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6. AUTHOR(S)
John M. Vance

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Dept. of Mechanical Engineering
Texas A&M University
College Station, TX 77843

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13. ABSTRACT (Maximum 200 words)
Sixteen graduate students in mechanical and aerospace engineering were supported on this grant, producing four M.S. graduates and three Ph.D. graduates during the grant period. Eight students are still pursuing research and studies toward their degree. Two students failed the Ph.D. qualifying examination and left Texas A&M. Six of the program participants are now employed by companies in the aircraft or aerospace propulsion field.

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**FINAL SCIENTIFIC REPORT
for
AFOSR-86-0297**

October 1991

AFRAPT Program at Texas A&M University

Program Manager (AFOSR): Julian M. Tishkoff

Principal Investigator (TAMU): J. M. Vance

Program Title: Research for Advanced Aircraft Engine Structures

Department of Mechanical Engineering
Texas A&M University

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Final AFRAPT Report - Texas A&M University

AFOSR Award #86-0297

AFRAPT Coordinator: Dr. John M. Vance

The graduate students supported on this grant along with their supervisory professors and a brief description of their research activities are as follows:

1. Student's Name: Steve J. Hensel
Degree Program: Ph.D. M.E.
Supervising Professor: Dr. Erian Baskharone
Research Title: A New Approach to Fluid-Induced Vibration of Seals and Turbomachinery Components

A finite element-based computational perturbation analysis for calculating the rotordynamic coefficients of a shrouded impeller was developed. The coefficients are obtained through examination of the fluid reaction, in the shroud-to-housing secondary passage, to virtual eccentricities of the impeller centerline. These include a simple linear displacement that is generally coupled with whirling and tilting motions. Mr. Hensel received his Ph.D. in the spring semester of 1990. He is currently employed as a senior engineer at Westinghouse Savannah River Laboratory in Aiken, South Carolina. His research has resulted in the publication of five papers in the ASME Transactions, as follows:

Baskharone, E., and Hensel, S., "A New Model for Leakage Prediction in Shrouded-Impeller Turbopumps," Journal of Fluids Engineering (ASME Transactions), Vol. 111, No. 2, June 1989, pp. 118-123.

Baskharone, E. A., and Hensel, S. J., "A Finite-Element Perturbation Approach to Fluid/Rotor Interaction in Turbomachinery Elements: Part I: Theory," Journal of Fluids Engineering (ASME Transactions), Vol. 113, No. 3, September 1991, pp. 353-361.

Baskharone, E. A., and Hensel, S. J., "A Finite-Element Perturbation Approach to Fluid/Rotor Interaction in Turbomachinery Elements: Part II: Application," Journal of Fluids Engineering (ASME Transactions), Vol. 113, No. 3, September 1991, pp. 362-367.

Baskharone, E. A., and Hensel, S. J., "Interrelated Rotordynamics Effects of Cylindrical and Conical Whirl of Annular Seal Rotors," Journal of Tribology (ASME Transactions), Vol. 113, No. 3, 1991, pp. 470-480.

Baskharone, E. A., and Hensel, S. J., "Moment Coefficients of Incompressible-Flow Seals with Conically Whirling Rotors," International Journal of Mechanical Sciences, Vol. 33, No. 2, 1991, pp. 151-167.

Baskharone, E. A., and Hensel, S. J., "A Finite-Element Perturbation Approach to Fluid/Rotor Interactions in Turbomachinery Elements: Part I: Theory," presented at the First Joint ASME-JSME Conference in Portland, Oregon, June 1991, and contained in the ASME Publication "Numerical Simulations in Turbomachinery," FED-Vol. 120, 1991, pp. 89-96.

Baskharone, E. A., and Hensel, S. J., "A Finite-Element Perturbation Approach to Fluid/Rotor Interactions in Turbomachinery Elements: Part I: Application," presented at the First Joint ASME-JSME Conference in Portland, Oregon, June 1991, and contained in the ASME Publication "Numerical Simulations in Turbomachinery," FED-Vol. 120, 1991, pp. 97-103.

2. Student's Name: Larry Hawkins
Degree Program: M.S.M.E.
Supervising Professor: Dr. Dara W. Childs
Research Title: Experimental Results for Labyrinth Gas Seals with Honeycomb Stators: Comparisons to Smooth Stator Seals and Theoretical Predictions

Larry Hawkins' thesis was completed and results from it were published as ASME Paper No. 88-Trib-40, and also in the Journal of Tribology. Mr. Hawkins received his M.S. in 1988 and is now working for Rocketdyne Division, Rockwell International, Canoga Park, California.

3. Student's Name: Joe Fuehne
Degree Program: M.S.M.E. and Ph.D. M.E.
Supervising Professor: Dr. John Engblom
Research Title: Finite Element Formulations for Laminated Composite Structures

Mr. Fuehne developed a "doubly-curved" finite element shell formulation which efficiently gives transverse shear and normal stress information for laminated composite structures. These stresses are useful in design due to low transverse strength properties. Mr. Fuehne received his M.S. degree in Spring 1988 and the Ph.D. in Fall 1990.

4. Student's Name: Robby Hibbs
Degree Program: M.S.M.E.
Supervising Professor: Dr. David Rhode
Research Title: A New Efficient Computational Model for the Prediction of Fluid Seal Flowfields

An original approach was developed and implemented into finite-difference program PRELIM which couples computational fluid dynamics and dynamic similarity. The flow adjacent to a recirculation zone is computed, taking the dividing streamline as the boundary of the domain. The CPU time and storage are only 4.7% and 22.6%, respectively, of that

required when the recirculation zone is included in the domain. For straight-through labyrinth seals, PRELIM predicts the leakage within 5.1% to 12.0% of the air leakage measurements of Stocker (1975). Program SIM also incorporates dynamic similarity and is a simple search program that relates a labyrinth cavity inlet Mach number to the pressure drop for that particular cavity. SIM predicts the leakage within 3.1% to 5.2% of the air leakage measurements of Childs (1986). Although PRELIM and SIM both predict the leakage through seals quite successfully, their utility to a designer is different. For a particular labyrinth cavity design, a designer would use SIM to quickly determine the optimum number of cavities for a specified pressure ratio. Mr. Hibbs successfully completed his degree in Fall 1988 and is now employed at Rocketdyne in Canoga park, California.

5. Student's Name: Robert Jones
Degree Program: Ph.D. M.E.
Supervising Professor: Dr. John Vance
Research Title: Nonlinear Rotordynamics in Turbomachinery

Mr. Jones began his project by doing literature surveys and designing a test apparatus. He failed the Ph.D. Qualifying Exam in the Fall 1989 semester and was not allowed to continue his graduate program at Texas A&M University. He is now employed at Sverdrup Technologies in Huntsville, Alabama.

6. Student's Name: Robert Burch
Degree Program: Ph.D. M.E.
Supervising Professor: Dr. Dara W. Childs
Research Title: CFS Approaches for Calculation of Seal Rotordynamic Coefficients

Mr. Burch assisted with experimental research on seals and performed literature searches in preparation for his research project. He failed the Ph.D. Qualifying Examination in the Fall 1989 semester and was not allowed to continue his graduate program at Texas A&M University.

7. Student's Name: Jim Havelka
Degree Program: M.S.M.E.
Supervising Professor: Dr. John Engblom
Research Title: Transient Response Predictions for Composite Structures

Mr. Havelka developed an airfoil mesh generator and incorporated damage predictions into transient response predictions for composite structures. He graduated in Spring 1988 with the M.S. degree.

8. Student's Name: Mark C. Johnson
Degree Program: Ph.D. M.E.
Supervising Professor: Dr. Gerry Morrison
Research Title: 3-D Laser Doppler Anemometer Measurements in Annular Labyrinth Seals

Mark C. Johnson was a participant in the AFRAPT program who received his Ph.D. in May 1989. Dr. Johnson's research involved the experimental study of fluid flow through annular and labyrinth seals. The research utilized a 3-D laser Doppler anemometer system to measure the mean velocity vector and the entire Reynolds stress tensor. This information is invaluable in gaining an understanding of the flow field inside the seals and for providing a data base for comparison with numerical predictions. The work has resulted in publications in Journal of Tribology (July 1989) and Journal of Engineering for Gas Turbines and Power (January 1991) with several more under preparation and/or review. Dr. Johnson is now employed at Allied Signal-Garrett Engine Division working on the development of a new generation of auxiliary power units.

9. Student's Name: Bradley Paul Cardon
Degree Program: M.S.M.E.
Supervising Professor: Dr. John M. Vance
Research Title: Advanced Engine Dampers

A gas operated bearing damper for aircraft engines, invented by the supervising professor, was analyzed and experimentally investigated. The damper utilizes air bled off from the compressor to feed actuator pockets around the bearing support. Using the analysis to guide the experiments, the design was evolved to produce a damping coefficient of 50 lb-sec./in (8756 N-S/M) with a power penalty of 7 HP (5.2 KW) at a supply pressure of 45 psi (310 KPa). Mr. Cardon left school for employment with Texaco Research in the summer of 1990. He has not completed the writing of his M.S. thesis, but his research results were published in ASME Paper 91-GT-249, "A Gas-Operated Damper for Turbomachinery."

10. Student's Name: Timothy Stuart Barrett
Degree Program: M.S.M.E.
Supervising Professor: Dr. Alan Palazzolo
Research Title: Casing Flexibility Effects in Active Vibration Control of Rotor Bearing Systems

Mr. Barrett began his research in 1989 and was still engaged in it at the expiration of this grant. The goal of this work is to investigate effects of including flexibility with an active vibration controlled simulation model of a rotor bearing system. The model will be used to predict both unbalanced response and stability for the closed loop system. The specific objectives of this research are as follows: 1) Develop an electromechanical model using piezoelectric actuators for active vibration control which incorporates a flexible rotor housing to better predict system stability and response; 2) Develop the governing differential equations to describe the feedback circuit, including piezoelectric actuator

control and dynamics; 3) Develop structural software, including gyroscopic effects, to model the rotor and the rotor casing. Nine node isoparametric finite elements will be used for the casing; 4) Synthesize electromechanical and structural models, and utilize combined modeling tools to predict rotor response and stability; and finally, 5) Investigate effects of flexible casing on predicted output, and compare with test data results.

The electromechanical model has been constructed, and the governing equations developed. The structural finite element code for 9 node elements has been written (FORTRAN source code) and tested, and models isoparametric elements satisfactorily. An input model for the rotor casing coordinates is currently being generated, and should be completed shortly.

11. Student's Name: Douglas Michael Roever
Degree Program: M.S.M.E.
Supervising Professor: Dr. Alan Palazzolo
Research Title: Independent Modal Space Control and Modal Filters for Active Vibration Control of Rotors

Mr. Roever started in 1989 and is still pursuing this research at the time of expiration of this grant. The goal of this work is to develop and verify algorithms for the active control of rotor-dynamical vibrations. The proposed algorithm incorporates Meirovitch's independent modal space control methodology. The variables are determined utilizing a modal filter approach that identifies the modal contributions to the overall response.

A thesis proposal has been written and approved as of the end of Spring Semester 1991. Small scale simulations of the control methods to be used (full order optimal control, independent modal space control, and modified independent modal space control) have demonstrated their effectiveness for such systems, except for the last method. Integration of these methods into the existing rotordynamics code written by Dr. Reng Rong Lin has been started. A code for implementation of a modal filtering method for modal state estimation is currently being written, and will later be integrated with the rotordynamics code. Once these codes are finished, experiments to verify them will be conducted.

12. Student's Name: David Oakeson
Degree Program: M.S.A.E.
Supervising Professor: Dr. Tom Pollock
Research Title: Experimental and Theoretical Determination of the Thermomechanical Response of Inelastic Structural Materials to High Energy Thermal Inputs

The general objective of this research (in progress) is to improve on existing theoretical models for predicting the response of inelastic aerospace structural components subjected to hostile thermal environments with emphasis on transient temperature conditions, radiation boundary conditions, extremely rapid heating rates, and possible phase change of the materials involved. For materials subjected to the conditions under study herein it is necessary to perform extremely complex experiments in order to determine the precise form of the theoretical constitutive equations. Finally, it is necessary to implement the resulting equations to boundary value problem solving algorithms in order to model the

response of structural components with stress, strain, and temperature gradient fields.

13. Student's Name: Ivan Daryl Chapman
Degree Program: M.S.A.E.
Supervising Professor: Dr. Alton Highsmith
Research Title: Development of a Thermomechanical Constitutive Model for Metal Matrix Composites at Elevated Temperatures

The objective of the research underway is to develop a failure theory for a generic chopped fiber or particulate metal matrix composite to be utilized at temperatures in excess of one-half the melting point of the matrix material. The development of such a model is complicated by several factors such as permanent deformations in the matrix and microcracking induced by stress concentrations near the fiber-matrix interface. In addition, the elevated temperature induces time-dependent diffusional mechanisms in the matrix so that classical rate independent plasticity theory is not sufficient for characterizing the matrix response. Instead, a much more complicated viscoplasticity theory is being incorporated in order to accurately account for time dependent permanent deformations. Mr. Chapman left Texas A&M to rejoin Pratt & Whitney Aircraft in the Spring of 1991. He has not completed the writing of his thesis.

14. Student's Name: Joseph John Zierer
Degree Program: M.S.M.E.
Supervising Professor: Dr. John M. Vance
Research Title: Effect of Labyrinth Seals on Rotordynamics

Mr. Zierer has been carrying out an experimental investigation of the effect of teeth-on-rotor seals on rotordynamic response and stability. He is also developing a computational model of the test apparatus in order to identify the seal force coefficients which represent the fluid/structure interaction. He is currently writing his thesis and is expected to graduate in December 1991.

15. Student's Name: Richard R. Schultz
Degree Program: M.S.M.E.
Supervising Professor: Dr. John M. Vance
Research Title: Effect of Labyrinth Seals on Rotordynamics

Mr. Schultz began his graduate program in the Fall of 1990. He is designing a test apparatus to explore Alford's hypothesis for damping of labyrinth seals in rotor-bearing systems.

16. Student's Name: Steven B. Handy
Degree Program: M.S.M.E.
Supervising Professor: Dr. John M. Vance
Research Title: Advanced Engine Dampers

Mr. Handy began his graduate program in the Fall of 1990. He is designing a test

apparatus to experimentally determine the performance of a gas swirl damper for aircraft engine rotors. He also plans to develop an analytical model to guide the experiments.