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NASA LeRC/AKRON UNIVERSITY GRADUATE COOPERATIVE FELLOWSHIP PROGRAM AND GRADUATE STUDENT RESEARCHERS PROGRAM

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16 Abstract

On June 1, 1980, the University of Akron and the NASA Lewis Research Center (LeRC) established a Graduate Cooperative Fellowship Program in the specialized areas of Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization, in order to promote and develop requisite technologies in these areas of engine technology. The objectives of this program were consistent with those of the NASA Engine Structures Program in which graduate students of the University of Akron have participated by conducting research at Lewis. This report summarizes the first year research effort which included the participation of six graduate students where each student selected one of the above areas as his special field of interest. Each student was required to spend 30 percent of his educational training time at the NASA Lewis Research Center and the balance at the University of Akron. His course work was judiciously selected and tailored to prepare him for research work in his field of interest. A research topic was selected for each student while in residence at the NASA Lewis Research Center, which was approved by the faculty of the University of Akron as his thesis topic for a Master's and/or a Ph.D. degree.

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SECTION 1

SUMMARY

On June 1, 1980, The University of Akron and the NASA Lewis Research Center (LeRC) established a Graduate Cooperative Fellowship Program in the specialized areas of Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization, in order to promote and develop requisite technologies in these areas of engine technology. The objectives of this program were consistent with those of the NASA Graduate Student Researchers Program in which graduate students of The University of Akron have participated by conducting research at Lewis.

The first year effort included the participation of six graduate students where each student selected one of the above areas as his special field of interest. Each student was required to spend 30 percent of his educational training time at the NASA LeRC and the balance at The University of Akron. His course work was judiciously selected and tailored to prepare him for research work in his field of interest. A research topic was selected for each student while in residence at the NASA LeRC, which was approved by the faculty of The University of Akron as his thesis topic for a Master's and/or a Ph.D. degree.

The objectives of the first year effort were successfully completed because all students were enthusiastic about the scope of the program and have expressed strong interest on the idea of working together with NASA engineers on highly specialized areas of Aerospace Technology. The problems encountered, in carrying out these objectives, were rather insignificant compared to the benefits obtained.

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FORWARD

This report presents the work performed on the "NASA LeRC/Akron University Graduate Cooperative Fellowship Program", NASA Grant NAG 3-50, June 1, 1980 to May 31, 1981, "Graduate Student Researchers Program", NASA Grants NGT 36-001-800 and NGT 36-001-801, September 1, 1980 to August 31, 1981, with Dr. C. C. Chamis, NASA Lewis Research Center, as Project Manager. It is the first in a series of reports regarding the progress and status of these educational grants. The Principal investigators and Directors for Grant NAG 3-50 are Drs. Demeter G. Fertis and Andrew L. Simon; for Grant NGT 36-001-800 is Dr. Demeter G. Fertis, and for Grant NGT 36-001-801 is Dr. T. Y. Chang - all of The University of Akron.

SECTION 2

INTRODUCTION AND OBJECTIVES

On June 1, 1980, under Grant Number NAG3-50, The University of Akron and the NASA Lewis Research Center established a Graduate Cooperative Fellowship Program in order to achieve common objectives in certain areas of aerospace research and engineering. The broad areas of specialization under this program were concentrated on Engine Structural Analysis and Dynamics, Computational Mechanics, Mechanics of Composite Materials, and Structural Optimization.

The research work and training in these four areas of specialization is intended to promote efforts towards the solution of problems related to aircraft engines. The general purpose is to develop the requisite methodology to solve linear and nonlinear problems associated with the static and dynamic analysis of rotating machinery, understand better their static and dynamic behavior, and develop better understanding regarding the interaction between the rotating and nonrotating parts of the engine. Research and training of this nature could result into improved engine designs with improved engine efficiencies and lower fuel consumption.

A specific purpose of the program was that linear and nonlinear structural engine problems be investigated by developing solution strategies and interactive computational methods whereby the man and computer could communicate directly in making analysis decisions. Representative examples include modifying structural models, changing material, parameters, selecting analysis options, and coupling with interactive graphical display for pre-and post-processing capability.

These research efforts will include the development of optimization techniques and methodology for the analysis of structural components made up of advanced materials, including composites that are subjected to various types of engine loads and performance constraints. This will require better understanding and more accurate determination of the mechanical properties of composite materials and their dependance to the various variations in processing procedures.

Through this program, NASA is expected to broaden the base for new ideas to develop in these areas of specialization, and bring fresh inspiration in the solution of complex problems of propulsion systems by increasing the availability of young talent for immediate employment in the aerospace industry. It will also provide a mechanism for assistance to senior government researchers in the identification and solution of such complex problems. The University of Akron is also benefiting from this fellowship program by having the opportunity to provide greater depths to its graduate programs, and by attracting high quality students to the University who will concentrate their efforts on current research needs. The students participating in this program have the opportunity to fully utilize the teaching and research expertise of the University community and the technical expertise of the NASA Lewis Research Center.

The Graduate Fellowship Program is organized and administered in a way that is expected to produce optimum results for both NASA and The University of Akron. The students who are participating in this program are selected on a competitive basis and they are under the tutelage of University of Akron faculty and Adjunct Professors appointed from NASA personnel. They are expected to complete a Master's and/or a Doctoral degree. Each student spends about 30 percent of his educational training time at NASA and the balance at The University of Akron. His coursework is judiciously selected and tailored to fit the requirements of his field of specialty.

His residency at the NASA Lewis Research Center consists of suitable continuous time intervals, usually during the summer months and/or during the four week Christmas recess, followed by a suitable part-time residency during school semester periods. In this manner the fellowship student maintains continuous contact with both institutions during the whole educational period required for his graduate degree. During his NASA residency he performs research work on a problem of his choice that is selected from a group of problems that are of interest to NASA and also related to the general areas of specialization discussed earlier. A Master's and/or a Doctoral thesis is expected to be completed as a result of this research work. The graduate degree is awarded to the student when the academic requirements at The University of Akron, as well as his NASA residency, are completed.

The NASA LeRC/Akron University Graduate Cooperative Fellowship Program is also coordinated with the Graduate Student Researchers Program that is established by NASA and administered by the University Affairs Office of NASA Headquarters in Washington, D.C. Graduate students of The University of Akron were selected to participate in this program with Lewis Research Center as the NASA Host Center.

Under this program the graduate students are selected by the individual NASA Host Center on the basis of their academic qualifications, the quality of the proposed research program and its relevance to NASA interests and needs, the student's utilization of research facilities at the NASA Center, and the availability of the student at a NASA Center for a sufficient time to accomplish the defined research. These requirements are similar in principle to those established by the NASA LeRC/Akron University Graduate Cooperative Fellowship Program and, therefore, the objectives of these two programs are served better by coordinating their graduate educational activities, training and availability of the student to the NASA Center to accomplish his defined research.

The students receiving support under these two graduate programs are not under any formal obligation to the Government of the United States, but the objectives of these programs are very well served by encouraging the students to actively pursue research or teaching in aeronautics, space science, or space technology after completion of their graduate studies.

SECTION 3

PROGRAM PARTICIPANTS

During the first year of the two programs, six graduate students were selected to participate in these programs. Four of the students are supported by the NASA LeRC/Akron University Graduate Cooperative Fellowship Program and the other two by the Graduate Student Researchers Program. A brief description of their interests and research objectives is given below in alphabetical order.

3-1. JAMES J. BENEKOS, Bachelor of Science in Civil Engineering, obtained the degree (B.S.C.E.) from the University of Pittsburgh and was selected to pursue graduate work at The University of Akron leading to the degree Master's of Science in Civil Engineering under the NASA LeRC/Akron University Graduate Cooperative Program. His research topic, "High Velocity Impact Testing and Analysis", involves experimental and analytical research work on high velocity impact using coupled Eulerian-Lagrangian Finite Element (CELFE), where the impacted structure was separated into two regions: the first region in the Eulerian zone surrounding the point of impact, and the second one in the Lagrangian zone comprizing the rest of the structure. There is also an interactive zone between the two regions where the coordinate mesh of both theories come together. The Eulerian system is best suited for large displacements coupled with material "flow" encountered in the vicinity of the impact. Structural dynamics is his area of specialization.

3-2. SAMUEL J. BROWN, JR., completed the degree Bachelor of Science in Engineering (B.S.E.) at the University of Southwestern Louisiana and the degree Master of Science in Engineering (M.S.E.) at the University of Florida. At The University of Akron, under the Graduate

Student Researchers Program, he is pursuing graduate work leading to the Ph.D. degree in Engineering. His area of specialization is Computational Mechanics and his Doctoral Dissertation research topic, under the title "On the Dynamic Response of Fluid Coupled Coaxial Cylinders", involves a comprehensive literature review and a study of the hydrodynamic response of fluid coupled coaxial cylinders, which include fluid-structural interactions and the associated influential parameters. The review and study cover both experimental and theoretical work with numerical solutions using the methods of finite difference and finite element.

3-3. TIMOTHY T. CAO, completed his undergraduate degree Bachelor of Science in Mechanical Engineering (B.S.M.E.) at The University of Akron and he is now working toward completion of the degree Master of Science in Mechanical Engineering (M.S.M.E.) at the same university under the Graduate Student Researchers Program. His area of specialization is "Structural Optimization", and his Master's thesis research deals with the determination of an optimum aerodynamic shape of engine stator vanes which are subjected to varying dynamic and thermal loadings. Under the title "Structural Optimization of Turbine Vanes', the initial phases of this research include simplified vane shapes to determine thermal stress distributions in these vanes and their barrier coating and check the validity of the results.

3-4. BRUCE GUILLIAMS obtained a Bachelor of Science in Civil Engineering (B.S.C.E.) degree from The University of Akron, and has also completed the degree Master of Science in Civil Engineering (M.S.C.E.) from the same university. He participated in the NASA LeRC/Akron University

Graduate Cooperative Fellowship Program for only one academic semester, and he performed research work on a special problem titled "A Unified Preprocessor for Finite Element Analysis". The objective of this research is to design a logical input sequence for Finite Element Analysis, so that the effort required for preparing the data can be reduced and the chance of making mistakes can be minimized. The data will be interpreted to different Finite Element Codes so that the user does not have to learn the input format of various programs.

3-5. DALE A. HOPKINS completed his Bachelor of Science degree in Civil Engineering (B.S.C.E.) at the University of Akron and he is currently working toward completion of his Master of Science degree in Civil Engineering at the same university under the support of the NASA LeRC/Akron University Graduate Cooperative Fellowship Program. His area of specialization is Mechanics of Composite Materials and his thesis research topic, "Nonlinear Analysis of Tungsten-Fiber-Reinforced Superalloy Turbine Blades", involves the development of a structural/stress analysis capability to assess the structural integrity and mechanical performance of Tungsten-Fiber-Reinforced Superalloy (TFRS) composite turbine blades. The objective is to specifically tailor this capability for application to composite turbine blades which are subjected to complex and cyclic thermo-mechanical loads, taking into account material nonlinearities arising from temperature dependent material properties, creep, and fiber degradation.

3-6. ROGER D. QUINN has selected Engine Structural Analysis and Dynamics as his area of specialization. He is working towards a Master of Science degree in Mechanical Engineering (M.S.M.E.) at The University of Akron under the support of the NASA LeRC/Akron University Graduate Cooperative Fellowship Program. He has obtained his Bachelor's of Science degree in Mechanical Engineering (B.S.M.E.) from the same university. His Master Thesis research topic is "Experimental Study of Uncentralized Squeeze Film Dampers" which involves an experimental procedure for the determination of the vibrational response of uncentralized squeeze film dampers with and without end seals. A good portion of this research work contains a complete literature review to determine the state of the art on the subject, and also contains the study that is required to design and build the experimental rotor system that is capable to be used for experimental studies on various cases of squeeze film dampers.

SECTION 4

RESEARCH PROBLEM DESCRIPTIONS AND RESULTS

The research work of each program participant is briefly discussed in this section and it is listed in the alphabetical order of their last name. The discussion of each problem contains background information and objectives regarding the research, development and results, and selected bibliography concerning the project. It should be pointed out, however, that the research work in each problem is not yet completed, and therefore the purpose of this report is to discuss briefly what has been accomplished during the first year effort. The work of each participant will be reported in detail as separate NASA reports when the research is completed.

4-1. HIGH VELOCITY IMPACT TESTING AND ANALYSIS

Researcher: James J. Benekos

Research Supervisors: Dr. Murray S. Hirschbein
Research Center
Dr. Demeter G. Fertis, The University of Akron

BACKGROUND AND OBJECTIVES

The purpose of this research project is to perform high velocity impact experimentation to correlate with theoretical results that can be obtained by using the newly developed CELFE computer code.

CELFE, the theoretical algorithm and consequent computer program, was developed for NASA by the Lockhead Missiles and Space Company, Inc., under Contract NAS3-18908. CELFE, meaning Coupled Eulerian-Lagrangian Finite Element, approaches the phenomenon of high velocity impact by separating the impacted structure into two regions as shown in Figs. (1) and (2). An Eulerian Zone which surrounds the point of impact and a Lagrangian Zone comprising the rest of the structure. An interfacing Eulerian-Lagrangian Zone is also incorporated which includes the region where the two coordinate meshes come together. The solution is based on finite element methods.

The Eulerian system is best suited for handling the large displacements encountered and severe material nonlinearities in the vicinity of the impact, while further from the impact conventional structural dynamics solutions based on a Lagrangian system can be used. There are also two additional features associated with CELFE. The first one is that it can handle composite materials and secondly the impacted structure can be analyzed by NASTRAN beyond the Eulerian Zone. The second feature makes it possible to analyze larger structures because NASTRAN can use a 2-D model while a 3-D one is required for CELFE.

DEVELOPMENT AND RESULTS

Like any other new computer program, CELFE also has to go through some adjustment procedures. The attempts that have been made to this point to run a problem on CELFE, resulted in very unrealistic results and the program stopped itself as a result of an internal check system built into the program. For example, a projectile approaching the target structure with zero velocity yielded 49 failure nodes, out of 120 total nodes, at 2×10^{-3} seconds.

Due to these difficulties, the major part of the time spent on the project was an attempt to correct the program. Unfortunately the error has not been found yet. However, much insight into this complex computer program has been gained and general areas where the error might be have been located. In the process of searching for the error the entire SELFE program was flow charted in detail and documented.

With respect to the physical experimentation it can be stated that the testing facilities have been made ready. Several low velocity tests were made to check the instrumentation in terms of detecting and recording the event. This part of the work was successfully completed.

In brief, the present status of the research project is that the facilities for physical testing of high velocity impact are ready. Once CELFE becomes functional, physical testing and theoretical analyses using this program can be performed, compare results, and prove if CELFE can adequately predict structural behavior due to high velocity impact.

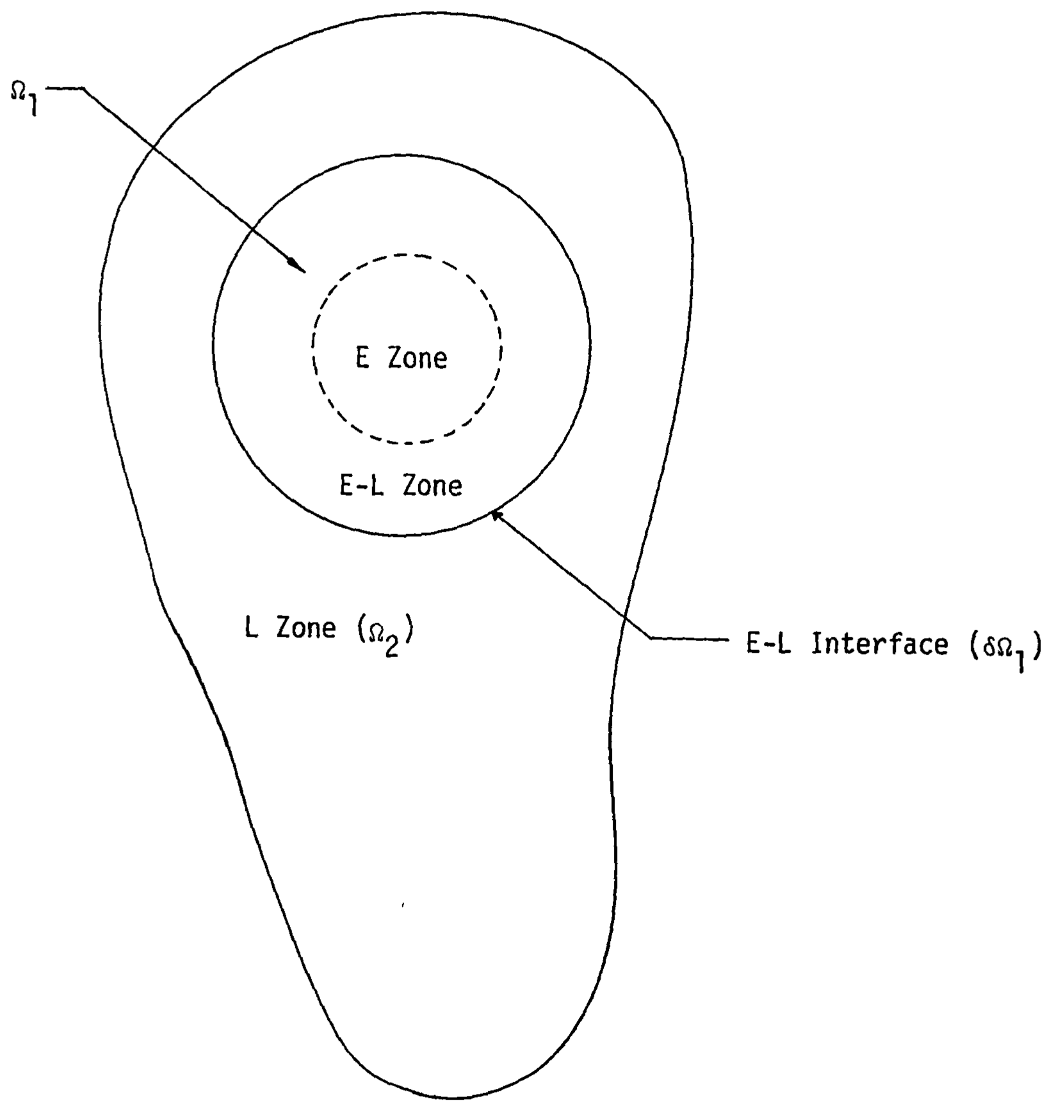


Fig. 1 - A Typical Configuration in Coupled Eulerian-Lagrangian Representation

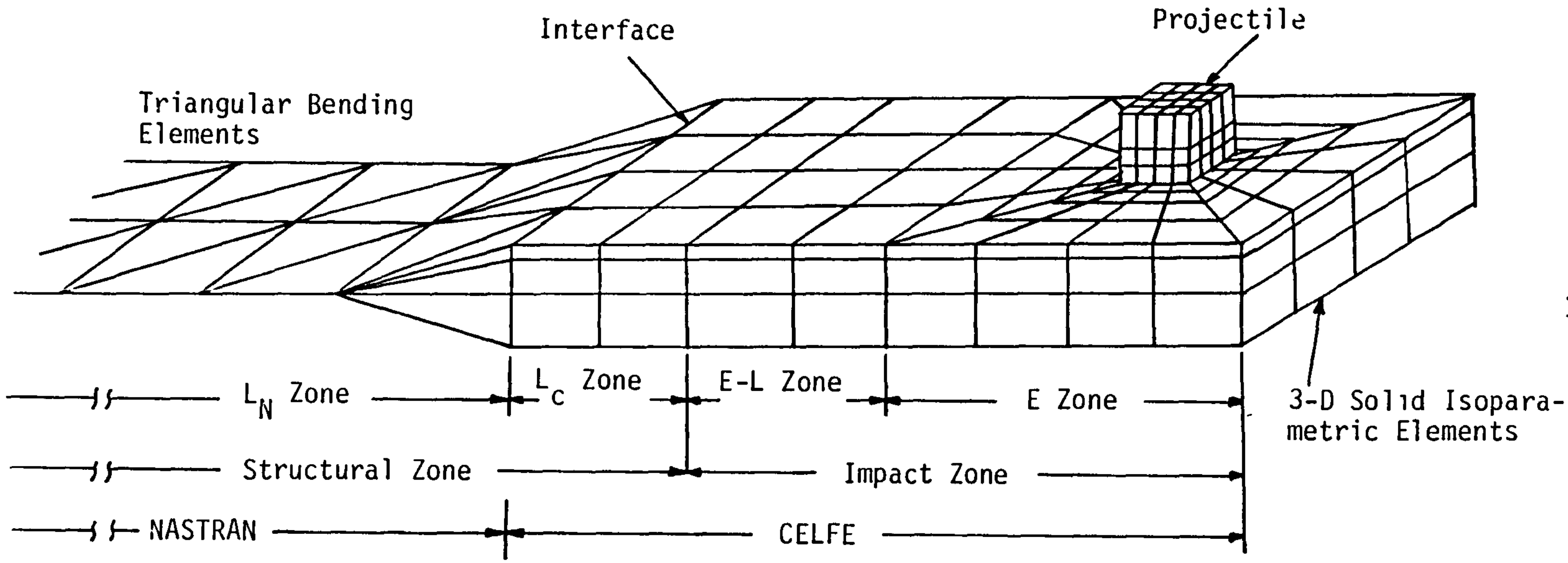


Fig. 2. Typical Finite Element Sketch in Global Analysis of High Velocity Impact

4-2. ON THE DYNAMIC RESPONSE OF FLUID COUPLED COAXIAL CYLINDERS

Researcher: Samuel J. Brown, Jr.

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center

Dr. T. Y. Chang, The University of Akron

BACKGROUND AND OBJECTIVES

A common geometrical configuration encountered in many dynamic analyses is the cylinder, and it is extensively used as pressure vessels, piping, tubing, shafts, inserts, containers, barriers, and structural members. In many applications the operating environment or medium is a fluid, whose presence can have a significant influence on the dynamic structural response of the cylinder. Fluid structure dynamic studies are generally categorized into four broad categories, namely: 1) Hydrodynamics or Fluid Dynamics; 2) Fluid Sloshing, 3) Flow Induced Vibrations, and 4) Fluid Structure Wave Propagation.

In the first category hydrocynamic fluid coupled coaxial cylinder problems are associated with the change in momentum of the fluid and structure as the fluid is squeezed in the annulus between the two cylinders with relative motion. As the clearance between the cylinders decreases, the effect of fluid damping becomes increasingly important. On the other hand, fluid damping is affected by fluid viscosity and velocity, in addition to clearance (Reynolds number). The excitation mechanism can be pump induced, seismic base of forced motion, fluid flow induced, and other types of excitation.

Fluid sloshing problems are generally associated with low frequency gravity waves in a moving container, while flow induced vibration in cylindrical structures are associated with fluid instability or eddying as a result of flow within or around the surfaces. Fluid structure wave propagation is generally concerned with a) low energy traveling and/or standing acoustic waves in the environment, and b) high energy pressure transient pulses. The former is usually concerned with structural configuration from the position of tuning via wave reflection, scatter, baffeling, etc. The latter is characterized by water hammer, blowdown via valve trip or pipe rupture, chemical reaction, etc.

The need to understand each of these areas for design purposes is important and have received increasing attention, particularly since the 1940's. The research work reviewed was limited to the study of the "hydrodynamic" response of fluid-coupled coaxial circular cylinders. A considerable amount of experimental and theoretical work has been devoted to this area of fluid-structure behavior (see Appendix). A synopsis of the review follows.

Many authors have treated this phenomena as consisting of two components of force: inertia and damping. The inertia term has popularly been utilized as an added mass or virtual (frequency domain solution) mass that is added to the actual mass of the structure. Others have studied a more general (temporal domain) approach and considered a more precise structural-fluid interaction formulation.

The effect of viscous damping has received less attention than inertia effects until recently because of either the uncertainty of the effect of viscosity, or lack of technical priority or incentive to spend research dollars in this area. The exceptions have been the interest promoted in the aerospace/lubrication technology program and the breeder reactor program.

The virtual mass method has enjoyed interest because of its ease in implementation (not necessarily ease in solution), relative good results in as much as comparisons exist, orientation to cost effective parametric studies, and in some instances the simple formulae that have been developed to provide the analyst with a method to obtain some preliminary and usually accurate answers. Formulae and coefficients have been developed for many effects such as accentricity, end flow, circumferential wave, and compressibility. The more general approaches on the other hand can give detailed data on nonlinear material and geometric behavior, but usually at a cost penalty.

The problem areas which are associated with this type of fluid structure coupling are: a) cylindrical vessels with thermal liners or shrouds such as heat exchangers, reactors, nozzels with thermal liners, pumps, and valves; b) tube-to-tube support annulus associated with tube fretting; c) rotating shaffs and inserts under oscillating loads such as pumps; d) piping and tubes with double walls, and e) instrumentation tubing.

DEVELOPMENT AND RESULTS

By using the virtual mass and damping method, the relationship of shell axial and circumferential made shape as a function of oscillating fluid pressure was investigated. Since there is interest in deriving simple formula for use by the designer and to compare it to independently determined values, the solution of the fluid pressure as a function of damping inertia forces and structural mode shape is reduced to simple formula.

Within the frame work of the assumptions used to develop to modal dependent virtual mass and damping coefficients, the study explores how these solutions may be incorporated cost effectively into existing modal analysis finite element computer codes. The finite element displacement method is compared to the virtual mass formula for an invicid fluid. Two-D and 3-D solutions are considered: 1) with fluid and structural finite elements 2) of the "in-air" eigenvectors and eigenvalues for use with the virtual mass and damping formula in order to determine the coupled frequencies. In the latter case, the mode forms or eigenvectors are assumed to be preserved from "in-air" to fluid coupled response.

In brief, the study consisted of: 1) a comprehensive survey, 2) solution of simple formula or coefficients dependent upon mode shape, boundary conditions, dimensions, and physical (material) properties, 3) comparison to finite element numerical data and 4) comparison to experimental data.

The survey reviewed most of the significant experimental, theoretical, and numerical studies into the dynamic response of fluid coupled circular coaxial cylinders. The significant milestones and significant formulae were thoroughly investigated.

This study also provides experimental-theoretical illustrations of some of the basic concepts stated earlier with respect to the virtual mass and damping coefficients: 1) the modal selection rule, 2) the experimental illustration of the effect of the axial as well as circumferential mode shape, 3) the frequency summation rule for fluid coupled cylinders, and 4) an illustration of the use of the percent fluid damping formula with the finite element method to compute displacement and stress responses in fluid coupled structures subjected to a base excitation.

4-3. STRUCTURAL OPTIMIZATION OF TURBINE VANE

Researcher: Timothy T. Cao

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center

Dr. Demeter G. Fertis, The University of Akron

Dr. Rudolph J. Scavusso, The University of Akron

BACKGROUND AND OBJECTIVES

In the hot section of a jet engine, the turbine vanes are subjected to high thermal gradients which introduce stresses and deformation in the vanes. In order to protect the vane material from high temperature, the vanes are coated with a ceramic barrier coating. The introduction of such a barrier coating produces stresses due to differential expansion tendencies of the vane and coating. A typical model of a turbine vane is shown in Fig. (1). There is a need today to increase the life of vanes by selecting material and vane geometry such that thermal stresses in vanes are minimized.

The purpose of this research is to design the stator vanes in the hot section of a jet engine so that their weight is minimized and/or durability is at maximum. The work will first involve a literature survey to determine the "state of the art" regarding this problem. Then, by selecting simplified models of vanes consisting of two materials, the resultant stresses and deformation in each material will be calculated by using the NASTRAN computer code, where the vanes are subjected to an assumed thermal gradient. The validity of the results will be checked by using a plane stress solution. Other types of loading such as those due to bending and natural frequency vibration will be investigated. It is hoped that the end result would include the development of a computer program for the optimization of turbine vanes.

DEVELOPMENT AND RESULTS

A preliminary literature survey was first carried out on the subject. A more thorough survey will be completed as the work progresses. The analysis was initiated by using a wedged shape vane model and subjecting it to a specific thermal gradient distribution. The NASTRAN computer program was used to calculate the thermal stress distribution in the vane and its barrier coating. An eight-node isoparametric element was used for both coating barrier and base alloy.

The properties of the coating material ($Y_2O_3Z_2O_2$) and base alloy (PWA 1422), are shown in Figs. (2), (3), and (4). The equations used for free thermal strains in vane are:

$$\varepsilon_{ox} = \alpha \Delta T_x \qquad 4\text{-}3.1$$

$$\varepsilon_{oy} = \alpha \Delta T_y \qquad 4\text{-}3.2$$

where

α = thermal expansion coefficient

ΔT_x = temperature differential in x direction

ΔT_y = temperature differential in y direction

ε_{ox} = strain in the x direction

ε_{oy} = strain in the y direction

For strains computed by NASTRAN

$$\varepsilon_x = \frac{u}{\ell_x} \qquad 4\text{-}3.3$$

$$\varepsilon_y = \frac{v}{\ell_y} \qquad 4\text{-}3.4$$

where

u = displacement in the x direction

v = displacement in the y direction

ε_x = strain in the x direction

ε_y = Strain in the y direction

ℓ_x, ℓ_y = Change in length in x and y directions, respectively

The constraint strains due to the differential expansion of the two materials are given by

$$\varepsilon_{cx} = \varepsilon_{ox} - \varepsilon_x \qquad 4\text{-}3.5$$

$$\varepsilon_{cy} = \varepsilon_{ox} - \varepsilon_y \qquad 4\text{-}3.6$$

and by Hooke's Law, the stresses σ_{cx} and σ_{cy} in the x and y directions, respectively, are given by the expression:

$$\sigma_{cx} = \frac{E}{1-\nu^2} [\varepsilon_{cx} + \nu\varepsilon_{cy}] \qquad 4\text{-}3.7$$

$$\sigma_{cy} = \frac{E}{1-\nu^2} [\varepsilon_{cy} + \nu\varepsilon_{cx}] \qquad 4\text{-}3.8$$

Tables (1) and (2) show the results for span-wise stress distributions in coating barrier from the NASTRAN and plane stress solutions, respectively. The analogous results for the chord-wise stress distribution are shown in Table (3). As can be seen, the plane-stress solution stresses differ by about 10 percent from those predicted using NASTRAN. This difference is acceptable for approximate analysis during optimization. The results for span-wise and chord-wise stress distributions for both solutions are also shown plotted in Figs. (5) and (6), respectively.

TABLE 1. Span-wise Stress Distribution in Coating Barrier by NASTRAN Solution

Temperature	σ_x stress in x-direction	σ_y stress in y-direction	ε_x strain in x-direction	ε_y strain in y-direction
°F	PSI	PSI	$in/in x 10^{-2}$	$in/in x 10^{-2}$
1800	12824	11766	1.51	1.453
1900	13639	12806	1.594	1.546
2000	14218	13626	1.673	1.642
2100	11776	12479	1.662	1.7
2000	11499	13615	1.568	1.682
1900	9465	12658	1.453	1.626

TABLE 2. Span-wise Stress Distribution in Coating Barrier by Plane Stress Solution

Temperature	σ_{cx} constraint stress x-direction	σ_{cy} constraint stress y-direction	ε_{cx} constraint strain x-direction	ε_{cy} constraint strain y-direction
°F	PSI	PSI	$in/in x 10^{-2}$	$in/in x 10^{-2}$
1800	11905	11443	3.53	3.28
1900	12636	12359	3.72	3.57
2000	13242	13261	3.86	3.87
2100	11190	12500	3.10	3.81
2000	10789	13485	2.81	4.27
1900	9549	13352	2.31	4.37

TABLE 3. Chord-Wise Stress Distribution In Coating Barrier by NASTRAN and Plane Stress Solutions

Temperature °F	σ_X NASTRAN Solution (PSI)	σ_{oc} Plane Stress Solution (PSI)	Ratio $\frac{\sigma_{oc}}{\sigma_X}$
2125	12906	12221	0.95
2100	11776	11190	0.95
2075	11651	10431	0.90
2050	11382	10143	0.89
2025	11238	10294	0.92
2000	11019	10435	0.95

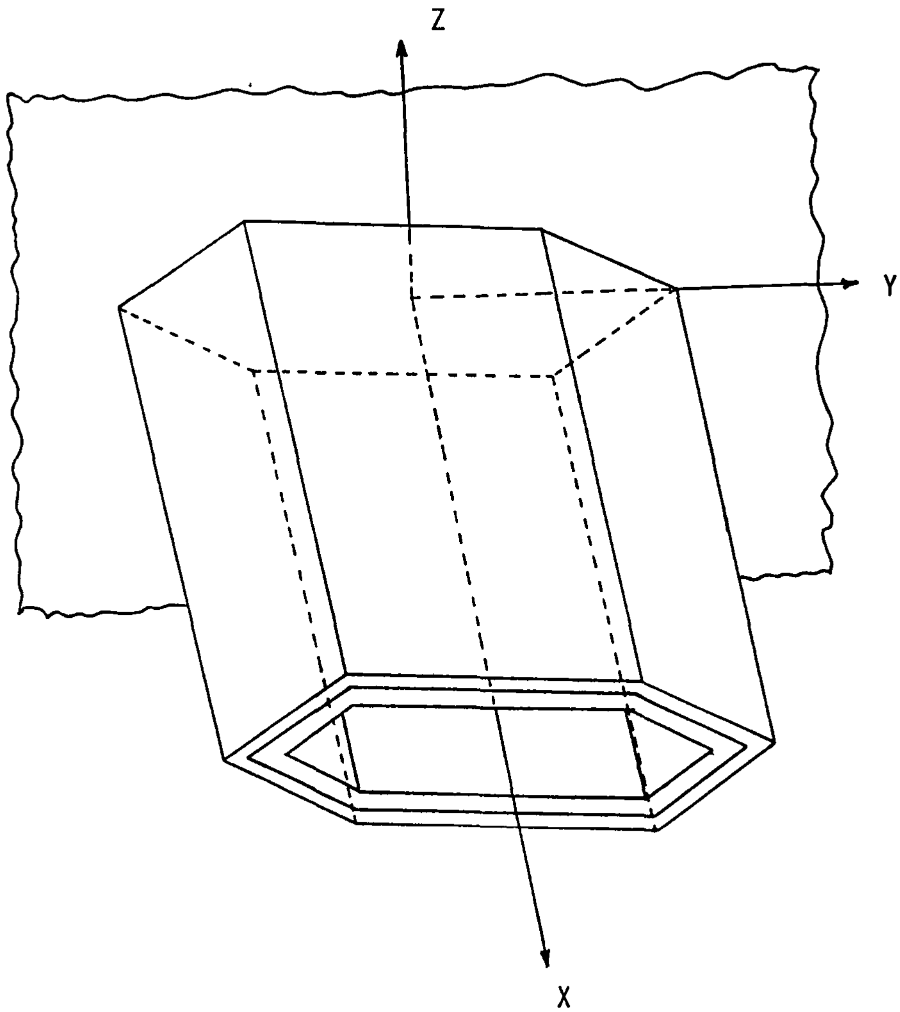


FIG. 1. MODEL OF VANE

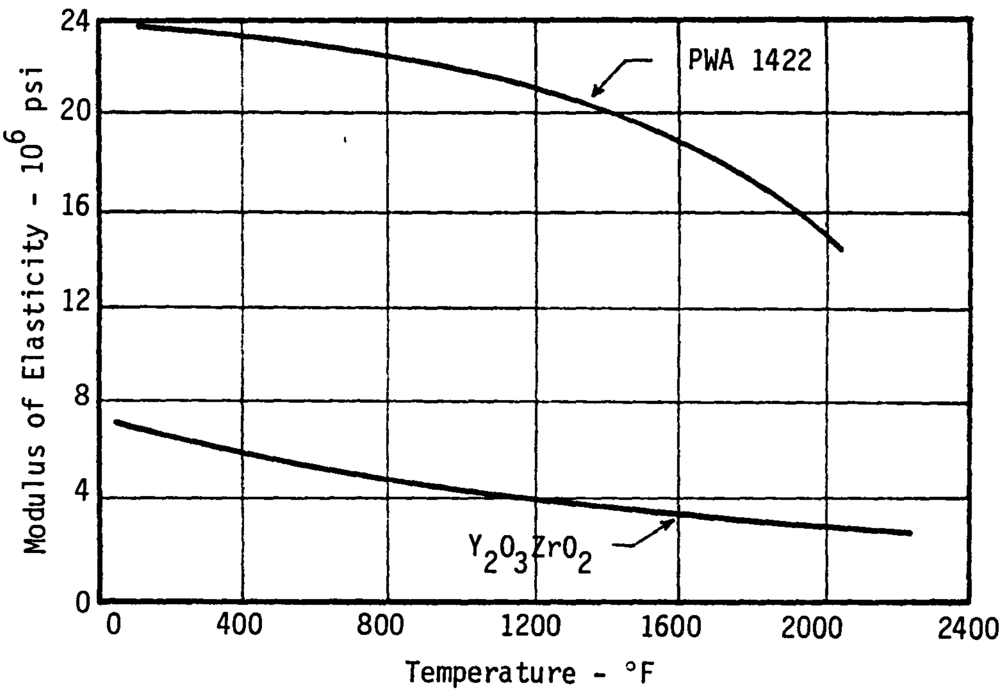


Fig. 2. Elastic Modulus

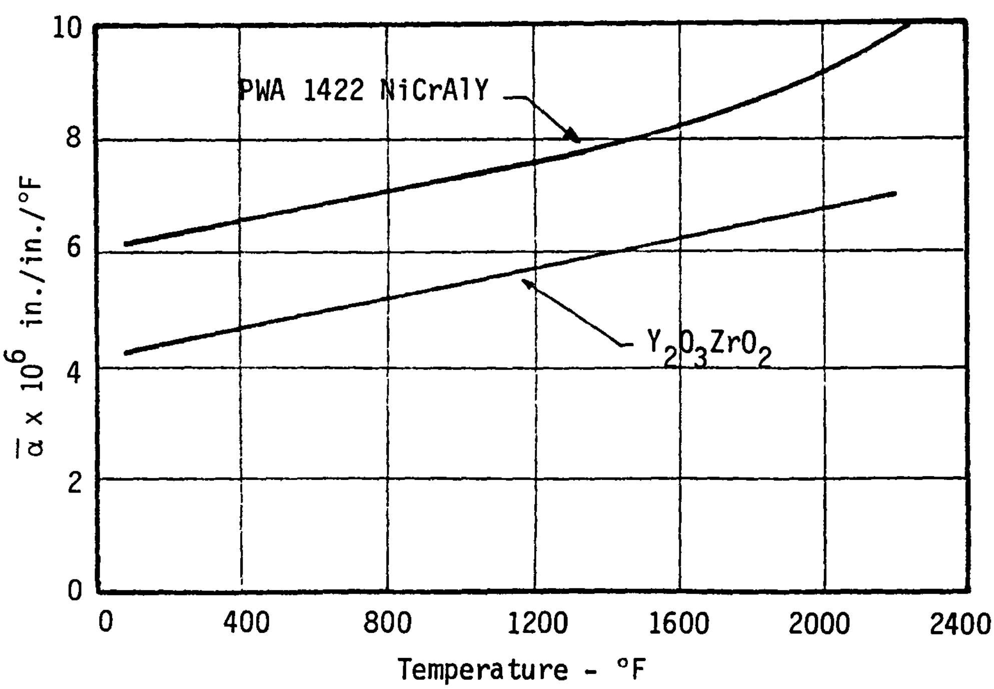


Fig. 3. Thermal Coefficient of Linear Expansion

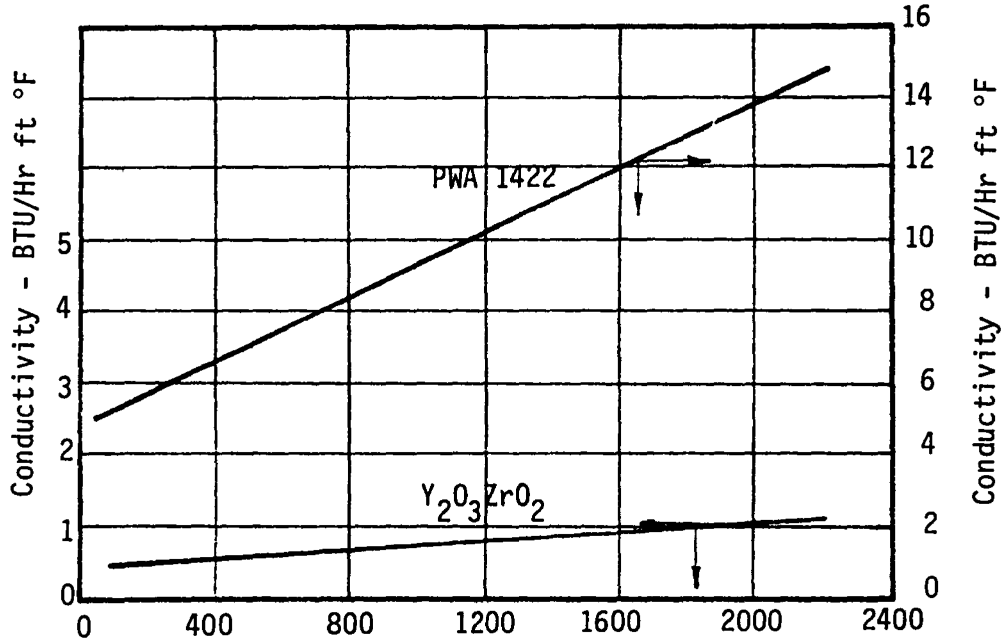


Fig. 4. Thermal Conductivity

Fig. 5 SPAN-WISE STRESS DISTRIBUTION

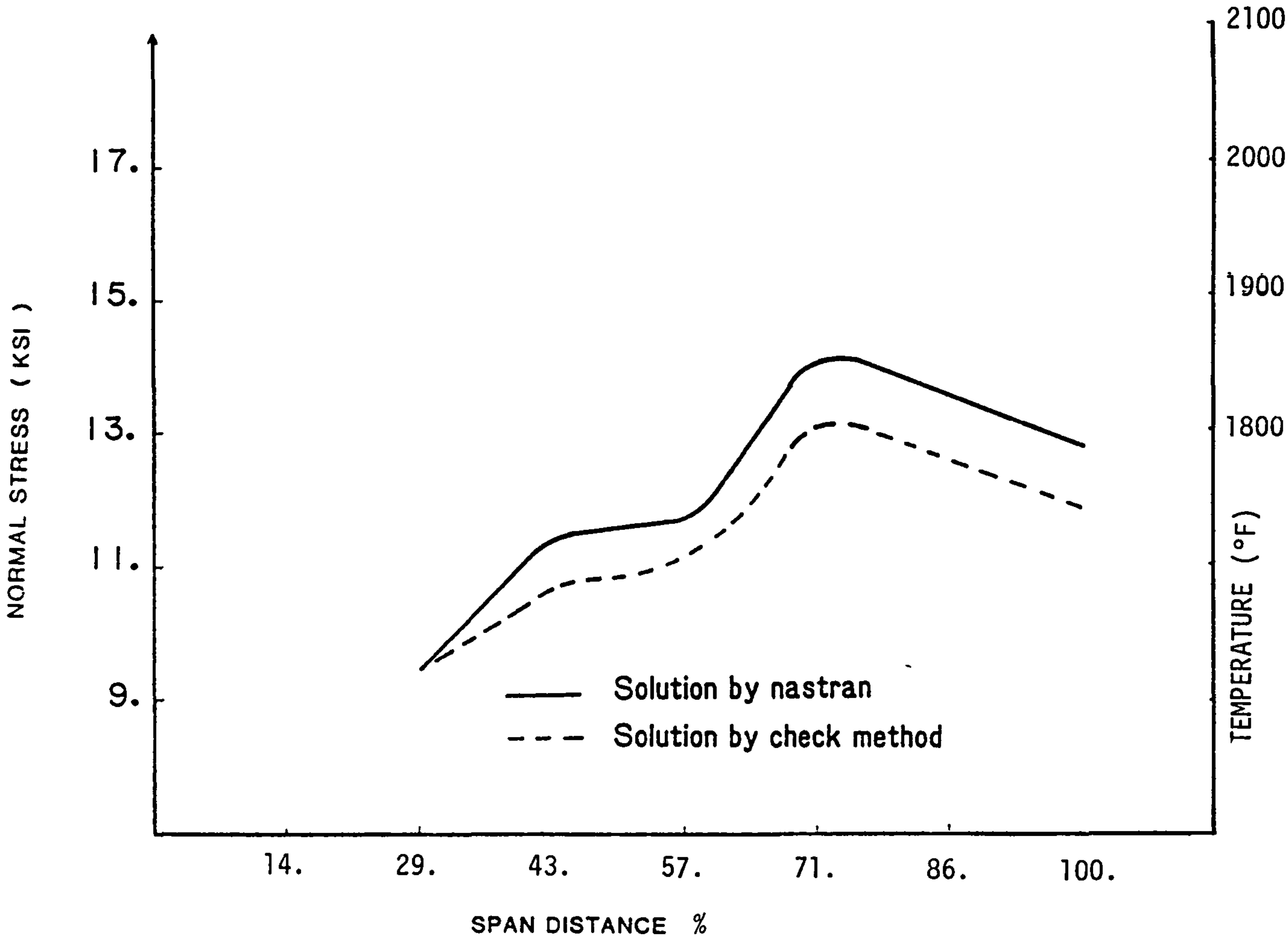
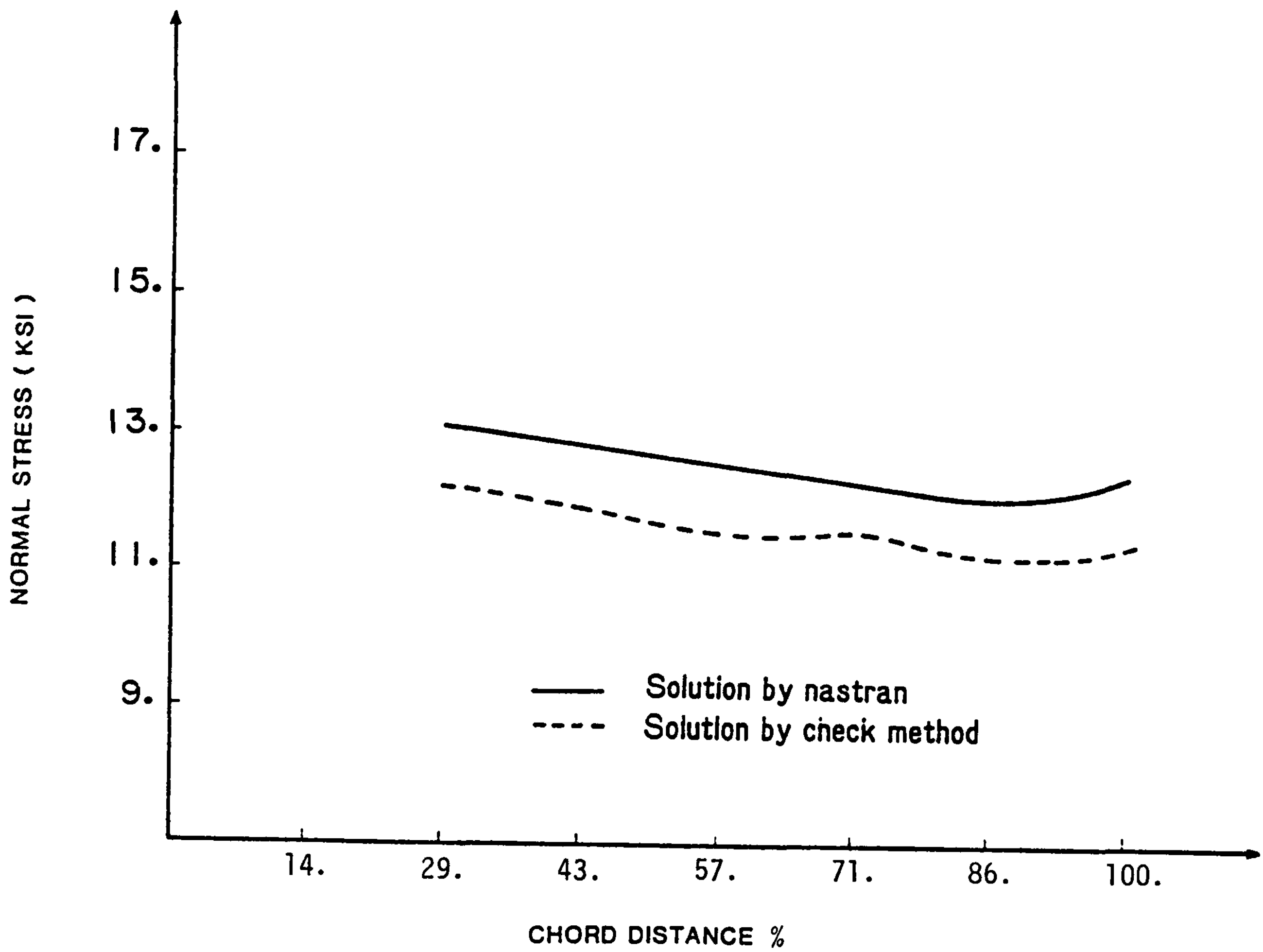


Fig. 6 CHORD-WISE STRESS DISTRIBUTION



4-4. A UNIFIED PREPROCESSOR FOR FINITE ELEMENT ANALYSIS

Researcher: Bruce Guilliams

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center
Dr. T. Y. Chang, The University of Akron

BACKGROUND AND OBJECTIVES

The objective of this research work is to design a logical input sequence for Finite Element Analysis in general, so that the effort required for preparing the data can be reduced and the chance of making mistakes will be minimized. Furthermore, the data will be interpreted to different Finite Element Codes in the way so that the user does not have to go through the painstaking to learn the input format of various programs.

DEVELOPMENT AND RESULTS

To this point, a review of an existing pre- and post-processor called GIFTS has been made with the intention that this program can be modified to suit the above stated purpose. After some close examination of GIFTS, it was decided that this program is not suitable for the intended purpose due to two major reasons: a) the size of GIFTS is too large and too complicated for modification, and b) some of the subroutines in the program are machine dependent. Consequently, other nonproprietory preprocessors were examined. One is a general purpose mesh generation package called INGEN, which was developed at the

Los Alamos National Laboratory. This program was adopted as a basis to design a preprocessor in conjunction with a Finite Element grid plot program.

A dedicated preprocessor is thus named MESHGEN, which was created from INGEN and a general purpose plotting package with hidden line algorithms. INGEN is a generator for two or three dimensional models. It contains surface and three dimensional generators to number nodal points, construct elements, and develop boundary conditions. It generates in the order of: first edges, then surfaces, then volumes. Each succeeding item of generation, such as a surface, is based on the preceeding item, its boundary edges. This makes it relatively simple to focus on certain areas of the model with a fine grid. There is also an option that allows the user to refine, or to make less fine, part or all of the model with the addition of only a few cards.

The remaining portion of MESHGEN was written to properly link the INGEN and a finite element program such as SAP or NASTRAN as well as manipulate their results and all other required information into the correct arrangement on tape for the future use.

One feature of MESHGEN is its macrostructure approach to input. There are certain groups of data, or types of information common to many finite element programs. These general groups are control cards, mesh cards (including node, element, and boundary initial conditions), property cards, and loading cards. For MESHGEN to differentiate between these, the groups need only start with a title card designated

*CONTROL, *MESH, etc. Thus, as long as the information in any particular group remains in the proper order, the larger macrogroups can be input in any order.

Program Subroutine Details

(In order of use)

MAIN - Driver

PROGCH - This reads the first card and identifies the finite element program for which the input is to be adapted.

MAIN - It reads the number of cards in the input deck to set up the required information for the dynamic allocation process. Then it rewinds the input.

READKV - It reads the entire deck as alphanumerics of the subscripted variable K.

STAR - It does a search for the beginning point and the length of each group of data. Also it identifies the order in which the groups exist.

INGEN 1 - This rewinds file 5 (the input file) and sends the *MESH group of data cards to file 5.

INGEN 2 - This one sets up the information required for the dynamic allocation used in the INGEN subroutines.

INGEN Subroutines - These generate the mesh. Besides the portions removed from INGEN, described above, other portions had to be modified. Provisions for rotational boundary conditions were added. All reference to material properties were removed. These are handled elsewhere. Also, output is put on tapes 40, 8, and 5. Tape 5 is used for the plotting subroutines. Tapes 40 and 8 are used in the data manipulation.

NFPLOT - If a plot is required (2D or 3D) these subroutines use file 5 to produce it.

NFAP - This reads file 8 to get the total number of elements, number of element groups, and the number of nodal points.

PROPN - This subroutine generates three types of material properties. The first type is node dependent (such as thickness). Another is element dependent (such as material type). The last is element group dependent (type of element, such as shell or plate). PROPN then arranges the generated material information, the data from INGEN on file 40, and portions of data from the subscripted variable K on file 5 in the proper sequence for the use of NFAP.

For each future program addition, a subroutine of this type should be added since the material properties are program dependent.

At present, only the mesh generation and grid plot in MESHGEN are completed. A flow chart of the program is shown in the attached figure. To run a problem, the following data must be provided:

i) Coordinate of key nodes defining all regions for mesh generation.

ii) Node number generation data.

iii) Controlling nodal points to define a region.

iv) Element number and nodal connectivity of the master element and element type.

v) Element generation data for each region.

vi) Plot option data.

Two sample problems were run: i) A 3/D cube and ii) a 2/D structure. The finite element meshes for both problems are shown in the figure. Input data required for those problems are extremely simple and easy to define. For the 3/D mesh, it is clearly seen that hidden line option was included in the plotting.

FUTURE EXTENSION

Although MESHGEN can generate finite element model and plot the data for a wide range of geometries, the capability of this program is still quite limited. Future extension of this program should include:

i) Mesh generation in an interactive mode.

ii) Model editing capability.

iii) Interface with finite element analysis programs such as NASTRAN, SAP, etc.

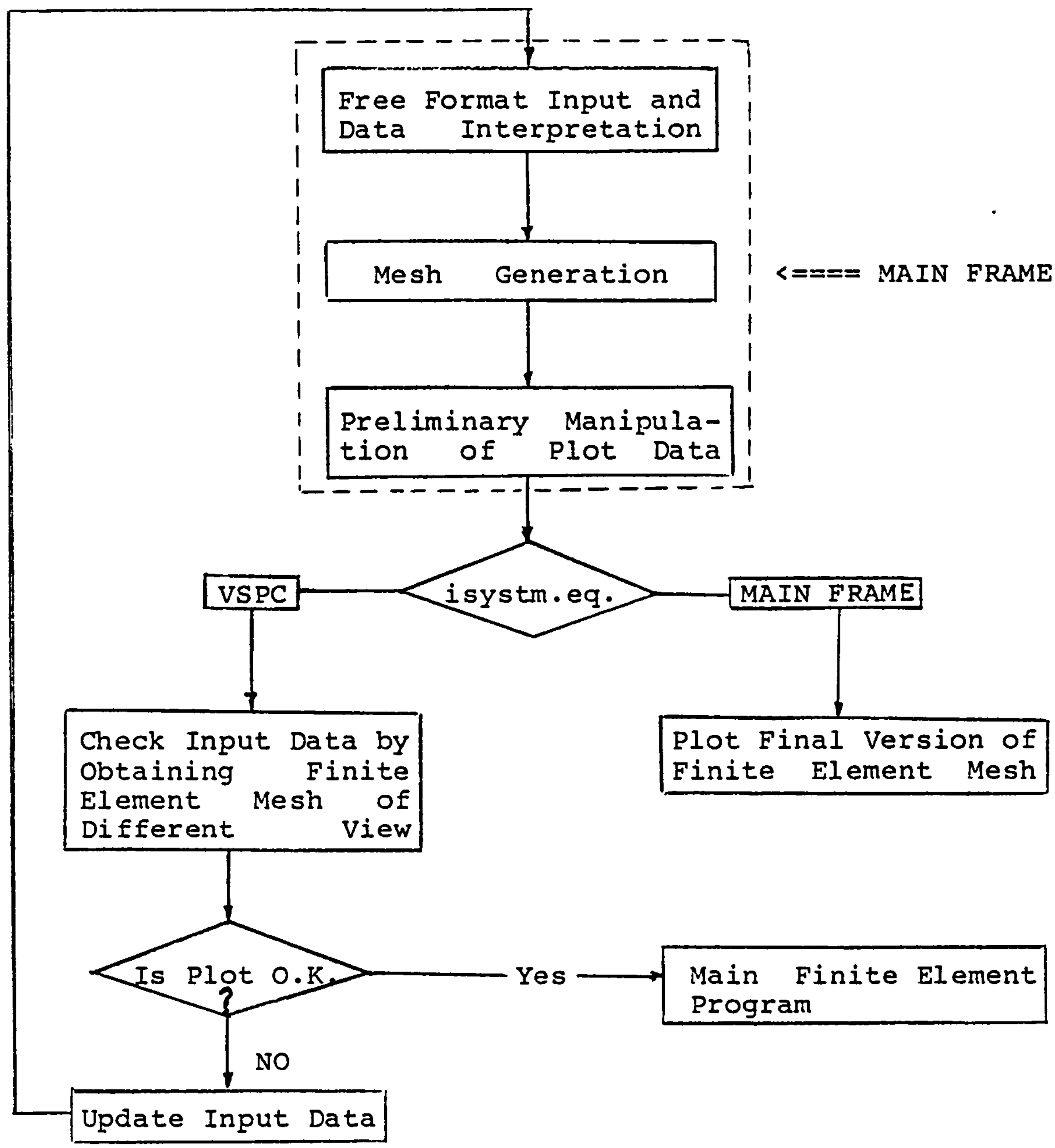


Fig. 1. A Flow Chart for MESHGEN

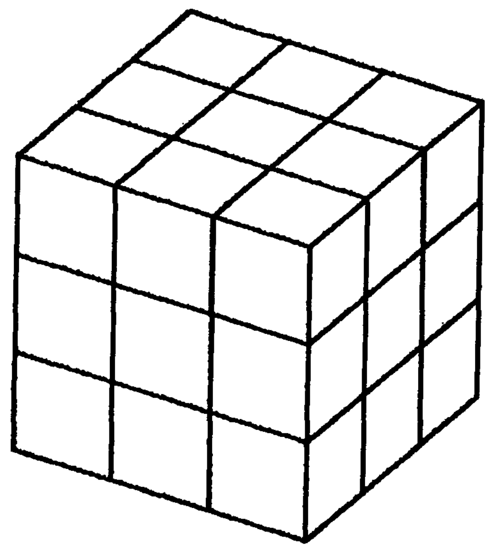


Fig. 2. Finite Element Model for a 3/D Cube

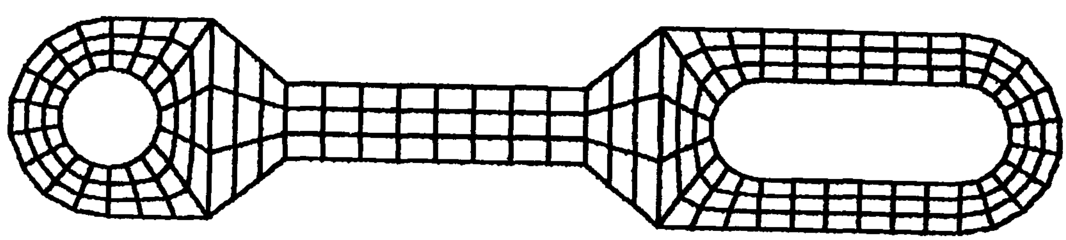


Fig. 3. Finite Element Model for a 2/D Structure

4-5A. SIMULATED COMBUSTOR LINER AND TURBINE BLADE STRUCTURAL ANALYSIS USING NASTRAN

Researcher: Dale A. Hopkins

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center
Dr. Demeter G. Fertis, The University of Akron

BACKGROUND AND OBJECTIVES

The combustor liner research project was undertaken to investigate the effects of high temperatures and thermal gradients on an axisymmetric double-shell structure which is characteristic of a typical combustion chamber liner structural system. The ultimate objective was to determine if the effects of the thermal loading and gradient would result in buckling of the structural system.

The turbine rotor blade research project was initiated to attempt an analytical computer simulation of the loads and responses experienced by a turbine blade during a cycle of operation, in order to verify the results achieved by a NASTRAN code analysis using three-dimensional "solid" isoparametric finite elements.

The research for both projects was performed during the researcher's first residency at LeRC (June 2, 1980 to August 23, 1980). The primary objective was to introduce the researcher to the complex analysis of hot engine structures.

SIMULATE COMBUSTOR LINER

To eliminate the cumbersome task of preparing a NASTRAN Bulk Data Deck directly, a simple FORTRAN code was developed to generate the data deck automatically for an axisymmetric double-shell model (simulating a combustor liner) with cross-sectional geometry as shown in Figure 1. The total deck consisted of 1254 lines of data with the actual model comprised of 421 nodes and 380 two-dimensional plate bending elements (CQUAD2). An axisymmetric temperature load was applied to the model at the nodes with a gradient along the longitudinal axis as shown in Figure 1. A prototype material (Incoloy Alloy 800) was chosen for modeling purposes with the material properties of the elements varying according to the average temperature at the element. The temperature load was applied such that there were no variations in temperature through the thickness of each plate. The model was defined in a cylindrical coordinate system and fixity was accomplished by restraining the radial translation and all three rotations of 4 of 5 nodal points along one axial line of nodes on the outer shell of the system. The fifth node of that nodal line was completely restrained against all translations and rotations.

NASTRAN static and buckling analyses were performed on the model with node displacements and element stresses requested as output in each case. From the static analysis, the nodal displacements were examined and those for the most critical cross-section (at $\theta = 180°$ from section containing fixed line of nodes) are plotted in Figure 2. Figure 3 gives an illustration of the critical section and the relative displacement of the section due to the loading. From the buckling analysis, the minimum eigenvalue was determined as 1.565476. From the real displacement eigenvector output, the displacements for six circumferential node lines were examined. The results are plotted in Figure 4 which shows the mode shapes of these circumferential lines. Also, from the static analysis, the nodal displacements around three circumferential lines of the inner shell were evaluated and the results are plotted in Figure 5. This figure verifies that the most critical section (i.e., that with the largest displacement) is indeed at $\theta = 180°$ from the fixity.

As a corollary to the combustor liner research project, a simple column buckling study was made to validate the use of the NASTRAN for the Buckling Analysis of the liner. A hinged-hinged rectangular column was loaded with a uniform thermal load and a comparison was made between the critical buckling temperature predicted by NASTRAN and the value as determined from the Euler Formula as follows:

$$\sigma_T = \alpha E(\Delta T) = \sigma_{cr} = \frac{\pi^2 E}{(L/r)^2}$$

$$\Delta T_{cr} = \frac{\pi^2}{\alpha (L/r)^2}$$

The details of the study along with the first three mode shapes of the column are illustrated in Figure 6.

The results of the Buckling Analysis on the combustor liner indicate that the structural system does buckle under thermal loading and an axial thermal gradient. The best illustration of this is that shown in Figure 4.

For further study, it would be of interest to investigate the additional effects of inducing a thermal gradient through the thickness of each shell plate.

SIMULATED TURBINE BLADE

The simulated turbine blade research project was to involve a series of analyses, with modifications being made for subsequent analyses according to the results of previous analyses.

Figure 7 provides the general geometry of the simulated blade and outlines the modifications that were made to the basic shape. As with the liner model, a FORTRAN code was developed to generate the data deck for the rotor blade model. The total deck was comprised of over 3500 data lines. The model itself contained 924 node points and 448 three-dimensional isoparametric elements (CWEDGE along the loading and trailing edges and CIHEX1 elsewhere). The node points contained in the root section were completely restrained in all six degrees of freedom so that the blade acted as a cantilevered structure. The same material as was used in the liner model was used for the blade model. A two-dimensional temperature gradient was applied to the blade with the boundary condition temperatures being shown in Figure 7 at the corners of the model. In addition to the thermal load, a centrifugal load was applied to the blade by specifying a rotational speed of 7200 rpm. Figure 8 is a NASTRAN Plot of the actual blade shape including the modifications.

The material properties of the elements were initially adjusted according to the temperature on each element. A NASTRAN Modal Analysis was performed on the model with nodal displacements and element stresses output as results. In this way, a material property temperature dependency was incorporated into the first analysis. For the second analysis, the stress results from the first analysis were to be used to adjust the basic material properties for the element according to the stress experienced by each element in the first analysis.* In order to do this, a curve of tangent modulus vs. stress was prepared from the stress-strain curve data. The tangent modulus-stress curve provided the necessary relationship by which to adjust the modulus for a particular value of stress. In this way, a material property stress dependency was to be incorporated into the second analysis. In the final analysis, the first and second analyses were to be combined to provide a temperature- and stress-dependent analysis.

At the end of the research period, only the first analysis had been completed. It is assumed the schedule will be completed in future work. Problems were encountered with accessing the data files containing the displacement-stress data for an analysis, manipulating the necessary data to adjust the material properties and effecting these changes in the NASTRAN Bulk Data Deck itself. It is expected that some topic related to the Turbine Rotor Blade will be developed into a Master's Thesis.

* Actually only the Young's Modulus was to be modified from one analysis to the next.

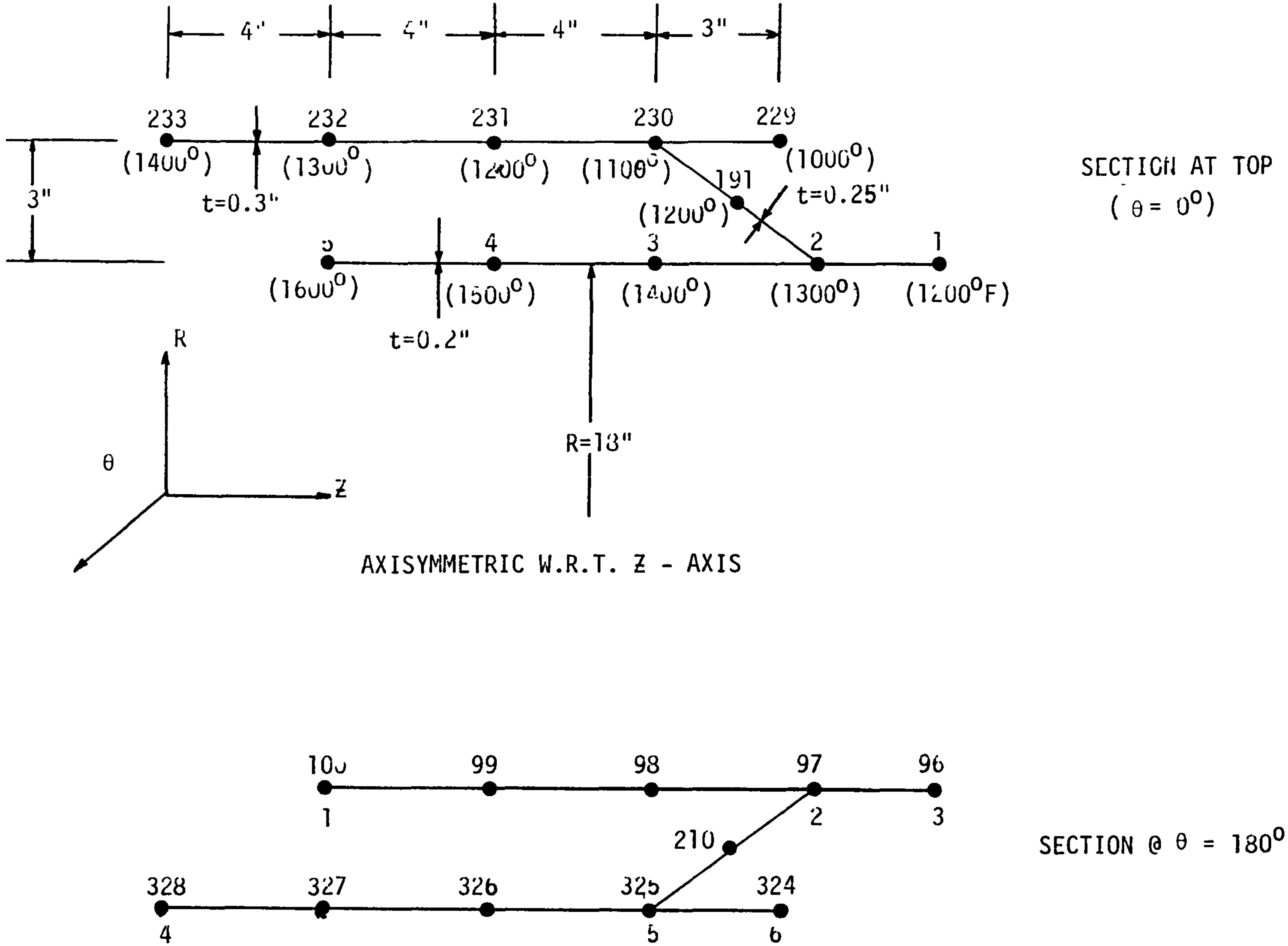


Fig. 1 - NASTRAN MODEL OF LINER

(NODE PATTERN AND NODAL TEMPERATURES)

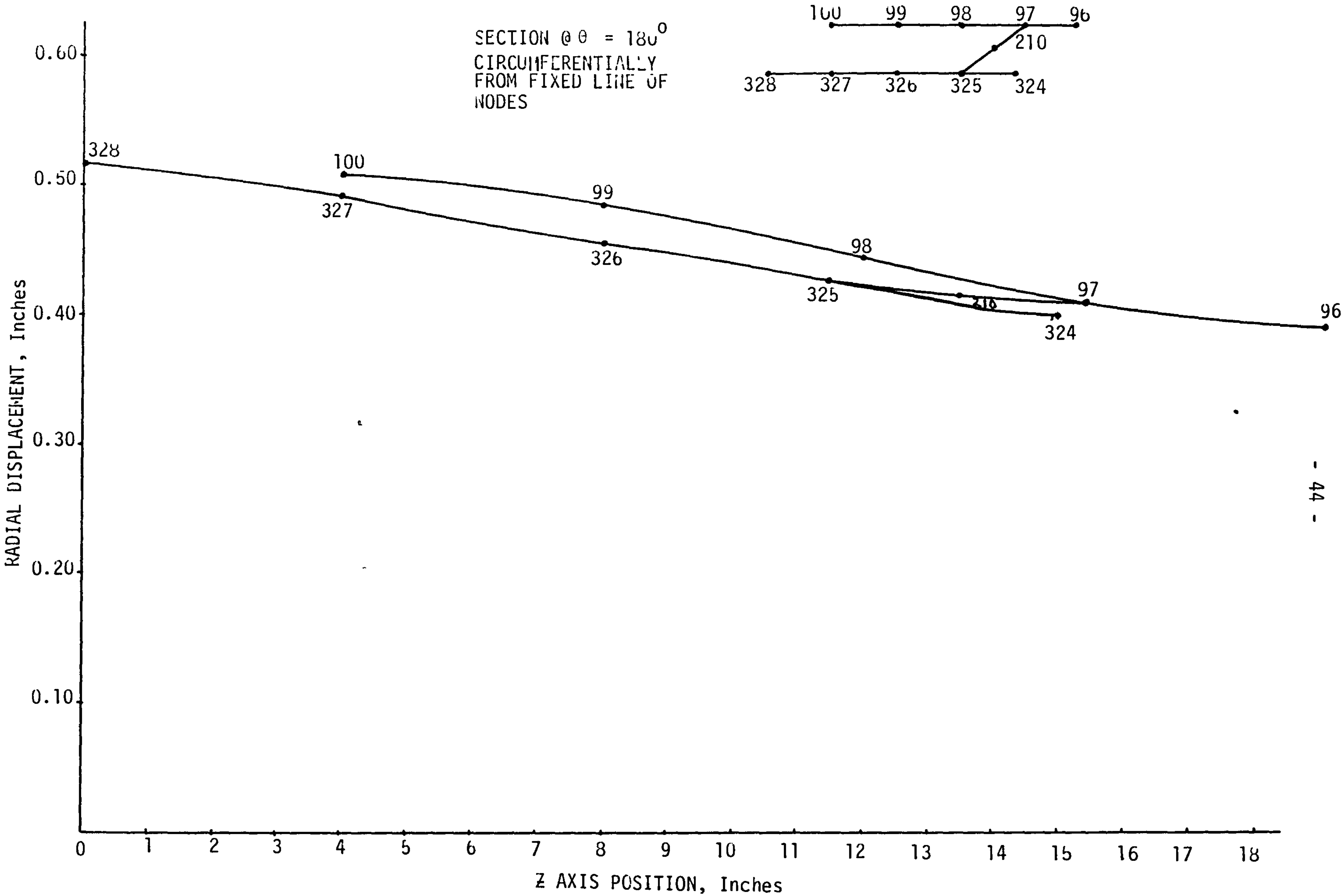


Fig. 2. STEADY - STATE (STATIC) DISPLACEMENT
(NASTRAN STATIC ANALYSIS, THERMAL LOAD).

SECTION @ $\theta = 180^{o}$ CIRCUMFERENTIALLY
FROM FIXED NODAL LINE

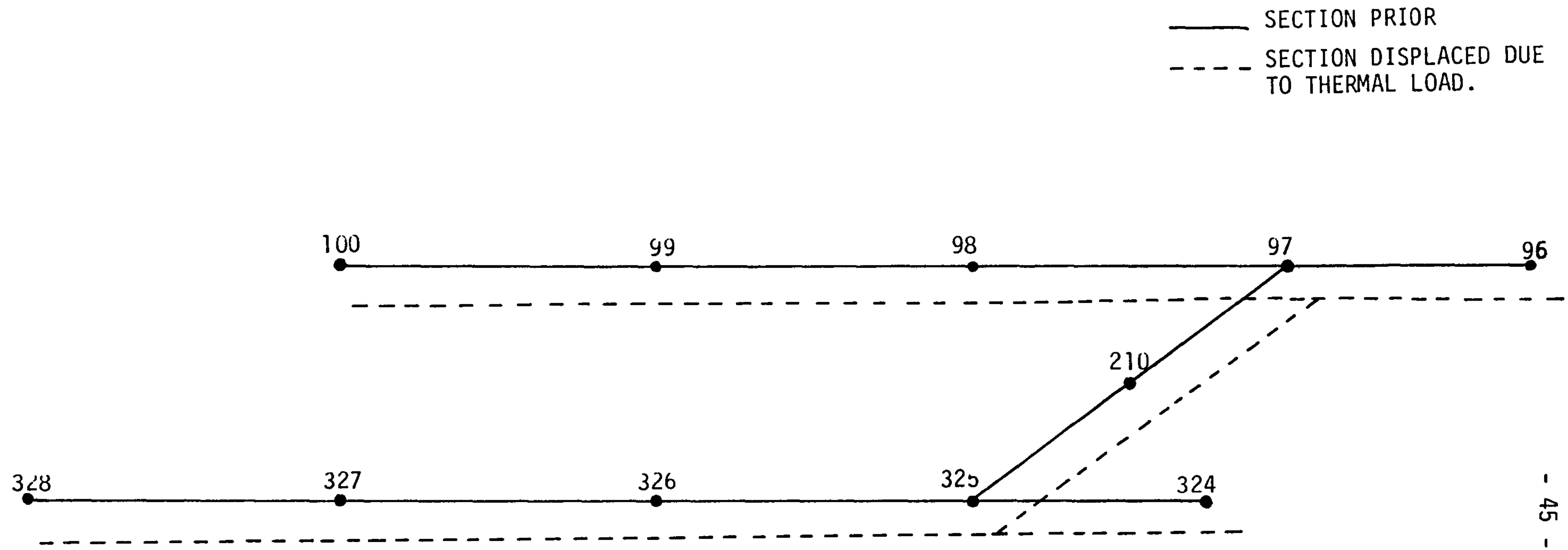


Fig. 3. DISPLACEMENT OF MOST CRITICAL SECTION DUE TO THERMAL LOADING

(Nastran static analysis for thermal load).

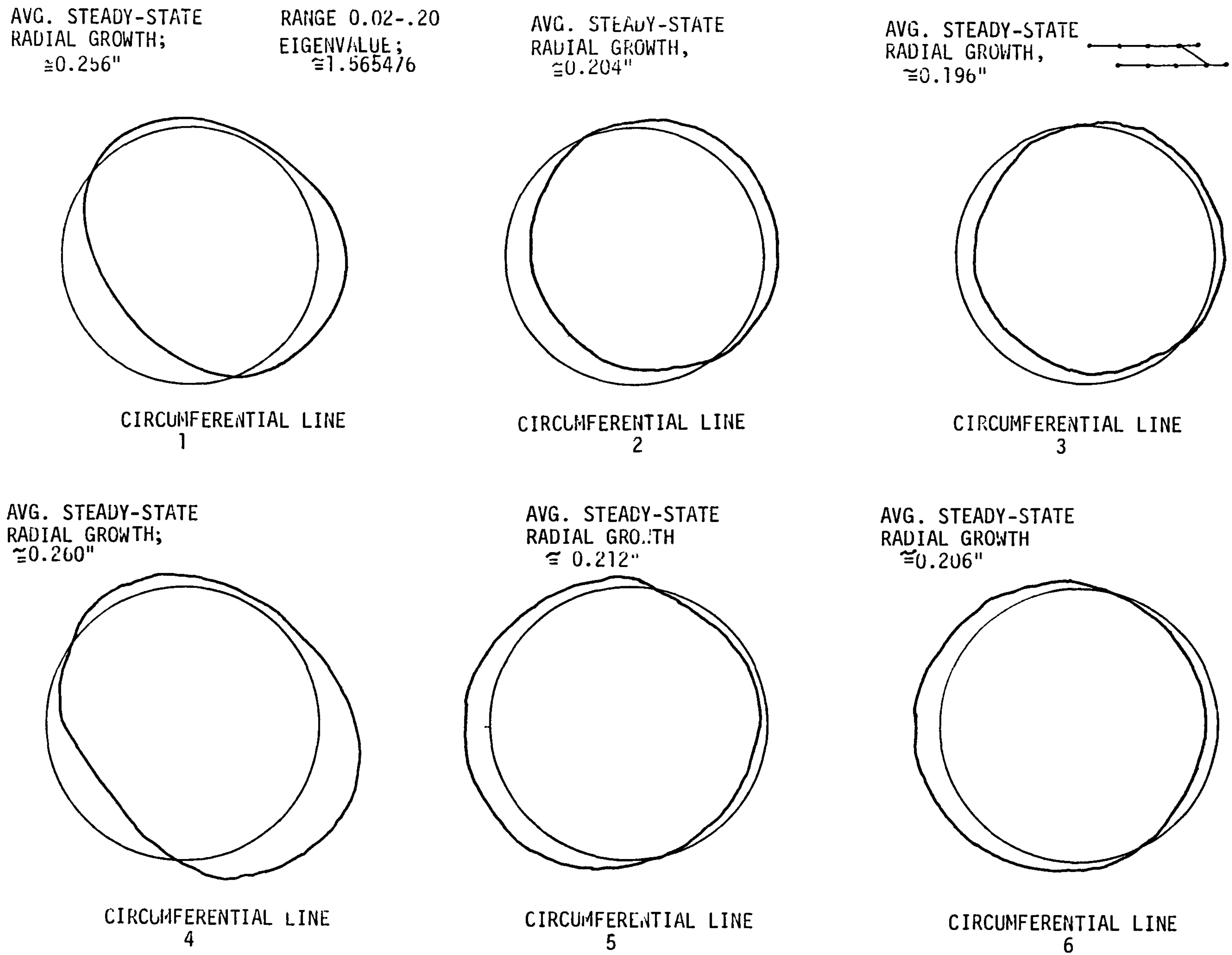


FIG.4- MODE SHADES
(NASTRAN BUCKLING ANALYSIS, RANGE 0.02-0.2, Eigenvalue1.565476)

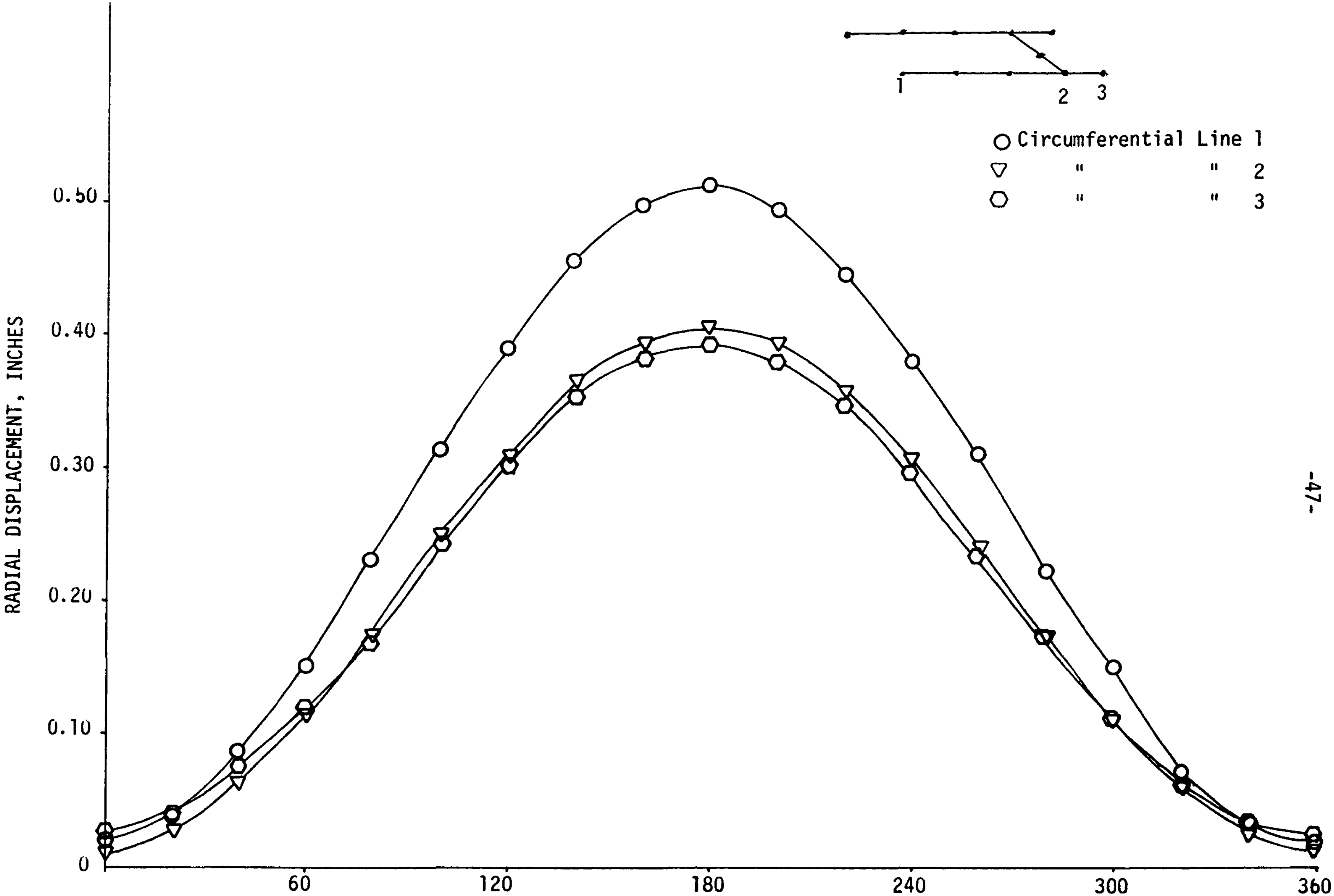
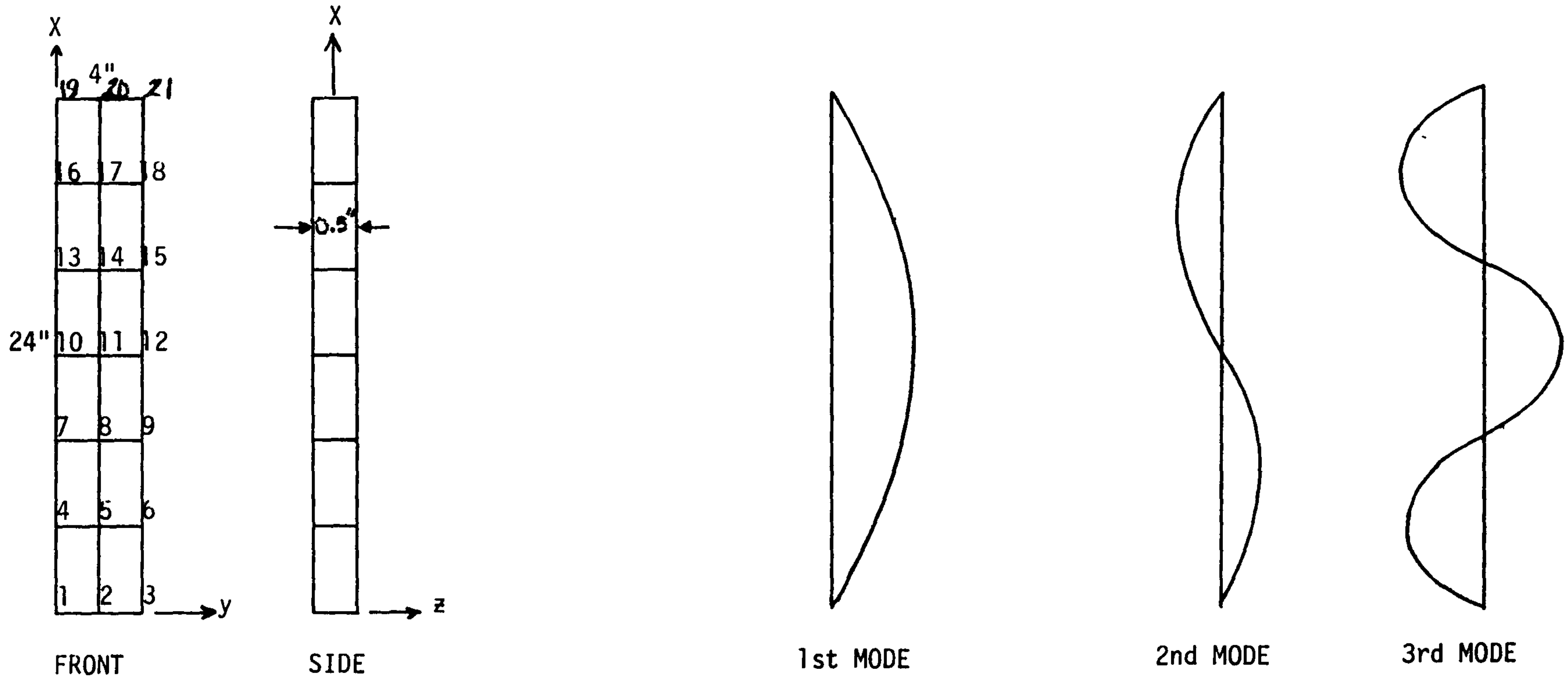


Fig. 5. STATIC DISPLACEMENT

(NASTRAN STATIC ANALYSIS, THERMAL LOAD)



BUCKLING TEMP.(°F);
NASTRAN - 43.0
* THEORY - 45.2

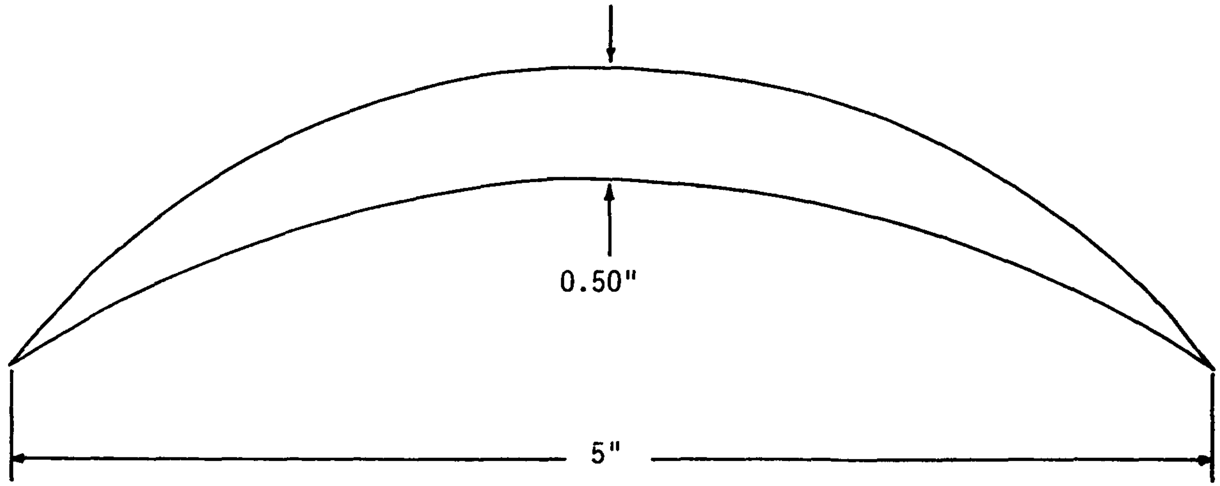
BUCKLING TEMP;
NASTRAN - 191.0
THEORY - 180.8

BUCKLING TEMP;
NASTRAN - 472.0
THEORY - 406.8

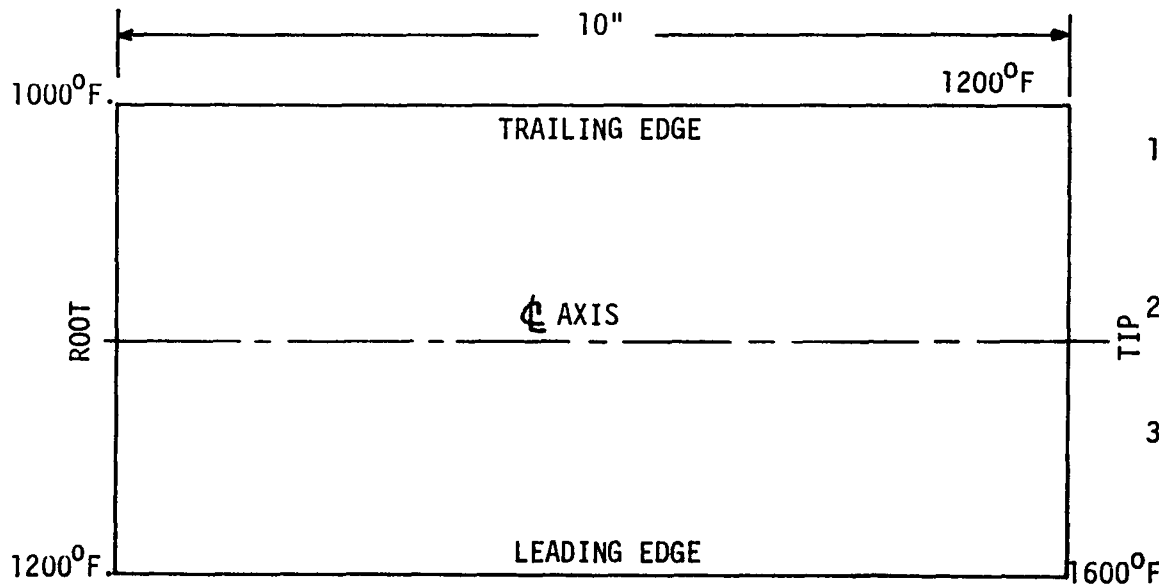
*EULER'S FORMULA

FIG. 6 - THERMAL BUCKLING OF SIMPLY SUPPORTED COLUMN

(DIMENSIONS: 4" x 24" x 0.5"; MODEL: 21 NODES, 12 ELEMENTS; THERMAL LOAD: ΔT=1000°F)



SECTION AT ROOT



PLAN VIEW OF UNMODIFIED BLADE

BLADE MODIFICATIONS:

1. Tapered from 0.50" ℄ Thickness At Root To 0.20" ℄ Thickness At Tip.

2. Twisted 30^{o} AT Tip (Leading Edge Down) About ℄ Axis.

3. Tilted 10^{o} Down From Root to Tip.

Fig. 7. ROTOR BLADE MODEL

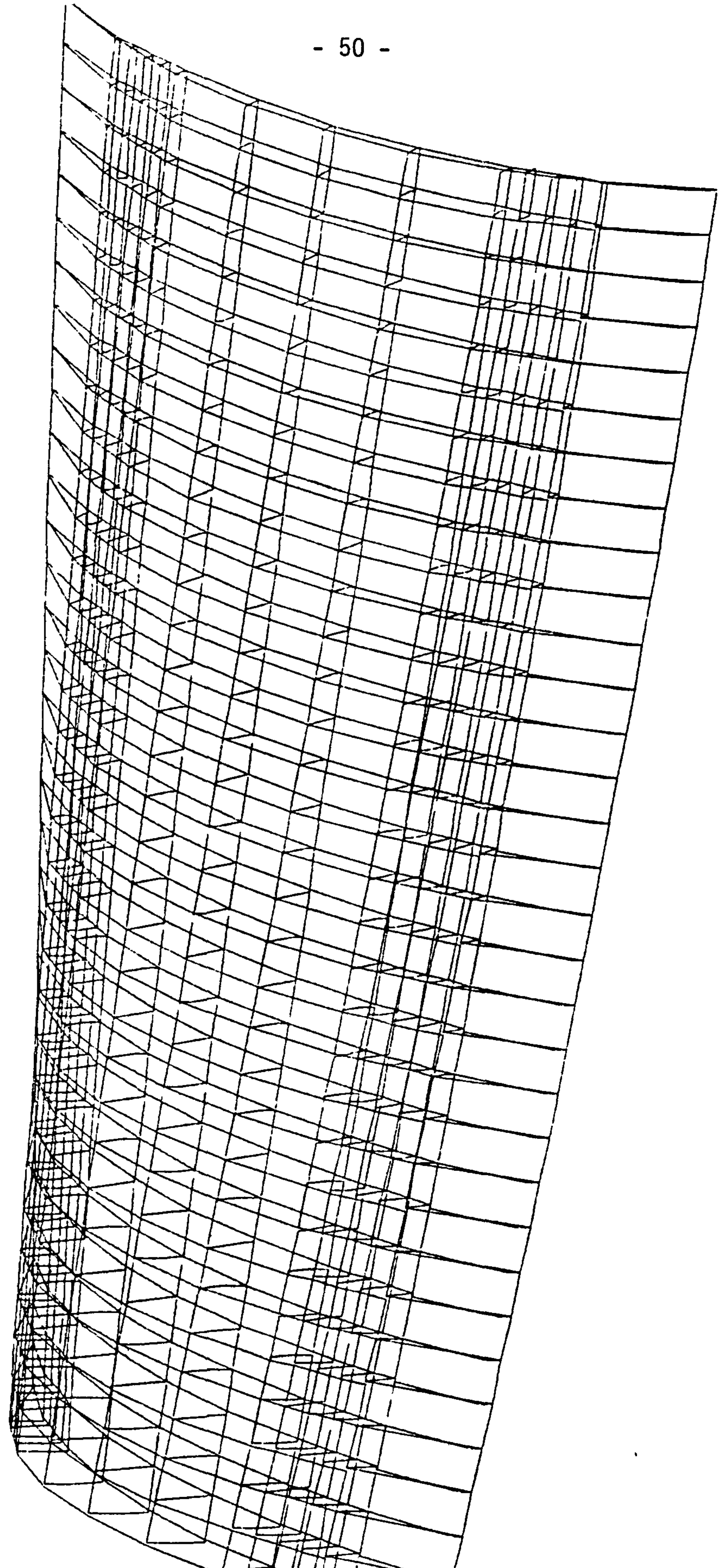


Fig. 8. NASTRAN Calcomp Plot of Rotor Blade Model

4-5B. NONLINEAR ANALYSIS OF TUNGSTEN-FIBER-REINFORCED SUPERALLOY TURBINE BLADES

Researcher: Dale A. Hopkins

Research Supervisors: Dr. Christos C. Chamis, NASA Lewis Research Center

Dr. Demeter G. Fertis, The University of Akron

BACKGROUND AND OBJECTIVES

During the past five years the cost of fuel for the commercial airline industry has increased nearly 500 percent. This has increased the percentage participation due to fuel cost in the total operating expenses from about 15 percent to 50 percent. Therefore, the major efforts and goals of the aircraft gas turbine engine industry have been directed toward improving engine performance, efficiency and durability. The success in achieving these goals will depend in part on what advances can be made in the field of materials technology and the related analysis capabilities associated with new materials development.

The particular materials-related factors that could provide a basis for new material development are increased temperature-strength capabilities and lower weight. It has been demonstrated that by increasing the turbine blade use-temperature of a gas turbine engine a significant improvement in engine performance can be obtained. Enhancing the use-temperature capabilities of a turbine blade would require development of a material that would maintain the required strength properties at the elevated temperatures proposed for turbine blade use. During the past five years the strength requirement of turbine blades has increased by 30 percent, and even higher increases are expected in the future. Composite materials represent a possible alternative in the area of increased temperature capabilities.

Refractory-fiber metal-matrix composites have many properties that make them attractive for aircraft turbine engine applications. For example, from studies made at NASA Lewis Research Center, it is shown that Tungsten-fiber-reinforced superalloy (TFRS) composites have excellent high-temperature strength characteristics[1]. A specific TFRS composite has been identified as having an excellent combination of complementary properties for potential use as a first generation composite turbine blade material which is referred to as W1.5%ThO_2/F_e(CrAlY). The matrix provides a high melting point, low density, excellent oxidation and hot corrosion resistance, limited fiber-matrix identification at proposed blade temperatures, and excellent ductility to aid in thermal fatigue resistance. The fiber provides for high stress-rupture, creep, fatigue, and impact strength, together with high thermal conductivity. The reported properties on this material indicate that they are adequate for turbine blade use[2]. Furthermore, its use could permit blade operating temperatures of over 50k greater than those of current directionally solidified superalloy blades.

The above indicate that the potential benefits represented by the use of TFRS composites are significant. However, at present, a quantitative assessment of TFRS composites in a turbine blade application relies on experimental evaluations which are costly and time consuming.

Therefore, there is a need for an analysis capability to assess the structural integrity and mechanical performance of TFRS composite turbine blades. The objective of this research work is to develop a structural/stress analysis capability specifically tailored for application to composite turbine blades which are subjected to complex cyclic thermomechanical loads, by taking into account material nonlinearities arising from temperature dependent material properties, creep, and fiber degradation due to fiber-matrix interdiffusion. The approach being taken involves the development of a nonlinear COBSTRAN with appropriate micromechanics equations to relate TFRS composite nonlinearities to the properties of the constituent material. COBSTRAN is a linear finite element code recently developed at NASA Lewis Research Center for the analysis of multi-laminate composite turbine blades. It incorporates linear composite micromechanics, laminate theory, and NASTRAN.

It is important to stress at this point that such a capability is nonexistent at present and therefore its development would be a significant contribution to the composite materials field, as well as to related fields such as structural analysis of high temperature structures. The fact that its development is being tailored for the above specific application does not limit its potential use for the analysis of general types of composite structures as well as heterogeneous and anisotropic materials. Isotropic material behavior is a "very" special case in this analysis capability.

DEVELOPMENT AND RESULTS

The basic operation of the proposed nonlinear COBSTRAN code is diagrammed in the flow chart of Fig. (1). The input data for an analysis includes constituent material properties, basic geometry and load and constraint conditions. The constituent material properties include reference values of the required thermal and mechanical properties of the fiber and matrix materials. The basic geometry supplies the coordinates of points which define the periphery of several sections of an actual blade shape. The user, in addition, supplies the information regarding the orientation and number of individual composite plies comprising a particular section, as well as ply thickness and basic geometry of a fiber. He also has the option of defining a multiple number of different ply types.

With given basic material and geometry information, the present version of COBSTRAN contains a feature which is capable to generate an equivalent NASTRAN Data Deck. On this basis, the linear COBSTRAN makes use of built-in laminate theory relationships and composite micromechanics. The load conditions involve the time histories of temperature, pressure, and centrifugal force experienced in a blade environment for a complete cycle of operation of a gas turbine engine. In this manner, a complete analysis involves "marching out" in time for a given time step increment. That is with an equivalent NASTRAN Data Deck a conventional NASTRAN analysis can be executed.

The output from an analysis includes global variables such as displacements, stresses, constraint forces, frequencies, and so on, as well as laminate stresses, which can be analyzed by using the composite mechanics equations in COBSTRAN. For each time-step iteration involved in a complete analysis, a local iteration is performed to establish equilibrium between applied force conditions and resultant stress fields. At any point in the time-step iterations of a complete analysis, the particular turbine blade being analyzed can be evaluated with respect to mechanical design requirements. If at some point these requirements are not satisfied, a basic change must be made to the blade shape, size, or constituent materials comprising the composite.

At the initial phase of the research project, it was decided to replace the existing complex version of composite micromechanics in COBSTRAN with a much simpler version, recently developed by C. C. Chamis of the NASA Lewis Research Center. Figs. (2) and (3) illustrate this new version of composite micromechanics. The equations provide the required relationships of composite properties to the properties of the constituents. The development of these equations also included an investigation to evaluate their performance. The investigation was performed by using a small finite element model to represent a single fiber surrounded by a square array of matrix. With judicious manipulation of the load and constraint conditions on the model, the simple cases of uniaxial tension, simple shear, and uniform thermal load were simulated. Then, by applying simple equations of strength of materials, a comparative evaluation of the composite micromechanics equations was made. A summary of the numerical test procedure is shown in Fig. (4), and the results are summarized in Fig. (5). It can be seen that the agreement is excellent ascertaining that the simplified equations are adequate for composite micromechanics.

Additional composite micromechanics equations are given in Figs. (6), (7), and (8). The micromechanics equations for the case where some fiber-matrix interdiffusion has occurred are given in Figs. (9) and (10).

The second phase of the research project involved the development of the nonlinear relationships which relate ply properties to the nonlinearities of the constituent material properties, and also account for temperature dependency of properties and creep. The results of these developments are given in Fig. (11).

The final phase of the research will include the implementation of these equations and relationships into the existing linear COBSTRAN code, which will involve all the required changes in order to perform the complete iterative nonlinear analysis.

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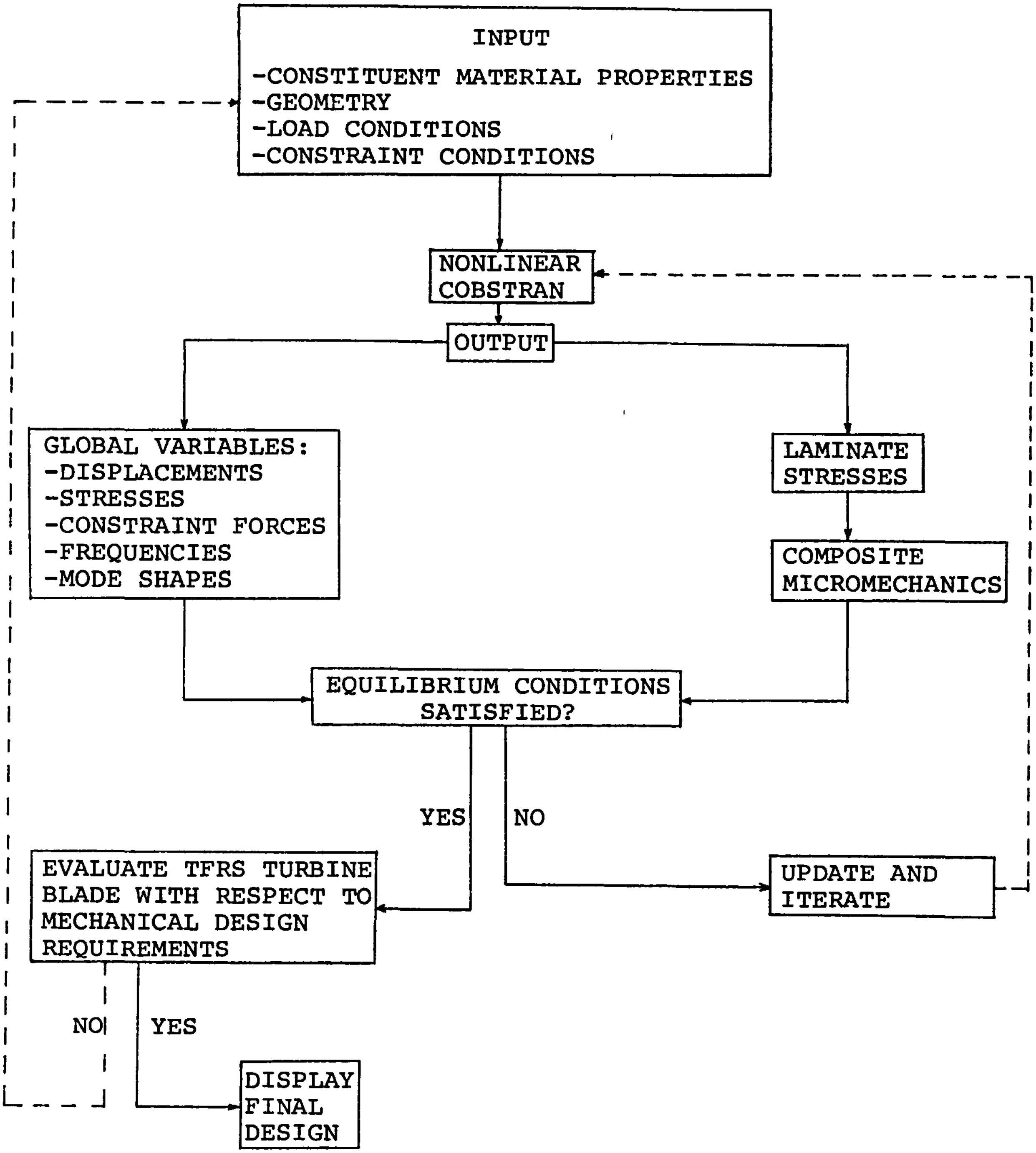

Fig. 1. Flow Chart for Nonlinear Analysis of Tungsten-Fiber-Reinforced Super Alloy Turbine Blade

Longitudinal Modulus: $E_{\ell 11} = k_F E_{f11} + k_m E_m$

Transverse Modulus: $$E_{\ell 22} = \frac{E_m}{1 - \sqrt{k_f}\ (1 - E_m/E_{f22})} = E_{\ell 33}$$

Shear Modulus: $$G_{\ell 12} = \frac{G_m}{1 - \sqrt{k_f}\ (1 - G_m/G_{f12})} = G_{\ell 13}$$

Shear Modulus: $$G_{\ell 23} = \frac{G_m}{1 - \sqrt{k_f}\ (1 - G_m/G_{f23}}$$

Poisson's Ratio: $\nu_{\ell 12} = k_f \nu_{f12} + k_m \nu_m = \nu_{\ell 13}$

Poisson's Ratio: $$\nu_{\ell 23} = \frac{E_{\ell 22}}{2\ G_{\ell 23}} - 1$$

For Voids: $k_f + k_m + k_v = 1$

k = volume fraction

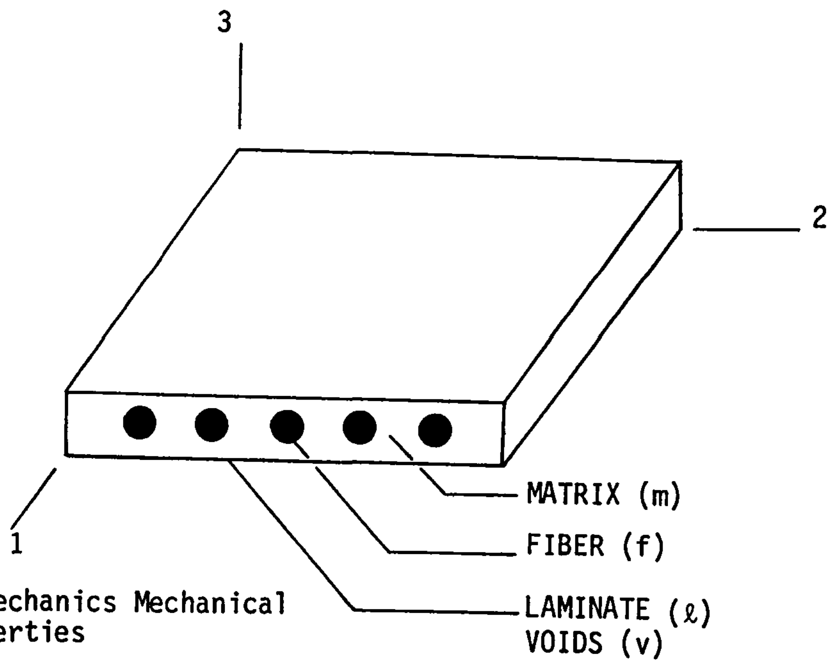

Fig. 2. Composite Micromechanics Mechanical Properties

Heat Capacity: $$C_\ell = \frac{1}{\rho\ell}\left(k_f \rho_f C_f + k_m \rho_m C_m\right)$$

Longitudinal Conductivity: $$K_{\ell 11} = k_f K_{f11} + k_m K_m$$

Transverse Conductivity: $$K_{\ell 22} = (1-\sqrt{k_f}\, K_m + \frac{K_m \sqrt{k_f}}{1-\sqrt{k_f}\,(1-K_m/K_{f22})} = K_{\ell 33}$$

For Voids: $$K_m = (1 - \sqrt{k_v}\,)\, K_m + \frac{K_m \sqrt{K_v}}{1-\sqrt{k_v}\,(1-K_m/K_v)}$$

Longitudinal Coefficient of Expansion: $$\alpha_{\ell 11} = \frac{k_f\, \alpha_{f11}\, E_{f11} + K_m\, \alpha_m\, E_m}{E_{\ell 11}}$$

Transverse Coefficient of Expansion: $$\alpha_{\ell 22} = \alpha_{f22}\sqrt{k_f} + (1-\sqrt{k_f}\,)(1+k_f \nu_m E_m/E_{\ell 11})\, \alpha_m$$

$$= \alpha_{\ell 33}$$

Fig. 3. Composite Micromechanics Thermal Properties

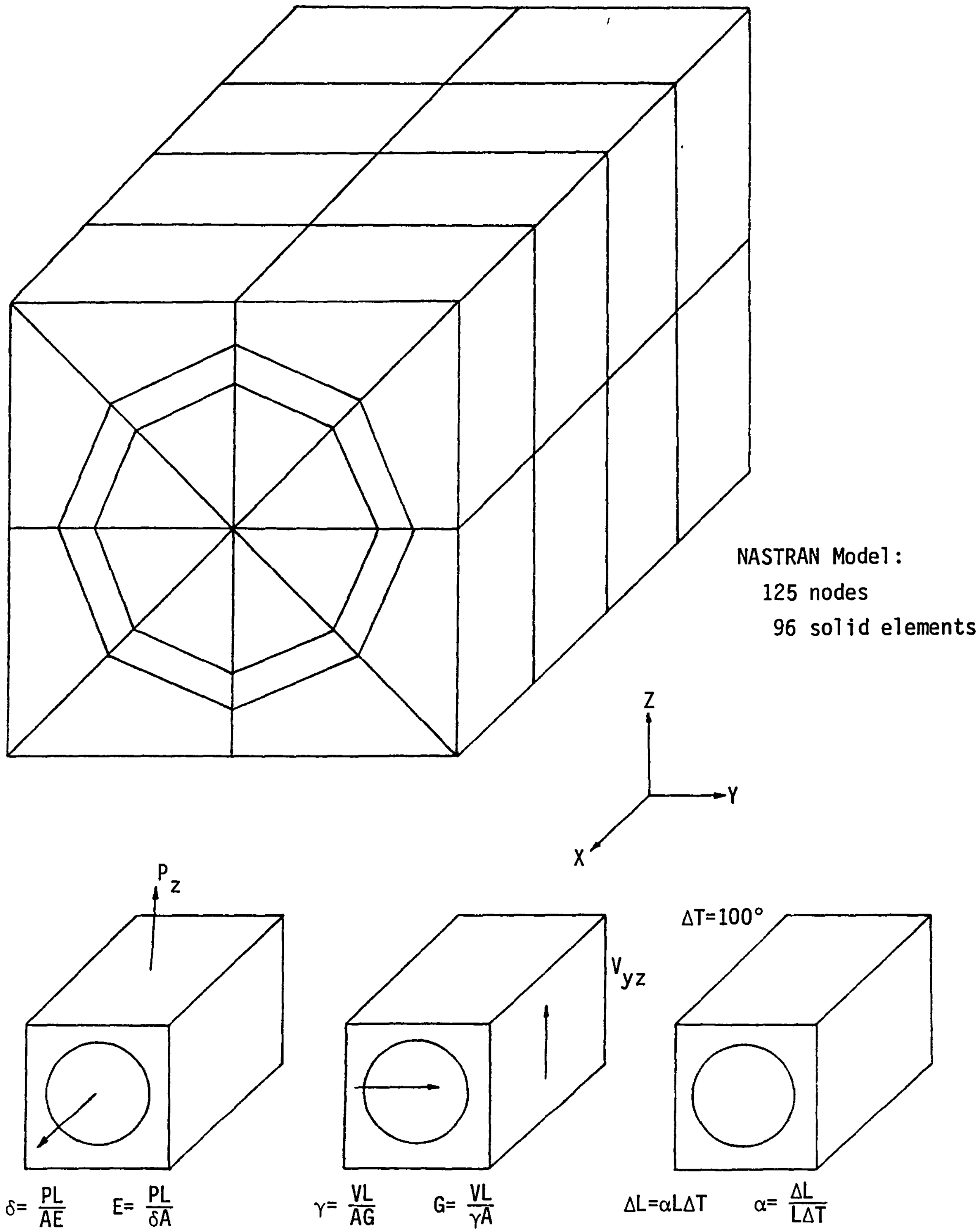

Fig. 4. NASTRAN Numerical Experiments for Composite Micromechanics

Property	Micromechanics Equation	Nastran Results
Longitudinal Modulus ($\times 10^6$ PSI)	$E_{\ell 11} = 39.90$	$E_x = 39.92$
Transverse Modulus ($\times 10^6$ PSI)	$E_{\ell 22} = E_{\ell 33} = 41.89$	$E_z = 41.42$
Shear Modulus ($\times 10^6$ PSI)	$G_{\ell 12} = G_{\ell 13} = 16.18$	$G_{xy} = 15.41$
Shear Modulus ($\times 10^6$ PSI)	$G_{\ell 23} = 16.18$	$G_{yz} = 16.96$
Poisson's Ratio	$\nu_{\ell 12} = \nu_{\ell 13} = 0.296$	$\nu_{xy} = 0.294$
Longitudinal Thermal Expansion Coefficient ($\times 10^{-6}$ in./in. - °F)	$\alpha_{\ell 11} = 3.63$	$\alpha_x = 3.64$
Transverse Thermal Expansion Coefficient ($\times 10^{-6}$ in./in. - °F)	$\alpha_{\ell 22} = \alpha_{\ell 33} = 3.57$	$\alpha_y = \alpha_z = 3.66$

Fig. 5. Comparison of Micromechanics Predictions With NASTRAN Test Model Results

Longitudinal Tensile Strength:

$$S_{\ell 11T} = S_{fT} \left(\beta_{fT} k_f + k_m E_m / E_{f11}\right)$$

Longitudinal Compressive Strength:

$$S_{\ell 11C} = \text{MIN.} \begin{cases} S_{fC} \left(\beta_{fC} k_f + k_m E_m / E_{f11}\right) \\ \\ S_{mC} \left(k_m + \beta_{fC} k_f E_{f11} / E_m\right) \\ \\ \left[\dfrac{F(k_y)\ G_m}{(1-k_f) + k_m G_m / G_{f12}} \right] \\ \\ \beta_{CS} S_{\ell 12S} + S_{mC} \end{cases}$$

where,

β's are correlation coefficients taken as unity for the present time

$$F(k_v) = \frac{1 - 2\left(\dfrac{k_v}{1-k_f}\right) + \left(\dfrac{k_v}{1-k_f}\right)^2}{1 - \left(\dfrac{k_v}{1-k_v}\right)}$$

Fig. 6. Composite Micromechanics Uniaxial Strengths

Transverse Tensile/Compressive Strengths:

$$S_{\ell 22T,C} = \frac{1}{\left[1-\sqrt{k_f}\left(1-\frac{E_m}{E_{f22}}\right)\right]\left[1+\phi_n(\phi_n-1)+\frac{1}{3}(\phi_n-1)^2\right]^{1/2}} S_{mT,C}$$

Lower Bound;

$$S_{\ell 22T,C} = \frac{\left[\left(\frac{\pi}{4\,k_f}\right)^{1/2} - 1\right]}{\left(\frac{\pi}{4\,k_f}\right)^{1/2}} S_{mT,C}$$

where

$$\phi_n = \frac{1}{\left(\frac{\pi}{4\,k_f}\right)^{1/2} - 1}\left[\left(\frac{\pi}{4\,k_f}\right)^{1/2} - \frac{1}{1-\sqrt{k_f}\left(1-\frac{E_m}{E_{f22}}\right)}\left(\frac{E_m}{E_{f22}}\right)\right]$$

Intralaminar Shear: Replace E and S_{mT} with G and S_{mS}, respectively.

Void Effects:

$$S_{mv} = \{1 - [4\,k_v/(1-k_f)\pi]^{1/2}\}\, S_m$$

Fig. 7. Composite Micromechanics Uniaxial Strengths (Cont'd.)

Mechanical Load:

$$\sigma_{m22}^{(A)} = \beta_v \, [1 - \sqrt{k_f} \, (1 - E_m/E_{f22})] \, \sigma_{\ell 22}$$

$$\sigma_{m12}^{(A)} = \beta_v \, [1 - \sqrt{k_f} \, (1 - G_m/G_{f12})] \, \sigma_{\ell 12}$$

$$\sigma_{m12}^{(A)} = \beta_v \, [1 - \sqrt{k_f} \, (1 - G_m/G_{f12})] \, \sigma_{\ell 23}$$

Thermal Load:

$$\sigma_{m33}^{(A)} = \sigma_{m22}^{(A)} = E_m \sqrt{k_f} \; \frac{(\alpha_{f22} - \alpha_m) \, \Delta T}{1 + \frac{1 - \sqrt{k_f}}{\sqrt{k_f}} [1 - \sqrt{k_f} \, (1 - E_m/E_{f22})]}$$

$$\sigma_{m33}^{(B)} = \sigma_{m22}^{(B)} = - \, (1 - \sqrt{k_f}\,) \, \sigma_{m22}^{(A)} / \sqrt{k_f}$$

Fig. 8. Composite Micromechanics Microstresses

Degraded Longitudinal Modulus.

$$E_{\ell 11D} = k_m E_m + k_f\{[1 - (D/D_o)^2]\, E_{\ell 11} + [1 - (1 - D/D_o)]^2\, E_{f11}\}$$

Degraded Transverse Modulus

$$E_{\ell 22D} = (1 - \sqrt{k_f})Em + \frac{(1 - D/D_o)\, E_m E_{\ell 22}}{(1/\sqrt{k_f} - 1)\, E_{\ell 22} + E_m}$$

$$+ \frac{(D/D_o)E_m E_{f22} E_{\ell 22}}{(1/\sqrt{k_f} - 1)E_{\ell 22}E_{f22} + (1 - D/D_o)E_m E_{f22} + (D/D_o)E_m E_{\ell 22}}$$

Similarly for $E_{\ell 33D}$

Degraded Shear Modulus:

$$G_{\ell 12D} = (1-\sqrt{k_f})G_m + \frac{(1 - D/D_o)G_m G_{\ell 12}}{(1/\sqrt{k_f} - 1)G_{\ell 12} + G_m}$$

$$+ \frac{(D/D_o)G_m G_{f12} G_{\ell 12}}{(1/\sqrt{k_f} - 1)G_{\ell 12}G_{f12} + (1 - D/D_o)G_m G_{f12} + (D/D_o)G_m G_{\ell 12}}$$

Similarly for $G_{\ell 13D}$ and $G_{\ell 23D}$

Degraded Poisson's Ratio:

$$\nu_{\ell 12D} = k_m \nu_m + k_f\{[1 - (D/D_o)^2]\nu_{\ell 12} + [1 - (1 - D/D_o)]^2 \nu_{f12}$$

Similarly for $\nu_{\ell 13D}$

Degraded Pisson's Ratio.

$$\nu_{\ell 23D} = \frac{E_{\ell 22D}}{2G_{\ell 23D}} - 1$$

Fig. 9. Composite Micromechanics for Degraded Fibers Mechanical Properties

Degraded Heat Capacity:

$$C_{\ell D} = K_m \frac{\rho_m}{\rho_{\ell D}} C_m + k_f \frac{\rho_f}{\rho_{\ell D}} \{ [1 - (D/D_o)^2] C_\ell + [1-(1-D/D_o)]^2 C_f \}$$

Degraded Longitudinal Conductivity:

$$K_{\ell 11D} = k_m K_m + k_f \{ [1-(D/D_o)^2] K_{\ell 11} + [1-(1-D/D_o)]^2 K_{f11} \}$$

Degraded Transverse Conductivity:

$$k_{\ell 22D} = (1- \sqrt{k_f}) K_m + \frac{(1-D/D_o) K_m K_{\ell 22}}{(1/\sqrt{k_f} - 1) K_{\ell 22} + K_m}$$

$$+ \frac{(D/D_o) K_m K_{f22} K_{\ell 22}}{(1/\sqrt{k_f} - 1) K_{\ell 22} K_{f22} + (1-D/D_o) K_m K_{f22} + (D/D_o) K_m K_{\ell 22}}$$

Similarly for $K_{\ell 33D}$

Fig. 10. Composite Micromechanics for Degraded Fibers Thermal Properties

Thermal Properties: (α, K, C): $$\frac{P}{P_o} = \left[\frac{T_M - T_o}{T_M - T}\right]^{n_T} \left[\frac{S_F - \sigma_o}{S_F - \sigma}\right]^{m_T} \left[\frac{\dot{\sigma}_H - \dot{\sigma}}{\dot{\sigma}_H - \dot{\sigma}_o}\right]^{\ell_T}$$

Mechanical Properties: (E, G, ν): $$\frac{P}{P_o} = \left[\frac{T_M - T}{T_M - T_o}\right]^{n_m} \left[\frac{S_F - \sigma}{S_F - \sigma_o}\right]^{m_m} \left[\frac{\dot{\sigma}_H - \dot{\sigma}_o}{\dot{\sigma}_H - \dot{\sigma}}\right]^{\ell_m}$$

Remaining Life: (S): $$\frac{S + S_c}{S_o} = \left[\frac{T_M - T}{T_M - T_o}\right]^{n_s} - C_1 \log_{10} N_T - C_2 \log_{10} N_m - C_3 \log_{10} t$$

Where,

T_M = melting temperature

T_o = reference temperature

S_F = fracture strength

σ_o = reference stress

$\dot{\sigma}_H$ = maximum stress rate

$\dot{\sigma}_o$ = minimum stress rate

S_o = reference strength

N_T = thermal load cycles

N_m = mechanical load cycles

t = time

n, m, ℓ = exponents evaluated from physical test data

C_1, C_2, C_3 = constants evaluated from physical test data

Fig. 11. Nonlinear Thermomechanical Relationships

4-6. EXPERIMENTAL STUDY OF UNCENTRALIZED SQUEEZE FILM DAMPERS

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INTRODUCTION AND OBJECTIVES

As the earth's material resources become more scarce and therefore more expensive, the development of greater sophistication in technologies which conserve materials becomes more imperative. In the power and aerospace industries more "power per pound" generally means lighter, higher speed, and more flexible rotating equipment. Since all rotors have some amount of unbalance which increases with use, higher rotating speed could mean unacceptable vibrations and instability problems. The need for a damping device to control vibration and instability is apparent.

Until recently there has been a rather insignificant amount of literature available pertaining to the design of uncentralized squeeze film dampers (SFD). The purpose of this research is to study experimentally the vibration response and characteristics of uncentralized SFD with and without end seals. The progress of the research as it is briefly reported here includes the design and building of the experimental rotor system required for the research work indicated above and a review of the available literature concerning this subject. The final report will include the complete review on the subject which will provide the "state of the art" and also the results of the experimental investigations.

DEVELOPMENTS

Since the early 1960's hydrodynamic squeeze film damper (SFD) has found increasing use over these past twenty years in the gas turbine industry. Today, most modern gas turbine engines use SFD coupled with rolling contact bearings. Since rolling contact bearings have little inherent damping, the extra damping is necessary for safe flexible rotor operation particularly at speeds near or in excess of the pinned-pinned critical speed of the rotor.

A SFD is a fluid (usually oil) filled annulus surrounding the bearing, or bearing housing, with a clearance in the order of 10 mils or less. The damper bearing is "dogged" to prevent rotation, but is free to "whirl" or precess about the center of rotation of the rotor while squeezing a pressure film ahead of it. The driving mechanism which causes the motion of the damper journal through the fluid film thereby creating the desired damping effect is the translational vibration of the rotor.

A properly designed squeeze film damper can a) reduce the level of forces transmitted through the bearing, b) reduce the amplitude of motion of the rotor, c) provide smooth operation through critical speeds, d) protect the rotor from sudden unbalance, and e) protect the rotor from self-excited instatility.

Since rolling contact bearing life is related to the applied forces, Item (a) above could mean great increases in bearing life. Blade tip clearance in compressors and turbines is critical, suggesting that Item (b) is a clear advantage, and the advantage of Item (c) is the capability for safe flexible rotor operation. Catastrophic failure from blade loss during operation could be avoided because of Item (d). Non-synchronous self-excited whirl instability can limit the operational speed of rotors mounted on fluid film bearings. This instability can be also caused by internal friction or variable aerodynamic loading with rolling contact bearing [1]. In view of Item (e), SFD could be a solution to this instability problem.

As suggested by Cookson and Kossa, SFD can be divided into two main categories based on basic design philosophy[2]. The design generally used in the United States is a SFD in parallel with a flexible rotor support which preloads the rotor centrally in the damper bearing. The flexible preloading is usually accomplished with a set of cantilever rods referred to as a "squirrel cage". On the other hand, the British design is a more basic uncentralized SFD with the rotor free to find its own position within the damper bearing.

In the early analysis of SFD the rotor center was assumed to follow a circular synchronous orbit around the center of the damper bearing clearance circle. This applies for centrally preloaded or vertical rotors. Though uncentralized SFD are simpler and less expensive, the analysis of this design is nonlinear and therefore much more complicated. Proper design however is important because a poor design can amplify rather than attenuate transmitted bearing forces[2].

A secondary classification of SFD which applies to both of the above types of design involves the use or non-use of end seals. Non-use of damper end seals allows damper fluid to flow freely longitudinally in the damper annulus yielding a parabolic longitudinal pressure distribution for a short bearing. A damper with no end seals and a "short" bearing can be analytically approximated with the "short bearing solution" of the Reynolds equation. The fluid feed for a damper with no end seals is usually accomplished with use of a circumferential groove in the center of the outer race of the damper bearing, which divides the damper into two parallel bearings.

A damper with end seals will have no longitudinal flow and, therefore, will have a constant longitudinal pressure distribution. This type of damper can be analytically approximated with the "long-bearing solution" of the Reynolds equation. Oil flow through this type of damper which is required for heat dissipation is usually maintained with the use of inlet and outlet ports located centrally in the damper annulus, 180° apart on the bottom and top, respectively.

Most designs include sealing devices, but the seals may be used to channel flow through the desired outlet at ambient pressure rather to form pressurizing end seals. The actual sealing arrangement can take many forms, but the sealing devices are usually o-rings, used in shear or compression, or piston rings. The particular application typically constrains the flow rate and, therefore, the sealing arrangement.

EXPERIMENTAL SET-UP

The rotor system was designed for use on a Bently-Nevada rotor dynamics test rig. The rotor is powered by a 1/10 hp. infinitely controllable drive motor experimentally proven capable of driving the test rotor at speeds up to 10,000 RPM. The system includes a 3/8 inch diameter shaft supported by two sets of preloaded duplex ball bearings, with each duplex set mounted in an uncentralized SFD. A 1/8 inch diameter quill shaft is used to couple the motor and shaft while eliminating the need for exact alignment of the motor and the two bearings. Rotor discs of various weights can be located at any position between the bearing stations. Each disc has threaded holes located symmetrically about its outside circumference for the positioning of balancing weights.

The bearing housings which preload the duplex bearings act as the camper journals. The damper bearings have interchangeable inserts allowing the radial clearance for the fluid annulus between the bearing and journal to be varied from 4 to 10 mils. Sealing between the journal and damper bearing is accomplished with O rings in shear. Circumferential grooves with outlet ports are located in the sides of the damper bearings at the edges of the inserts. Also inlet and outlet ports are located centrally in the inserts at the top and bottom of the dampers. With the appropriate outlet ports closed or open and the appropriate inserts in place, the end seal or no end seal condition is possible.

Vibration detection is accomplished with Bently-Nevada non-contacting proximity displacement transducers. The output of the proximitors is wired into a digital vector filter (VDF2) also manufactured by Bently-Nevada. The DVF2 provides a digital readout of magnitude of vibration, RPM, and phase angle for location of the rotor's "high spot" for balancing. Two Tektronix oscilloscopes, an X-Y-Y plotter, and an HP spectrum analyzer are also available for aid in studying vibrational response. The above electronic equipment and rotor system is presently designed and built in the Machine Dynamics Laboratory of The University of Akron.

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SECTION 5

CONCLUSIONS

The first year effort regarding the "NASA LeRC/Akron University Graduate Cooperative Fellowship Program" and the NASA "Graduate Student Researchers Program" proved to be successful for the following reasons: a) the participating graduate students expressed very favorable opinions regarding the quality and purpose of the program; b) the opportunity for the students to work with NASA engineers and be exposed to the research facilities of the NASA Lewis Research Center was received with great enthusiasm; c) the student researchers of both programs showed strong interest in the four areas of specialization and they were pleased with the thesis research topic they have selected; d) some students have already expressed their desire to make engine structural dynamics their life-long area of interest and become experts; e) the program has attracted well-qualified students to work such complex engine structural and dynamic problems; and f) the students put their efforts on problem areas where research and development is desperately needed.

The problems that have been encountered in carrying out the objec- of these grant programs during the first year effort were rather insignificant compared to the benefits obtained. Considerable emphasis was given on program organization, and on advising and educating the participating students as to the scope, objectives, and anticipated results of the program.

APPENDIX

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