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NASA Lewis Research Center/University Graduate Research Program on Engine Structures

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ABSTRACT

NASA Lewis Research Center established a graduate research program in support of the Engine Structures Research activities. This graduate research program focuses mainly on structural and dynamics analyses, computational mechanics, mechanics of composites and structural optimization. The broad objectives of the program, the specific program, the participating universities and the program status are briefly described.

INTRODUCTION

As an important part of the Engine Structures Program, NASA Lewis Research Center established a Graduate Cooperative Fellowship Program with several universities 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 education in these four areas of specialization is intended to promote readiness towards the solution of problems related to an aircraft turbine engine. 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 and develop better understanding regarding the interaction between the rotating and nonrotating parts of the engine. Research and training of this nature could result in improved engine designs with accompanying improvements in engine efficiencies and fuel consumption.

This paper includes (1) the background leading to this program, (2) a description of the specific program with the respective universities, and (3) a summary of the results to date including degrees awarded and research topics.

BACKGROUND

The realization of projected benefits in aircraft engine performance and increased durability required by our national need for efficient energy use now demands that research be conducted to describe the interaction of internal flow aerodynamics with the engine structural components. To do so effectively, it is necessary that the engine (Fig. 1) be treated as a complex system of dynamically interacting components. To provide the needed research into aircraft turbine engine structures, NASA Lewis Research Center formulated a major program for advanced structural analysis, structural dynamics, aeroelasticity, and life prediction of turbine engine structures and structural components, with particular emphasis on hot section components (Fig. 2). The general objective of this program is to develop the technology to permit the rational structural design and analysis of components for advanced gas turbine engines as well as the overall engine system. To implement this program, analysis methods were identified which were required in the following major area of research (disciplines): (1) structural analysis, (2) structural dynamics, (3) aeroelasticity, (4) fracture mechanics, (5) life prediction, and (6) optimization. It was recognized at the outset that the overall engine structures program must involve university grants and research contracts in addition to NASA Lewis Research Center in-house efforts. A general approach was selected (Table I) to identify topics within each discipline where academia and industry could participate most effectively in conjunction with the in-house effort. This general approach included near, intermediate and long-term research efforts as well as anticipated contribution from each major participant (academia, industry, and NASA) (Table II).

As a part of the in-house effort of the Engine Structures Program, an advanced education program (Master's level curriculum) was developed at Lewis Research Center. The objective of this advanced education program was to familiarize involved Lewis researchers with the latest developments in advanced structural analysis, structural dynamics, aeroelasticity and thermomechanical design. The participants in this advanced program would then be prepared to conduct and/or direct research to implement the Engine Structures Program (Fig. 3). Local universities were invited to submit proposals to teach the courses of this program (Table III). The proposals contained

detailed information on schedules, instructors, textbooks, and assignments. The University of Akron was selected to conduct the program.

In order to help interested and qualified university investigators decide how they would like to participate in the Engine Structures Program, through university grants, a 1-1/2 day workshop was held at Lewis Research Center on October 10-11, 1979 (Table IV). The major discipline areas with requisite generic and fundamental research (Table V) were described during the workshop. University investigators were invited to submit research grant proposals which were in their specialty and which were consistent with the generic fundamental research needed in support of the engine structures program. The number of proposals received and selected in the various technology areas are summarized in Table VI. The program summarized in Table VII constitutes the "NASA Lewis Research Center Engine Structures Grants Program". Grants awarded in support of the graduate assistantships (University of Arizona) and graduate fellowships (The Akron University) are also included in this table.

The graduate assistantship and fellowship grants program is directed mainly towards the education and advanced training of future researchers in engine structures. Each student participant is required to spend 30 percent of his educational training time at NASA and the balance at his university. His course work is judiciously selected and tailored to prepare him for research work in his field of interest. A research topic is selected for each student while in residence at NASA, which is approved by the faculty of his university as his thesis topic for a Master's and/or a Ph.D. degree. Collectively, these grants constitute the "NASA Lewis Research Center/University Graduate Research Program on Engine Structures" and are described in subsequent sections.

GRADUATE RESEARCH ASSISTANTSHIPS

University of Arizona

A general consensus expressed at the NASA Lewis Research Center/University Workshop was that modern computational methods encompass a large share of the methodology development needed in support of the engine structures program. Difficult problems within each discipline (Table V) can only be solved by personnel trained in the fundamentals of engineering and possessing advanced computing skills. Present undergraduate engineering curricula do not generally prepare such personnel. The alternative for preparing such personnel is through highly focussed graduate studies. As a consequence, a graduate research program on "Computational Structural Apprenticeships" was proposed by the University of Arizona and was selected for support under NASA Grant NAG 3-45.

The program consisted of a 15-month Master's degree program wherein the students spent six months at NASA Lewis Research Center, three months before, and three months after an academic year program at the University of Arizona. A Master's Report on a project of interest to the Center to be supervised by faculty at the University and research staff from the Center was also required. The program contained a heavy dose of numerical analysis and emphasized an engineering approach to current problems. The proposal asked for three students each year for two years.

The educational program at the University of Arizona was formulated as summarized in Table VIII. This program varied somewhat according to the individual students desires. The elective subjects included at least 25 different courses offered by the Aerospace and Mechanical Engineering, Engineering Mechanics, Computer Science, Civil Engineering, Electrical Engineering and Mathematics Departments.

The Master's report topics were selected jointly by NASA research scientists and the students and approved by the university. The educational program and project activity was tailored to help the students acquire the knowledge and ability to successfully complete their research. The research was carried out with the assistance of the NASA research staff and the program faculty.

Six students were selected and awarded Computational Structural apprenticeship grants. This was done through national advertising in university engineering departments and by personally contacting top engineering and science students at the University of Arizona. Top applicants were selected by the principal investigators. A brief discussion of the research projects of the participants follows.

BRIEF DESCRIPTION OF RESEARCH TOPICS

1. Research Topic: A Model Formulation of Loads and Clearances Between Engine Rotor and Case Due to Blade Loss

Using modal syntheses, the interaction of the rotor and casing in blade loss situations was mathematically formulated and the assumptions and simplifications identified. The resulting equation is a second order differential equation which is nonlinear in displacement and velocity terms with nonsymmetric matrices in blade loss analysis. A fourth order Adams Predictor corrector method with a fourth order Runge-Kutta starter routine was chosen. The routine was tested against analytical solutions, NASTRAN, and published examples. The results showed the routine was accurate. Using the program developed, specific blade loss problems were solved. Changes in parameters such as bearing stiffness and location were also examined, and their impact on design clearances between engine rotor and case investigated.

2. Research Topic: Evaluation of Plasticity-Creep Models for Nonlinear Stress Analysis

Plasticity-creep models available in MARC (trade name for a general purpose, finite element structural/stress analysis computer program) were evaluated for the analysis of test specimens designed to simulate cyclic plasticity in aircraft turbine blades. These models were used to describe the cyclic plasticity-creep of a benchmark notch test specimen. Specifically, the benchmark test specimen was analyzed using the isotropic kinematic, combined isotropic kinematic, ORNL and Mroz models in MARC as well as a viscoplastic model developed under a NASA contract. These models were evaluated with respect to (1) correlation with experimental data, (2) computational efficiency, (3) input data requirements, (4) ease of user model set-up for analysis, and (5) ease in displaying and interpreting results.

3. Research Topic: Computerized Analysis of Hybrid Composite Structures

Available computer programs at Lewis for hybrid composite micromechanics were integrated into one computer program. Laminate theory equations for hybrid composites were coded and made a part of this integrated computer program. The computer program was designed to be used in either the batch or interactive modes. Appropriate interphase routines were developed to couple this program with NASTRAN. The resulting "second-level-integrated program" can be used to analyze engine structural components such as blades, frames, and casings made from hybrid composites and

subjected to engine operating loads including temperature and moisture. This research led to the development of the INHYD computer code which is available from COSMIC.

4. Research Topic: A Parametric Study of the Free Vibration Characteristics of Rotating Cantilever Blades

The governing differential equations of motion suitable for describing bending in two perpendicular principal planes and torsion of a rotating cantilevered blade were established using Hamilton's variational principle. These equations were developed for a long, slender, homogeneous, isotropic beam with variable mass and stiffness properties, elastic and tension axis offsets, and variable built-in twist. The three integropartial differential equations with variable coefficients were used in a computer program ASTROMIC (Aeroelastic Structural Response of a Mistuned Cascade) to determine the aeroelastic stability characteristics of nonuniform blades of bladed-disk assemblies.

5. Research Topic: Structural Response of a Layered Composite Beam with Progressively Weaker Adhesive Layers

Environmental conditions can cause softening of layered composites in a structure. The adhesive layers soften faster than the composite layers, which causes the structural response to change.

A beam composed of four composite layers joined together with three adhesive layers was analyzed with the finite element method. The finite element computer program NASTRAN was used to study the bending, buckling, natural modes, and frequency response of the beam. Quadrilateral membrane elements were used to model the composite and adhesive layers of the beam. Softening of the adhesive layers was represented by a reduction of Young's Modulus. Eight different values of adhesive modulus were used for the bending, buckling, and modal analyses; three were used for the frequency response problem.

GRADUATE COOPERATIVE FELLOWSHIP

The University of Akron

Following the NASA Lewis/University Workshop, the University of Akron and the NASA Lewis Research Center established a Graduate Cooperative Fellowship Program under NASA Grant NAG 3-50 in order to achieve common objectives in certain areas of aerospace engineering. Through this program, NASA broadened the base for new ideas to develop and bring fresh inspiration into the solution of complex problems of propulsion systems by increasing the availability of young talent for immediate employment in the aerospace industry.

The University of Akron benefited from this fellowship program by providing greater depths to its graduate programs, and by attracting high quality students to the University which concentrated their efforts on current research needs. Under this program, the selected students had the opportunity to fully utilize the teaching and research expertise of the university community and the technical expertise of the NASA Lewis Research Center.

Based on the objectives stated above and by also taking into consideration the close geographical proximity between the two institutions, as well as past and present technical exchanges, the Graduate Fellowship Program is organized and administered in a way which is expected to produce optimum results for both NASA and The University of Akron. On a competitive basis, the graduate students selected to participate in this Fellowship Program are under the tutelage of University of Akron faculty and adjunct professors

appointed from NASA personnel. Each student spends about 30 percent of his educational training time at NASA and the balance at The University of Akron.

His residency at the NASA Lewis Research Center consists of a suitable continuous time interval, usually during the summer months and/or during Christmas recess, followed by a suitable part-time residency during school periods. In this way the fellowship students maintain continuous contact with both institutions during the whole educational period required for their graduate degree. The degree is awarded to the student when the academic requirements at The University of Akron, as well as his NASA residency, are completed.

During his NASA residency, the student performs research work on a problem of his choice, which is selected from a group of problem areas that are of interest to NASA. A master's and/or doctoral degree is expected to be completed as a result of this research work. The broad areas of specialization under this fellowship program are as follows: (1) Engine Structural Analysis and Dynamics, (2) Computational Mechanics, (3) Mechanics of Composite Materials, and (4) Structural Optimization. The graduate fellowships are expected to be evenly distributed among the four areas outlined above. The program is summarized in Table IX. The research topics are briefly described subsequently.

BRIEF DESCRIPTION OF RESEARCH TOPICS

1. Research Topic: Structural Optimization of Variable Cross Section Components

This research includes a preliminary study of a cantilever beam of variable circular cross section along its length. Its end diameters, DB and DT, and its constant wall thickness, t, are the design variables which are to be optimized for a given load condition. The design variables and the selected load conditions involve a uniformly distributed load and a point load at the free end. The objective of the research is to develop a FORTRAN program which will incorporate an optimization technique wherein the design variables are optimized in such a way as to make the weight of the beam a minimum. The design variables are determined by satisfying a number of constraint equations which are used to maximize the beam's flexural stress, the deflection at the free end, critical buckling, and its fundamental natural frequency.

2. Research Topic: Mesh Refinement Criteria

This research includes a study of a heuristic mesh refinement criteria based upon the establishment of patterns formed by the gradients and variations of typical finite element output (such as displacements, stresses and strains). The detection of these patterns is accomplished numerically considering such measures as standard deviation, mean, integral square error and the comparison of maximum values along given lines of action. The application of such a criteria would appear most useful in situations where a problem is well defined geometrically, yet is being subjected to multiple loading histories or being analyzed iteratively. In such situations an engineer, not wishing to stop at each time step to inspect the adequacy of his model, might require a computationally simple and storage efficient criteria which could supply needed decision making information to a self adaptive mesh refinement program.

3

3. Research Topic: Nonlinear Constitutive Relation-
ships
        This research deals with the experimental evalua-
tion of available constitutive relationships of high
temperature superalloys. Isothermal and nonisothermal
loadings are applied at temperatures ranging from 800
to 1200 °F. The results obtained will be compared with
those predicted using available constitutive relation-
ships in order to determine their applicability in this
temperature range.

4. Research Topic: High Velocity Impact of Composites
        This research involves experimental and analytical
research work on high velocity impact using Coupled
Eulerian-Lagrangion 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
between the two regions where the coordinate meshes of
both theories come together . The Eulerian system is
best suited for large displacements coupled with mater-
ial "flow" encountered in the vicinity of the impact.
Experiments will be performed on fiber composite speci-
mens. The results obtained from these experiments will
be compared with the predicted values.

5. Research Topic: Dynamic Response of Fluid Coupled
Coaxial Cylinders
        This research involved a comprehensive literature
review and a study of the hydrodynamic response of
fluid coupled coaxial cylinders, which included fluid-
structural interactions and the associated influential
parameters. The review and study covered both experi-
mental and theoretical work with numerical solutions
using the methods of finite difference and finite ele-
ment. The Navier-Stokes equations were used to derive
inertia and damping forces as a function of the oscil-
lating circular coaxial shell mode shapes which bound
viscous fluid within a finite length annular region.
Simple expression axial mode coefficients were derived
that may be used with the virtual mass and damping
approach. Important points developed were the signifi-
cant effect of shell or shaft mode shape on fluid film
pressure and the use of the finite element displacement
modal method to solve fluid coupled cylinder modal
time-history and spectrum response analysis.

6. Research Topic: Structural Optimization of Turbine
Vanes
        This research deals with the determination of an
optimum aerodynamic shape of engine stator vanes which
are subjected to varying dynamic and thermal loadings.
The initial phases of this research included simplified
vane shapes to determine thermal stress distributions
in these vanes and their barrier coating.

7. Research Topic: Rotor Dynamics - Data Acquisition/
Reduction Methods
        This research deals with the design of a graphics
subsystem to be added to the Bladed-Disk Data Acquisi-
tion System (BDDAS) which was developed by the NASA
Lewis Research Center. This addition of graphics view-
ing modes was to be accomplished without substantial
modification of the existing BDDAS as much as possible,
and, by using equipment and parts available in stock
at Lewis Research Center.
        The BDDAS can record large amounts of data in a
very short period of time, approximately 400 000 data
points in 70 ms. Presently the only means of analyzing
this data is by Fast Fourier Transform techniques,
which is done off line. Since there is no real-time
mode giving information about the bladed-disk assembly,
the operator has to guess when the best time would be

to collect data. Along with the real-time mode, Lewis
Research Center recognizes the need for a post-
processing visual mode that allows viewing of detailed
blade motion as a supplement to Fast Fourier Transform
analyzer frequency output. Accordingly, the research
required a design of a graphics subsystem to be added
to the BDDAS.

8. Research Topic: Composite Micromechanics/Finite
Element Substructuring
        This research involved the use of finite element
substructuring to predict unidirectional fiber compos-
ite hygral (moisture), thermal, and mechanical proper-
ties. COSMIC NASTRAN and MSC/MASTRAN were used to
perform the finite element analysis. The results ob-
tained from the finite element model were compared
with those obtained from simplified composite micro-
mechanics equations. A unidirectional composite struc-
ture made of boron/HM-expoxy, S-glass/IMHS-expoxy and
AS/IMHS-expoxy was studied. The finite element analy-
sis was performed using three-dimensional isoparametric
brick elements and two distinct models. The first
model consisted of a single cell (one fiber surrounded
by matrix) to form a square. The second model used
the single cell and substructuring to form a nine-cell
square array. To compare computer time and results
with the nine-cell superelement model, another nine-
cell model was constructed using conventional mesh
generation techniques. An independent computer program
consisting of the simplified micromechanics equation
was developed to predict the hygral, thermal, and
mechanical properties for this comparison. The results
indicate that advanced techniques can be used advan-
tageously for fiber composite micromechanics.

9. Research Topic: Preprocessors For Finite Element
Analysis
        This research involved the development of a uni-
fied preprocessor for finite element analysis. The
objective of this research was 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 were interpreted for different finite element
codes so that the user does not have to learn the input
format of various programs. The result of the research
was a computer code module called MESHGEN (Mesh
Generator).
        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 mode, element, and boundary ini-
tial 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.

10. Research Topic: Nonlinear Analysis of Tungsten-
Fiber-Reinforced Superalloy Turbine Blades
        This research involved the development of a unique
"upward-integrated top-down-structured" capability for
nonlinear analysis of high-temperature multilayered
fiber composite structures. A special purpose com-
puter code was developed (nonlinear COBSTRAN) which is
specifically tailored for the nonlinear analysis of
tungsten-fiber-reinforced superalloy (TFRS) composite
turbine blade/vane components of gas turbine engines.
Special features of this computational capability in-
clude accounting of; micro- and macro-heterogeneity,

nonlinear (stress-temperature-time dependent) and anisotropic material behavior, and fiber degradation. A demonstration problem is presented to manifest the utility of the upward-integrated top-down-structured approach, in general, and to illustrate the present capability represented by the nonlinear COBSTRAN code. Results indicate that nonlinear COBSTRAN provides the means for relating the local nonlinear and anisotropic material behavior of the composite constituents to the global response of the turbine blade/vane structure.

11. Research Topic: Parametric Studies of Swept Tuboprops
This research involves the sensitivity of advanced turboprops on the design variables sweep and twist. Specifically, these design variables are first selected to provide an aerodynamically acceptable turboprop design. This design is then analyzed to ascertain its adequacy for all other mechanical design requirements. The analysis requires nonlinear displacement analysis and attendant vibration modes, frequencies and flutter.

12. Research Topic: Experimental Studies of Uncentralized Squeeze Film Dampers
This research focused on the development of an experimental procedure for the determination of the vibrational response of uncentralized squeeze film dampers with and without end seals. A complete literature review to determine the state of the art on the subject was performed. Also, a study of what is required to design and build an experimental rotor system for experimental studies on squeeze film dampers was performed. The experimental rotor can be operated with or without end seals to conduct an experimental study of the system's vibrational response. Inlet pressure, viscosity and clearance were each found to have a great influence on damper performance. Comparisons were made with the results found in available literature and with a simplified computer analysis. Suggestions are included for design improvements and for future work.

CONCLUDING REMARKS

The NASA Lewis Research Center/University Graduate Research Program on Engine Structures has been very successful. Fourteen of the participating students completed the program. Eleven of these received their Masters Degree. One received a Ph.D. Degree. Four enrolled in Ph.D. programs and four accepted employment at NASA Lewis. It is the consensus of those associated with this program that a program such as this is a very effective means of educating and preparing young researchers to conduct research in highly specialized and complex technical disciplines. Participation in this program helped also to improve performance in the classroom since the subject matter was closely related to the participant's research work.

TABLE I. – GENERAL APPROACH TO ENGINE STRUCTURES RESEARCH FOR
METHODOLOGY DEVELOPMENT

Generic research	Fundamental level, mainly grants, in-house
Applied research	General problem area, components level mostly contracts; low level in-house
Specific research	Near term or current problems contracts, selective in-house
Graduate fellowships	Educational, both faculty and future researchers

TABLE II. – PROGRAM IMPLEMENTATION RESOURCES AND PARTICIPANTS

Goal	Participant impact		
	In-house	Contract, industry	Grant, university
Near term, specific research	Minor	Major	Negligible
Intermediate, applied research	Significant	Considerable	Minor
Long term, generic research and education	Considerable	Considerable	Significant

TABLE III. – ENGINE STRUCTURAL ANALYSIS ADVANCED TRAINING PROGRAM

CURRICULUM SUMMARY

First quarter	Second quarter	Third quarter
1.1 Advanced Mechanics of Materials	2.1 Advanced Mechanical Behavior of Materials (Fatigue, Creep, Life Prediction)	3.1 Theory of Elasticity and Plasticity
1.2 Advanced Vibrations	2.2 Structural Dynamics	3.2 Random and Acoustic Vibrations
1.3 Advanced Structural Analysis	2.3 Theory of Plates, Shells, and Buckling	3.3 Themo-Mechanical Analysis and Design
1.4 Applied Numerical Methods	2.4 Finite Element Theory	3.4 Aeroelasticity

TABLE VI. – SUMMARY OF GRANT PROPOSALS RECEIVED AND SELECTED
FROM THE WORKSHOP

Discipline	Proposals received	Proposals selected for support
Nonlinear constitutive relationships	5	3
Aeroelasticity and vibrations	6	3
Advanced structural analysis	4	3
Nonlinear fracture mechanics	3	2
Life prediction	3	2
Optimization	0	0
Totals	21	13

TABLE V. – DISCIPLINES SELECTED FOR GENERIC AND FUNDAMENTAL RESEARCH
IN SUPPORT OF THE ENGINE STRUCTURES PROGRAM

Discipline	Generic and fundamental research
Nonlinear constitutive relationships	Three-dimensional cyclic stress, temperature, creep, ratcheting
Aeroelasticity and vibrations	Interaction – rotor/flexible shaft, shaft/bearing, fluid/structure, forcing function models
Advanced structural analysis	Dyn. Substructuring, C.E.A. for nonlinear solutions, F.E. with holes, S.A. solution strategies.
Nonlinear fracture mechanics	Requisite methodology, critical parameters, models for crack growth and fracture
Life prediction	Methodology and models based on: engineering, micromechanistic, probabalistic.
Optimization	Formulation strategies, algorithm packaging multiple objective functions

TABLE IV. – LeRC/Univ. – WORKSHOP ON ENGINE STRUCTURES

Objective:	Invite university investigators to participate, commensurate with their interests and expertise, in support of this program.
Dates held:	October 10-11, 1979
Invited:	About 150 investigators throughout the U.S.A.
Attended:	80
Universities:	40

During the workshop we described the engine structures program and the
disciplines that were identified for fundamental research support.

TABLE VII. – UNIVERSITY GRANTS SUMMARY

– EXISTING AND INCLUDING THOSE

FROM THE WORKSHOP

Discipline	Number of grants
Nonlinear constitutive relationships	4
Aeroelasticity and vibrations	4
Advanced structural analysis	4
Nonlinear fracture mechanics	2
Life prediction	4
Composite analysis	2
Graduate assistantships and fellowships	4
Totals	24

TABLE VIII. – COMPUTATIONAL STRUCTURAL APPRENTICESHIPS
SUMMARY OF COURSES
(University of Arizona)

First semester	Second semester
AME 539. Advanced Concepts in Finite Element Analysis. F.E. Mathematics. Applications to elasticity, heat conduction and fluid flow. Dynamics, buckling, fracture mechanics.	AME 538 Finite Element Analysis in Nonlinear Solic Mechanics. Material nonlinearity (elastic, plastic, visco-elastic) geometric nonlinearity (finite deformation), numerical solution methods and nonlinear programs.
Math 475a. Mathematical Principles of Numerical Analysis: Introduction to theoretical numerical analysis with applications to errors, inter-polation, approximations. Numerical, integration and differentiation; solution of ordinary and partial differential equations.	Math 475b.
Math 575a. Numerical Analysis: Partial differential equations and methods for their numerical solu-tions; error analysis; stability; linear and nonlinear equations of different types; "weak" solutions.	Math 575b.
AME 437. Engineering Program Design and Implementation: Finite differ-ence and finite element methods; mesh generation and display; computer graphics; program documentation and maintenance.	EE571. Digital Systems Design: Com-puter organization, memory systems, AHPL, control unit design, micropro-gramming, input-output, computer arith-metic, features of large computers, time sharing.
Elective	Elective
Master's Report Project	Master's Report Project

TABLE IX. – GRADUATE RESEARCH PROGRAM – THE UNIVERSITY OF AKRON

Research topic	Degree status
Structural Optimization of Components With Defects	Ph.D. (third year)
Dynamic Finite Element Remodeling	Masters[a] (first year Ph.D. student)
Nonlinear Constitutive Relationships	Masters[b] (second year)
High Velocity Impact Testing and Analysis	Masters thesis in preparation
On the Dynamic Response of Fluid Coupled Coaxial Cylinders	Ph.D.[a]
Structural Optimization of Turbine Vane	Masters (changed spciality)
Rotor Dynamics–Data Acquisition/Reduction Methods	Masters[a,b]
Composite Micromechanic/Finite Element Substructuring	Masters[a,b]
A Unified Preprocessor Finite Element Analysis	Masters[a]
Nonlinear Analysis of Tungsten–Fiber–Reinforced Superalloy Turbine Blades	Masters[a,b]
Structural Analysis/Optimization of Turboprops	Masters (second year)
Experimental Study of Uncentralized Squeeze Film Dampers	Masters[a]

[a]Degree awarded.
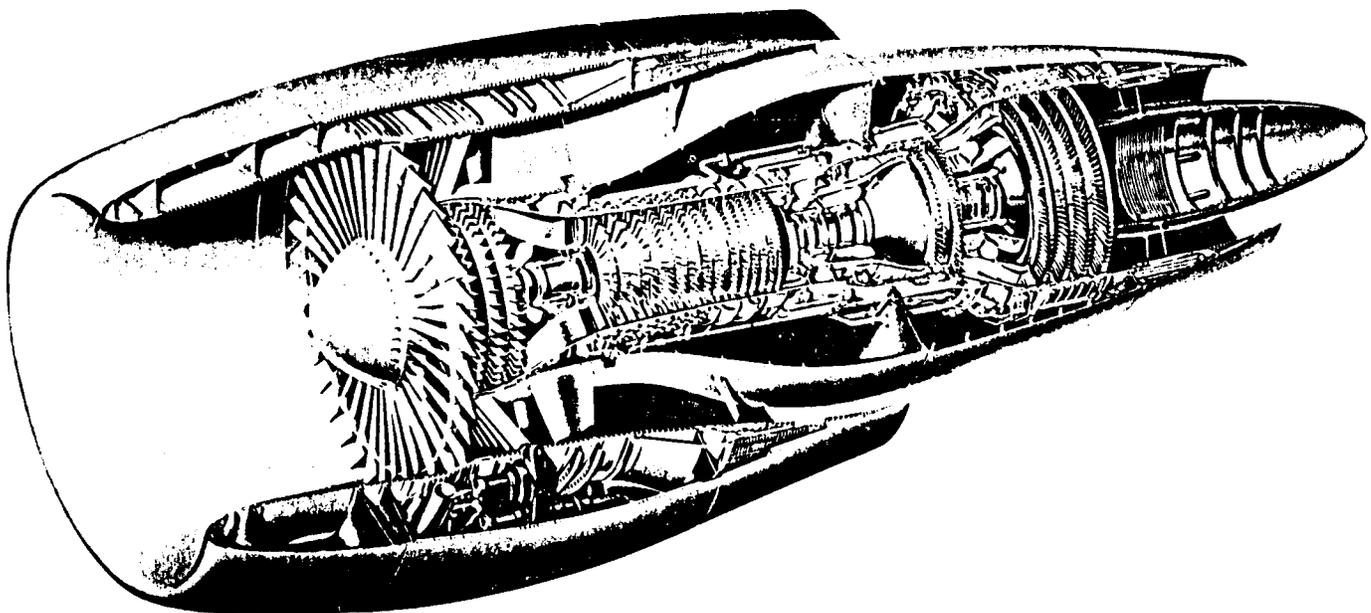[b]Accepted employment at Lewis.

FIGURE 1. AIRCRAFT ENGINE

FIGURE 2. ENGINE HOT SECTION COMPONENTS

COMBUSTOR LINER
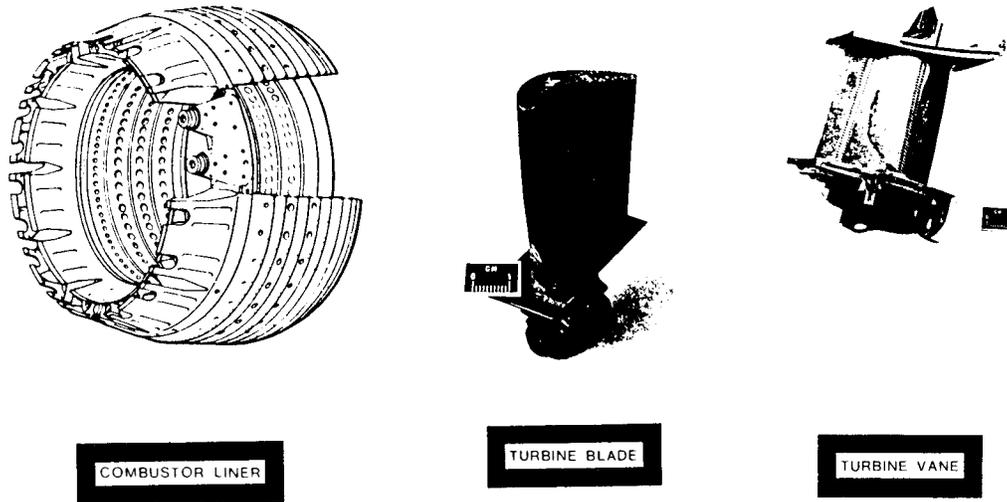
TURBINE BLADE

TURBINE VANE

FIGURE 3
ADVANCED TRAINING PROGRAM FOR ENGINE STRUCTURAL ANALYSIS OBJECTIVE
FLOW CHART

FORMAL
COURSES

ENGINE STRUCTURES
SEMINARS

DISCIPLINES

COMPONENT

LOAD CONDITIONS

ENGINE STRUCTURES
PROBLEMS

COMPUTER PROGRAMS
FAMILIARIZATION

F.E. MODELING
AND ANALYSIS

STRUCT. ANAL.
ENG. MECH
COMP. MECH
AERO ELAST.
MAT. BEH.
AOV. DESIGN
COMPUT. METH

STATIC
ROTATING
COMBINED

STATIC
THERMAL
CYCLIC
DYNAMIC
RANDOM EXCIT.

COMPONENTS
SUBSYST.
INT. SYSTEM

NASTRAN
MARC
ADINA
COBSTRAN
CODSTRAN
CISTRAN

PRE AND POST
PROCESSORS
COMPONENTS
SUBSYSTEMS
INT. SYSTEMS

PARTICIPANTS
CAPABILITY

INTEGRATE COMPUTER
PROGRAM CAPABILITY

CENTER-OF-EXCELLENCE
IN ENGINE STRUCTURAL
ANALYSIS