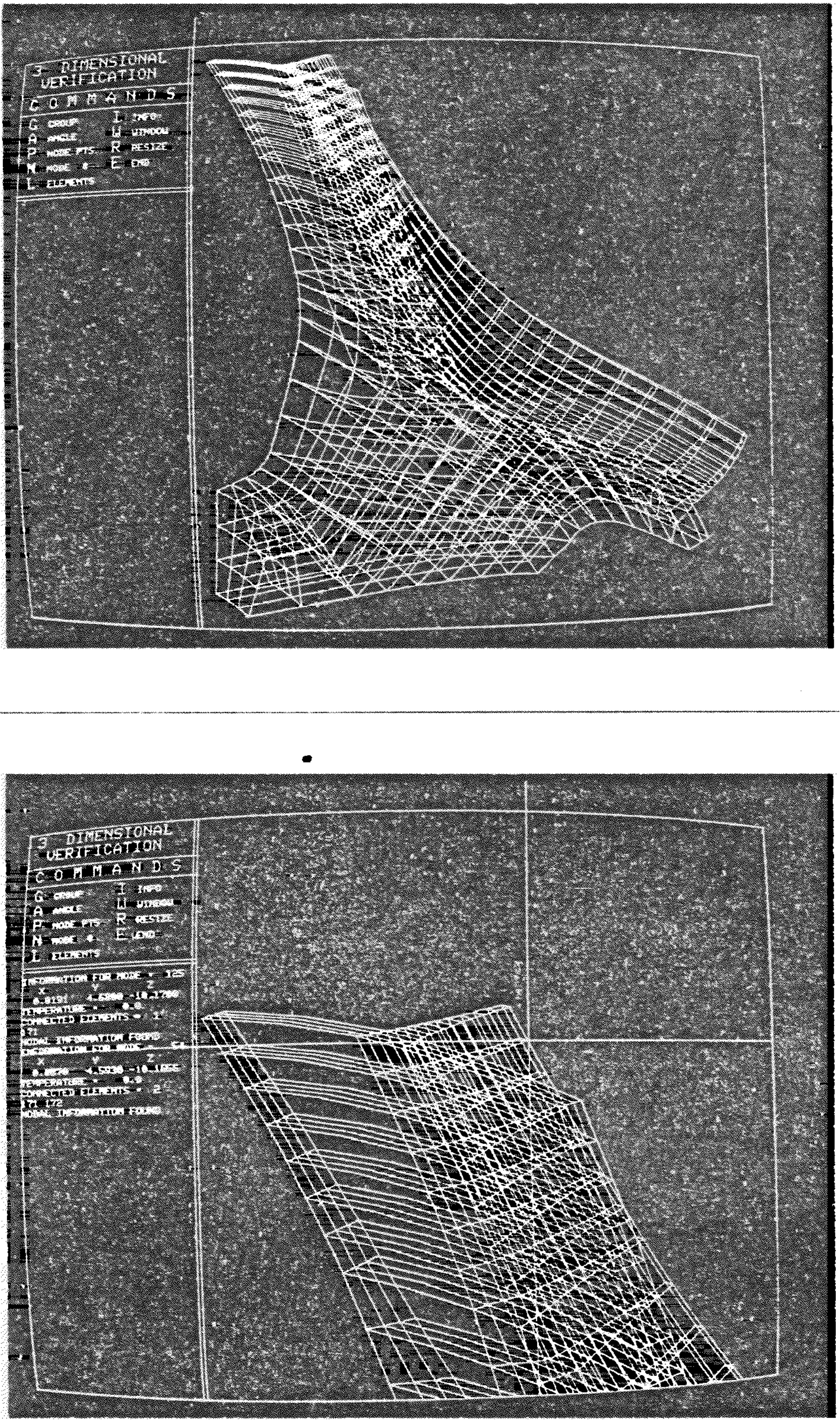


FIGURE 7. F.E. MODEL OF IMPELLER SHOWING "ZOOM" CAPABILITY

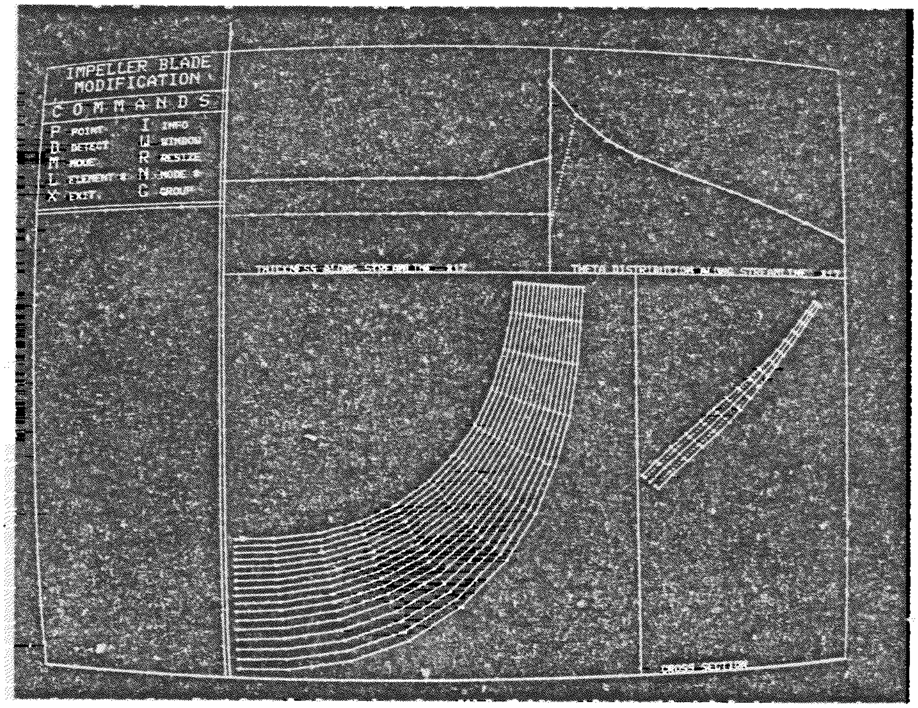


FIGURE 8. IMPELLER BLADE THICKNESS MODIFICATION