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HIGH CYCLE FATIGUE (HCF) SCIENCE AND TECHNOLOGY PROGRAM 1999 ANNUAL REPORT

Multiple Authors

Prepared by:

Universal Technology Corporation
1270 North Fairfield Road
Dayton OH 45432-2600

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PROPULSION DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7251

NOTICE

Daniel E. Thomson

Daniel E. Thomson, AFRL/PRTC

Theodore G. Fecke

Theodore G. Fecke, AFRL/PRTC

William E. Koop

WILLIAM E. KOOP
Chief of Technology
Turbine Engine Division
Propulsion Directorate

REPORT DOCUMENTATION PAGE

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Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

Universal Technology Corporation
1270 N. Fairfield Rd.
Dayton, OH 45432-2600

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Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

POC: Daniel E. Thomson
AFRL/PRTC
937-255-2081

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13. ABSTRACT ***(Maximum 200 Words)***
This third annual report of the National Turbine Engine High Cycle Fatigue (HCF) Program is a brief review of work completed, work in progress, and technical accomplishments. This program is a coordinated effort with participation by the Air Force, the Navy, and NASA. The technical efforts are organized under eight Action Teams including: Materials Dâmage Tolerance Research, Forced Response Prediction, Component Analysis, Instrumentation, Passive Damping Technology, Component Surface Treatments, Aeromechanical Characterization, and Engine Demonstration. Daniel E. Thomson, AFRL/PRTC, Wright-Patterson AFB, is the Program Manager.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

FOREWORD

This document, the third annual report of the National Turbine Engine High Cycle Fatigue (HCF) Science and Technology (S&T) Program, is a summary of the objectives, approaches, and technical progress of ongoing and planned future efforts.

High cycle fatigue (HCF) results from vibratory stress cycles induced from various aeromechanical sources. The frequencies can be thousands of cycles per second. HCF is a widespread phenomenon in aircraft gas turbine engines that historically has led to the premature failure of major engine components (fans, compressors, turbines) and in some instances has resulted in loss of the total engine and aircraft.

Between 1982 and 1996, high cycle fatigue accounted for 56% of Class A engine-related failures. HCF is a major factor negatively impacting safely, operability, and readiness, while at the same time increasing maintenance costs. In fiscal year 1994, HCF required an expenditure of 850,000 maintenance man-hours for risk management inspections. Estimates put the cost of high cycle fatigue at over $400 million per year.

The National HCF S&T Program officially began in December 1994. The purpose of this national effort was to help eliminate HCF as a major cause of engine failures. The Program is directed by an Air Force led steering committee consisting of representatives from the Air Force, the Navy, and NASA, along with an adjunct industry advisory panel. The Organizational Structure of the HCF Team is shown below.

The HCF S&T Program is specifically directed at supporting the Integrated High Performance Turbine Engine Technology (IHPTET) Program, and one of its goals: to reduce engine maintenance costs. This program will try to achieve that goal through technical action team efforts targeted at a 50% reduction of HCF-related maintenance costs. In addition, the program could contribute to a reduction in HCF-related "real" development costs of over 50%. When combined with the Test and Evaluation (T&E) program, and future health monitoring approaches, the HCF S&T program should ensure the production of much more damage-tolerant high-performance engines.

The specific component objectives of the HCF S&T program are listed below:

	Fans	**Compressors**	**Turbines**
Determine Alternating Stress Within...	20%	25%	25%
Damp Resonant Stress By...	60%	20%	25%
Reduce Uncertainty in Capability of Damaged Components by...	50%	50%	50%
Increase Leading Edge Defect Tolerance...	15x (5-75 mils)	n/a	n/a

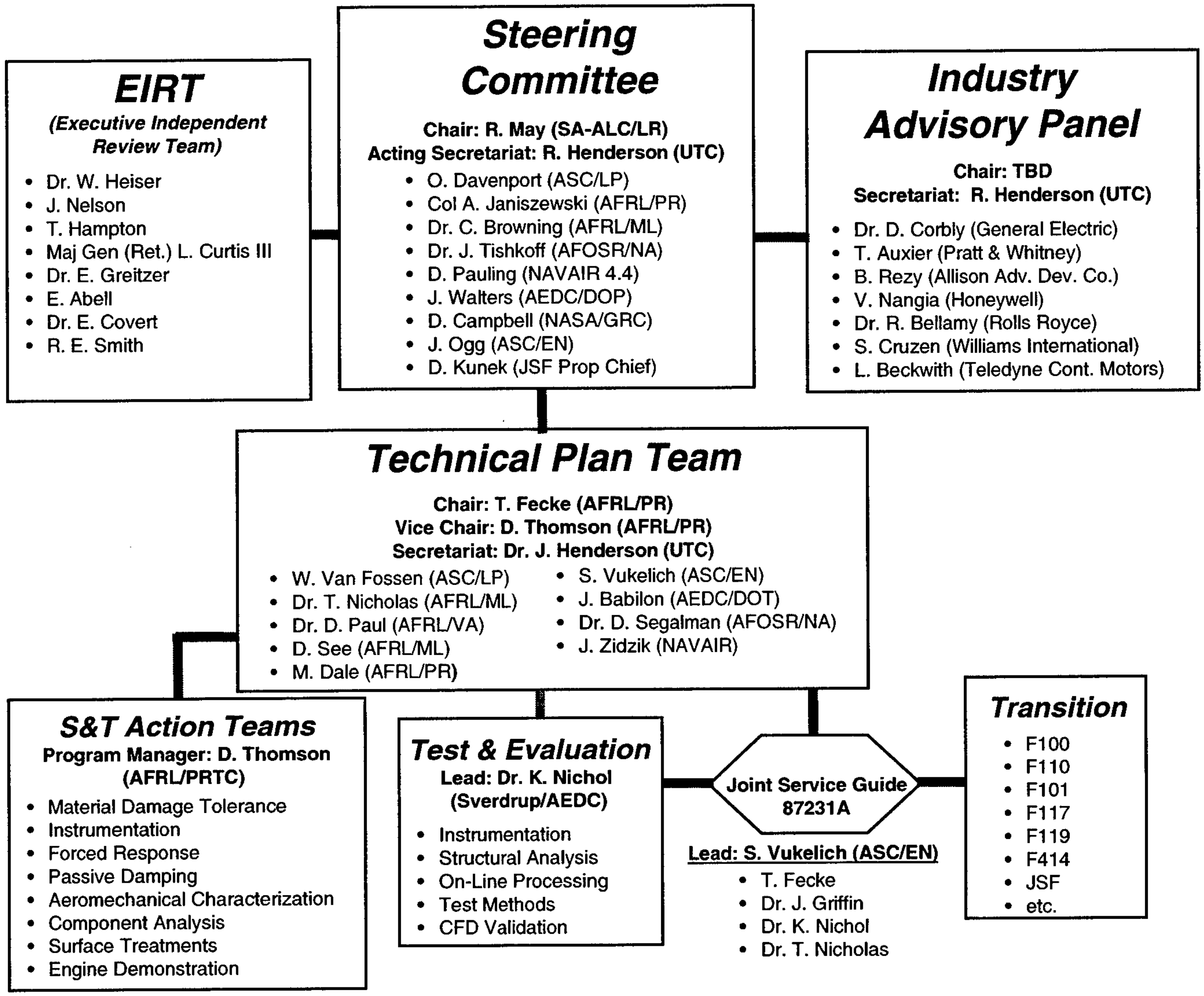


FIGURE 1. HCF Team Organizational Structure

The technical efforts are organized under eight action teams:

- Component Surface Treatments
- Materials Damage Tolerance Research
- Instrumentation
- Component Analysis
- Forced Response Prediction
- Passive Damping
- Aeromechanical Characterization
- Engine Demonstration (added in 1999)

Over the last several years, the technologies developed under the High Cycle Fatigue (HCF) Science and Technology (S&T) Program have helped solve several difficult field engine programs. As a result, we are now seeing considerably fewer major HCF events.

Today, excellent progress in the HCF program continues. For the first time, it appears that this once-arcane topic is being managed to a point where significant cost reductions are being realized, positively impacting the operations, maintenance, and readiness of our combat forces. However, HCF is a very difficult technology challenge that has continued to evolve multiple technology development and transition risks. During the fall of 1999 the HCF National Action Team completed a Project "Relook" study defining the efforts necessary to mitigate these critical risk issues, both current program "shortfalls" and "new requirements." Reprogramming options have been reviewed with the HCF Steering Committee, the Industry Advisory Panel, and a special Executive Independent Review Team (EIRT) (see Fig. 1), and implementation plans are being finalized.

In the future, the HCF S&T Program will continue as a very high priority national effort. Meeting the total technology challenge could essentially eliminate engine HCF-related aircraft mishaps and greatly enhance overall aircraft systems readiness.

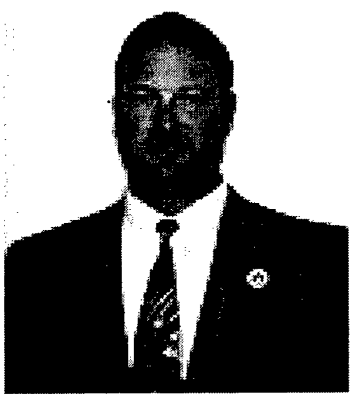
Your comments regarding the work reported in this document are welcome, and may be directed to Mr. Brian Garrison of Universal Technology Corporation (brian.garrison@wpafb.af.mil, 937-255-5003), or Mr. Daniel Thomson, the HCF Program Manager, of the Air Force Research Laboratory, Propulsion Directorate (AFRL/PRTC, Daniel.Thomson@wpafb.af.mil, 937-255-2081).

1.0 COMPONENT SURFACE TREATMENTS

BACKGROUND

The Component Surface Treatments Action Team (Surface Treatments AT) has the responsibility of fostering collaboration between individual HCF surface treatment efforts with the goal of increasing leading edge defect tolerance by 15x (5 mils to 75 mils). The Surface Treatments AT provides technical coordination and communication between active participants involved in Laser Shock Peening (LSP) and related technologies. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Surface Treatments AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for LSP programs, and coordinate with the Technical Plan Team (TPT) and Industry Advisory Panel (IAP). The Chairman (or Co-Chair) of the Surface Treatments AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in surface treatment technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

ACTION TEAM CHAIRS



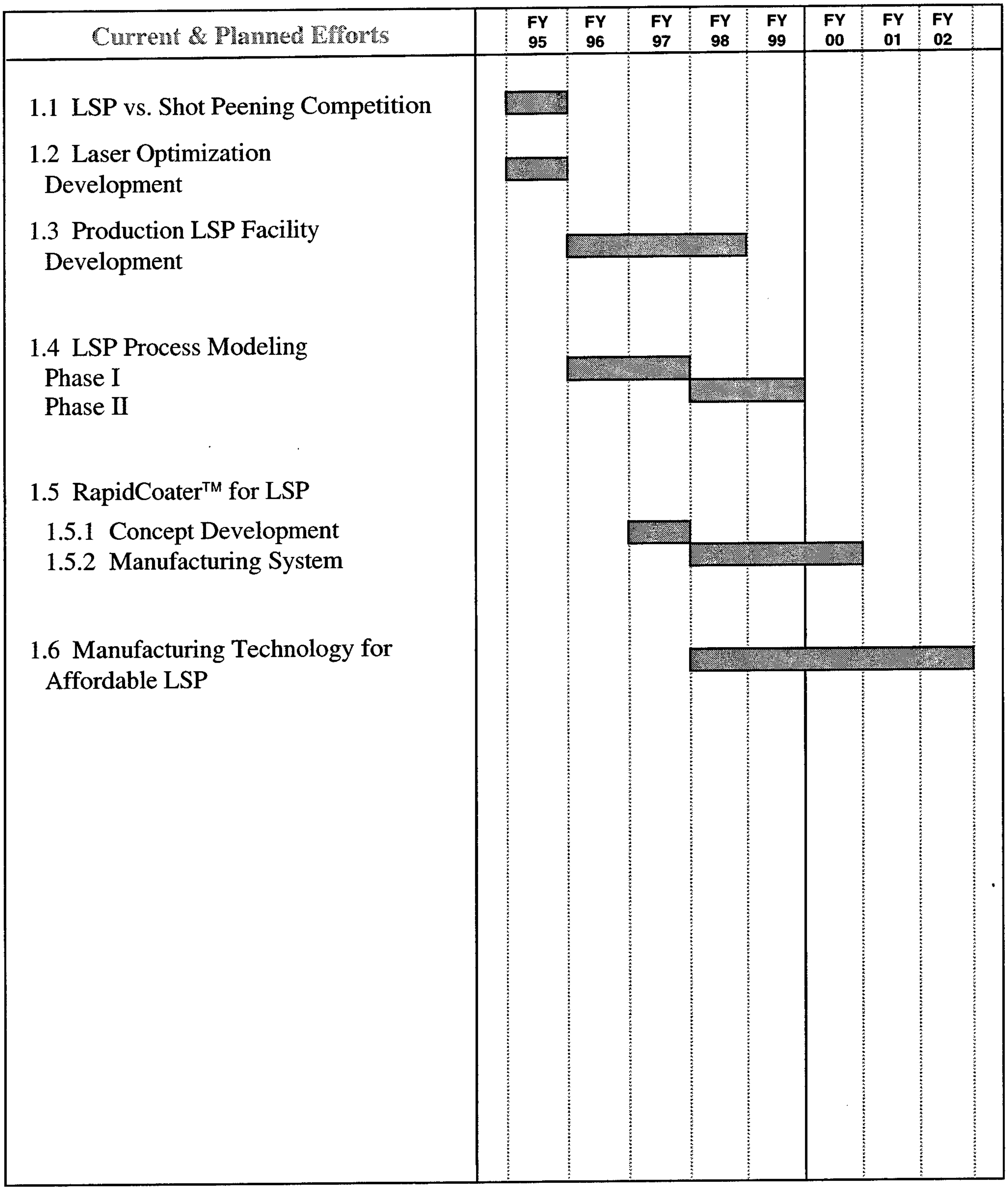
Chair
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 904-4387
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Co-Chair
Mr. Paul R. Smith
U.S. Air Force
AFRL/MLLM, Bldg. 655
2230 Tenth St., Suite 1
Wright-Patterson AFB, OH 45433-7817
Phone: (937) 255-1384
Fax: (937) 255-3007
Email: Paul.Smith@afrl.af.mil

INTRODUCTION

The following pages summarize the schedules, backgrounds, and recent progress of the current and planned projects managed by this action team.

Component Surface Treatments Schedule



1.1 Laser Shock Peening (LSP) vs. Shot Peening Competition

FY 95

Background and Final Results: In September 1995, a comparative study between a new surface treatment technology called "Laser Shock Peening" (LSP), and an established surface treatment technology called "shot peening," was conducted. This study evaluated the damage tolerance improvements produced by these processes, specifically rating their influence for enhancing the fatigue life of turbine engine fan blades damaged by foreign objects (FOD). Critical blade characteristics, such as surface finish, change in aerodynamic profile, and manufacturability, were factored into the evaluation. The test matrix was configured to make the assessment as realistic and objective as possible. The resulting data showed that *damaged* Laser Shock Peened F101 fan blades with a 250-mil notch actually demonstrated *greater* fatigue strength than the baseline *un*damaged untreated fan blades (Fig. 2). Figure 3 describes the Laser Shock Peening process in more detail.

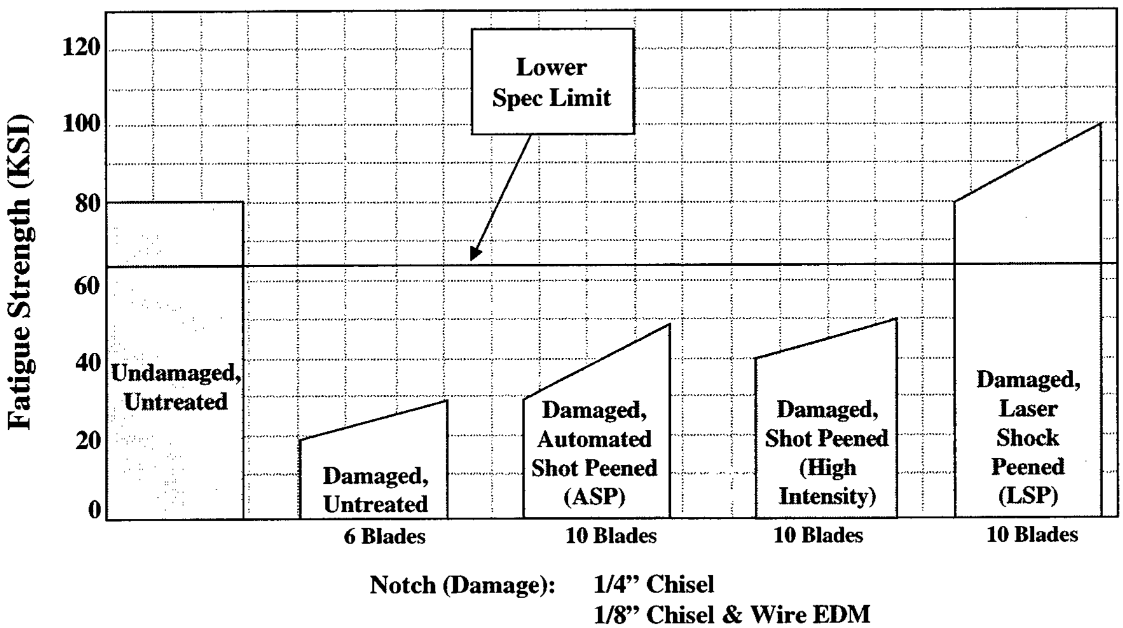


FIGURE 2. Damage Tolerance Data Indicating That Fatigue Strength of LSP'd Blades Is Equal to or Better Than That of Undamaged, Untreated Blades

Participating Organizations: GRC International, Inc.

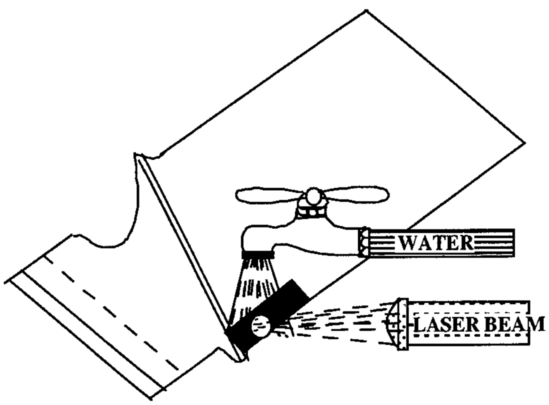
Points of Contact:

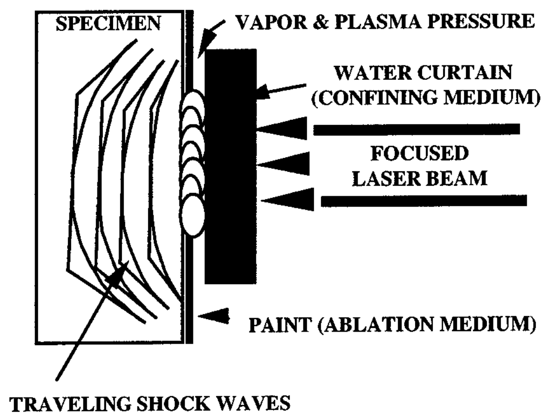
Government
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 255-3612
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Contractor
Mr. Paul Sampson
GRC International, Inc.
2940 Presidential Dr., Suite 390
Fairborn, OH 45424-6223
Phone: (937) 429-7773
Fax: (937) 429-7769
Email: psampson@grci.com

What Is Laser Shock Peening?

- A high energy laser pulse strikes a coated surface covered by a layer of water, causing a localized high pressure energy wave.





- A repetitive pattern of laser pulses results in an area of deep compressive stress.
- Results of industry and government testing have indicated the ability to stop crack initiation and propagation.

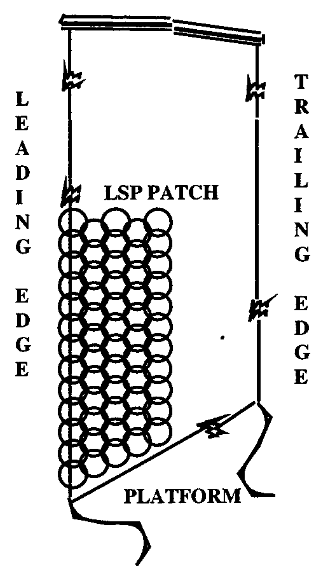


FIGURE 3. What Is Laser Shock Peening?

1.2 Laser Optimization Development

FY 95

Background: The primary objective of this program was to demonstrate the effectiveness of laser peening with elliptical and circular spots in terms of its ability to increase the fatigue life of an airfoil. A secondary objective was to demonstrate the ability to sharpen the rise time of the laser pulse using an optical switch, rather than using the traditional aluminum blow-off foil.

Final Results: Airfoil-shaped test specimens were laser peened using elliptical spots and circular spots and fatigue tested by the Air Force. A study of the rise time of the temporal laser pulse was conducted to confirm that an optical switch could modify the rise time of the laser pulse as effectively as an aluminum blow-off foil. An aluminum blow-off foil has traditionally been used to sharpen the leading edge of the laser pulse. A sharp rise time is important for many LSP conditions because it increases the peak pressure of the shock wave. Both elliptical and circular spots showed significant increases in fatigue life. A rise time comparable to the rise time generated with an aluminum blow-off foil was demonstrated (Fig. 4). Using the optical switch would eliminate concerns over the presence of aluminum vapor produced by the aluminum blow-off foil and the associated risks involving the health of personal and optical-component damage. It also increases the repeatability of the process.

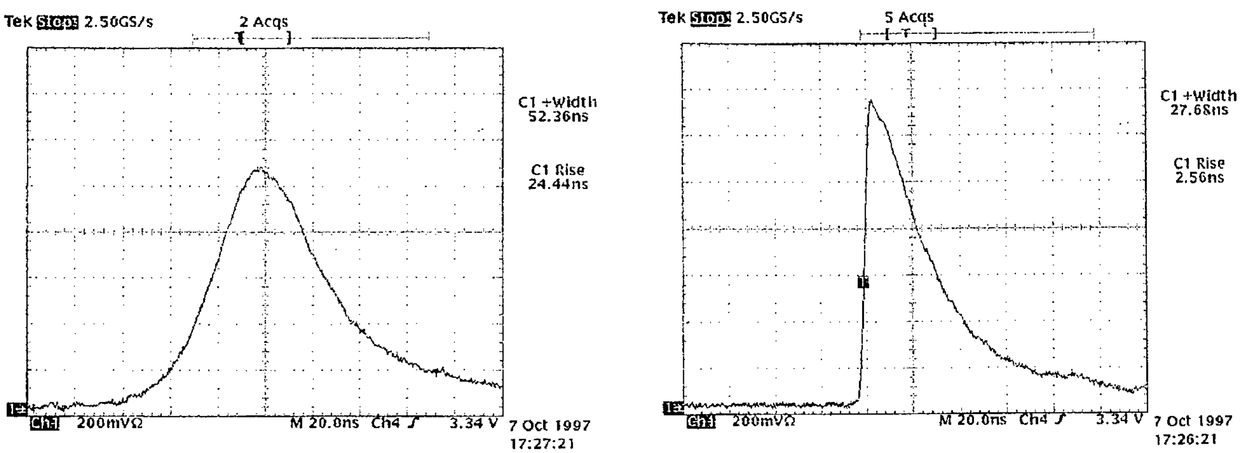


FIGURE 4. Peak Rise Time Before & After Laser System Modifications

Participating Organizations: LSP Technologies, Inc.

Points of Contact:

Government
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 255-3612
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Contractor
Dr. Jeff L. Dulaney
LSP Technologies, Inc.
6145 Scherers Place
Dublin, OH 43016-1272
Phone: (614) 718-3000 x11
Fax: (614) 718-3007
Email: jeff.dulaney-lspt@worldnet.att.net

1.3 Production LSP Facility Development

FY 96-98

Background: The primary objective of this program was to design and develop a Prototype Production Laser (PPL) capable of low levels of production. There were no commercially available lasers capable of meeting the requirements of the laser peening process. The program had three phases:

Phase I: Using working laboratory prototype lasers for the baseline design, the design was reviewed, outstanding technical issues related to the design were resolved, and the laser design was finalized. Specific technical issues to be resolved included:

1. The optical layout of the laser.
2. What system diagnostics would be used.
3. The mechanical design for the laser enclosure and electrical cabinets.

Phase II: Component acquisition, assembly, and subsystem checkout were accomplished during Phase II.

Phase III: Final laser system checkout and demonstration were accomplished in Phase III.

Final Results: The system, consisting of the laser, the facility, and the process (Fig. 5) was successfully demonstrated in January 1998, and the laser is now available for use by the Air Force and industry.

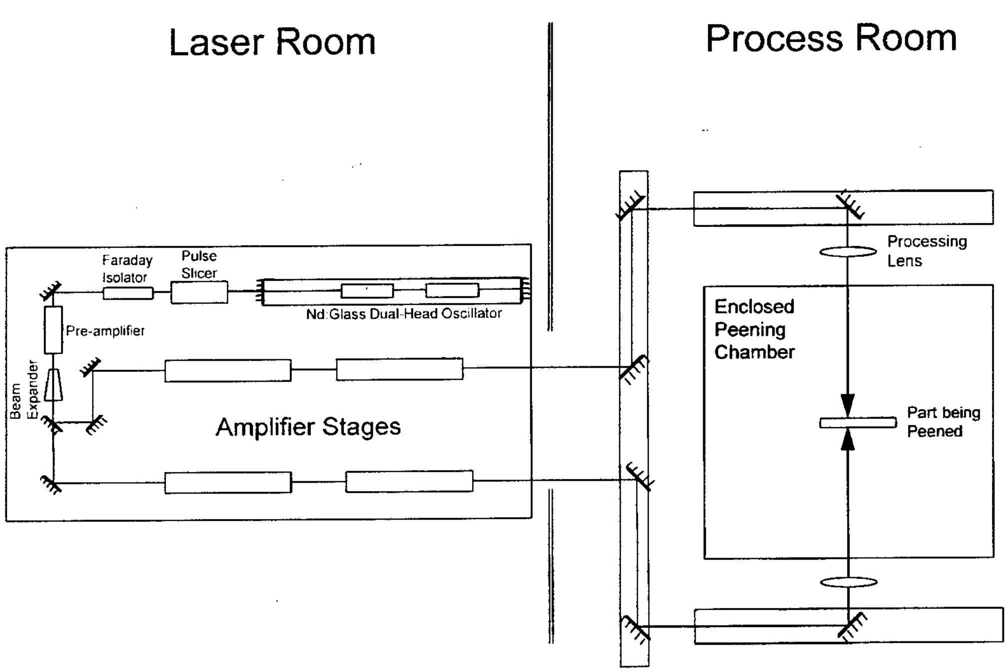


FIGURE 5. Schematic of Laser System Operations

Participating Organizations: GRC International, Inc.

Points of Contact:

Government
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 255-3612
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Contractor
Mr. Paul Sampson
GRC International, Inc.
2940 Presidential Dr., Suite 390
Fairborn, OH 45424-6223
Phone: (937) 429-7773
Fax: (937) 429-7769
Email: psampson@grci.com

1.4 LSP Process Modeling

FY 96-99

Background: In Phase I (FY 96-97) of this two-phase program, it was demonstrated that a residual stress profile could be modeled for a single laser spot. The objectives of Phase II (FY 98-99) are (1) to develop models for predicting the in-material residual stress profiles produced by multiple-spot Laser Shock Peening, (2) to verify and validate the residual stress profiles by comparison to experimental measurements, and (3) to gather appropriate data for input to the models.

A model for large-section thicknesses laser shock peened from one side has been developed and shows good correlation with experimental residual stress profiles. The correlation between the modeled and measured residual stress profiles for two different laser peening intensities (peak pressures on the metal surface) is shown in Figure 6. The thin and intermediate section thicknesses are being modeled with two-sided laser peening. This is a much more difficult problem, and several constitutive equations for the material of interest are being explored and tested with the models.

Recent Progress: Modeling of thick sections laser peened from one side was successful. Figure 6 shows the residual stress profiles compared to experimental profiles at two different laser peening intensities. Model verification was based on the comparison of residual stress measurements performed on LSP'd coupons with those predicted by the model. The residual stress profiles developed in a part depend not only on the laser peening intensity, but also on the material and part geometry.

In addition, significant progress was made in defining the issues involved with modeling of residual stresses in thin sections, and determination of appropriate approaches to address these issues. Modeling of laser peening residual stresses in thin sections will not be possible until these issues are resolved.

Based on the modeling results, a follow-up task is needed to develop process optimization schemes to decrease the time and cost for process optimization. Funding sources are being sought for the follow-up effort.

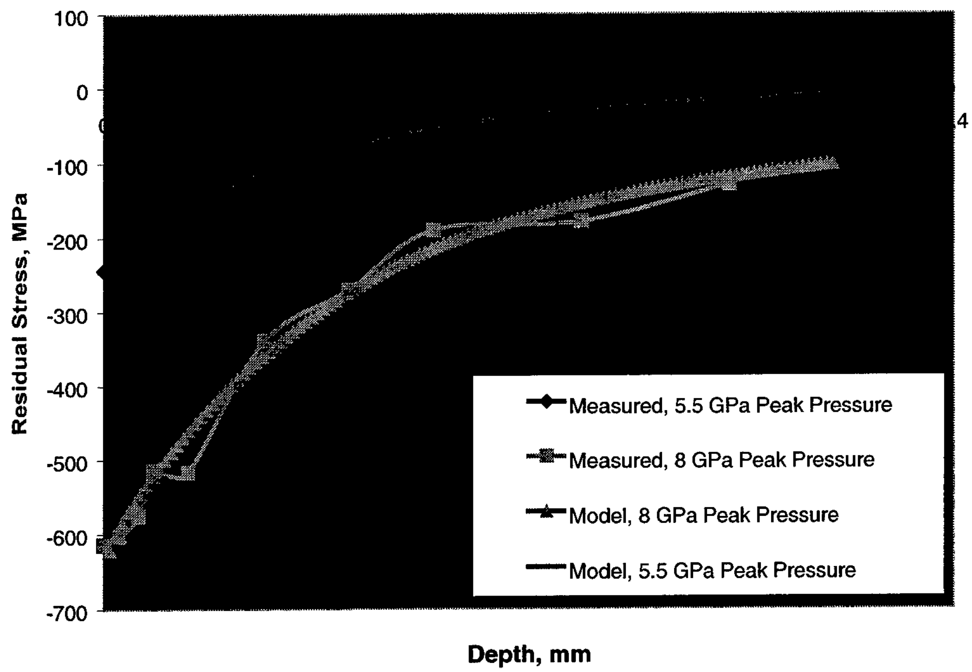


FIGURE 6. Comparison of Modeled and Experimental Residual Stresses for Similar Pressure Conditions

Participating Organizations: LSP Technologies, Inc., Ohio State University, University of Dayton Research Institute

Points of Contact:

Government
Mr. Joseph G. Burns
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
Wright-Patterson AFB, OH 45433-7817
Phone: (937) 255-1360
Fax: (937) 255-4840
Email: Joseph.Burns@afrl.af.mil

Contractor
Dr. Allan H. Clauer
LSP Technologies, Inc.
6145 Scherers Place
Dublin, OH 43016-1272
Phone: (614) 718-3000 x12
Fax: (614) 718-3007
Email: allan.clauer-lspt@worldnet.att.net

1.5 RapidCoater™ for LSP
FY 97-00

Introduction: One of the significant shortcomings of the current Laser Shock Peening process is slow processing, which is primarily due to the inability to remove the opaque overlay (paint) rapidly. Current practice requires the application and removal of the paint outside of the laser workstation. Under current practice, a part that requires multiple shots must be transported back and forth several times, from the laser workstation where it is peened, to a separate area where the overlay is removed, then back to the laser workstation, and so on. Sections 1.5.1 and 1.5.2 below explain what is being done to solve this problem. Section 1.5.1 describes the development, selection, and demonstration of a prototype system to rapidly remove the overlay system. Section 1.5.2 describes the development of a production system. The Points of Contact: and Participating Organizations listed below apply to both of these efforts.

Participating Organizations: LSP Technologies, Inc.

Points of Contact:

Government
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 255-3612
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Contractor
Dr. Allan H. Clauer
LSP Technologies, Inc.
6145 Scherers Place
Dublin, OH 43016-1272
Phone: (614) 718-3000 x12
Fax: (614) 718-3007
Email: allan.clauer-lspt@worldnet.att.net

1.5.1 Rapid Overlay Concept Development
FY 97

Background and Final Results: The objectives of this program were to identify and evaluate promising methods for applying and removing the opaque overlay rapidly during laser peening. Two coating application methods were investigated: (i) water-soluble paint applied with a spray gun, and (ii) paint or ink application with an ink jet. The water-soluble paint/spray gun application method was selected as the most promising approach. The rapid overlay system concept was developed around this method. The rapid overlay demonstration test unit was assembled and tested to provide a working demonstration of the concept. The demonstration, which consisted of sequential application of the paint overlay, application of the overlay water film, firing the laser, and removal of the paint overlay in continuous, repetitive cycles, was successful. The successful demonstration system has been designated the RapidCoater™ System.

1.5.2 Development of a RapidCoater™ Manufacturing System
FY 98-00

Background: The objective of this program is to develop a rapid-overlay-removal manufacturing system to be integrated into a production laser peening system. The production RapidCoater™ System should accommodate a range of parts and operate reliably at the laser repetition frequency. Another objective is to develop a control system that will monitor the coating process and interface with the laser control system.

The ultimate objective of the Component Surface Treatment Action Team and of all the efforts described in this section is to develop an affordable Laser Shock Peening system. The relationship of all these efforts is shown below in Figure 7.

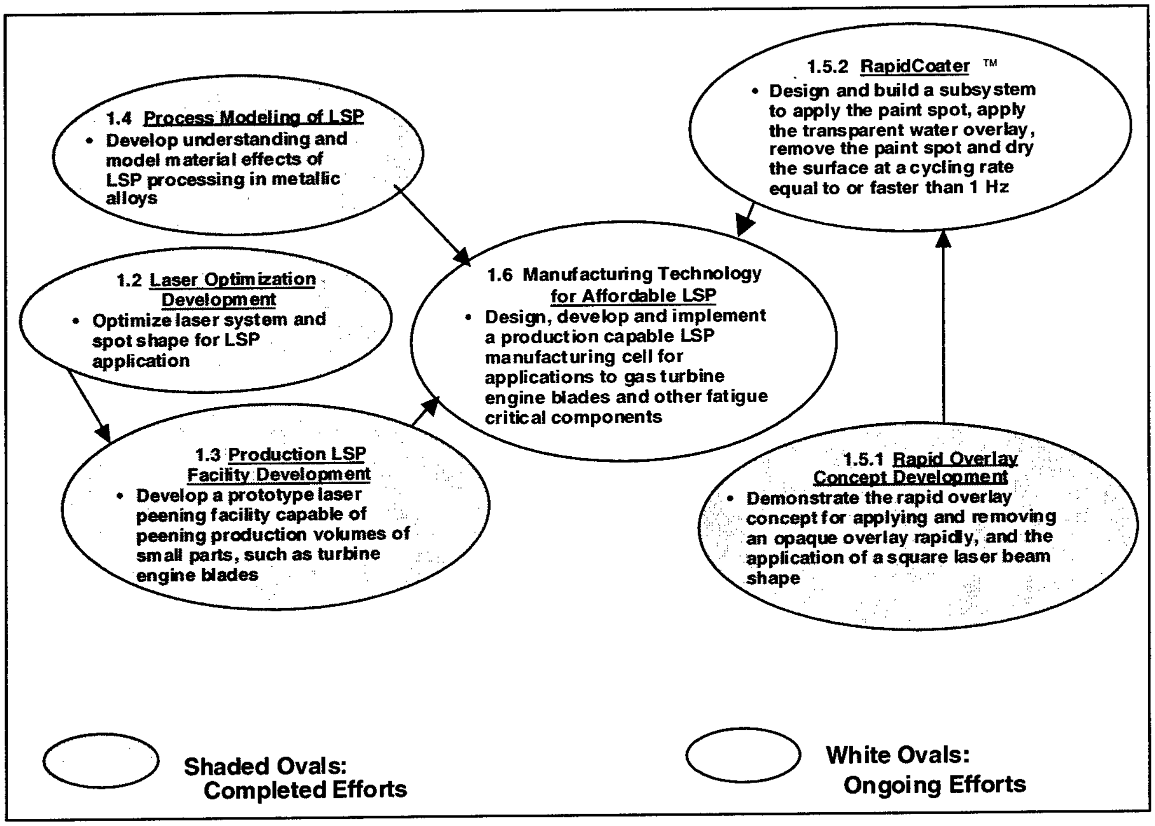


FIGURE 7. Interrelationship between LSP Programs

Recent Progress: A pre-prototype applicator head was successfully demonstrated. The resulting prototype applicator head has been built and will be demonstrated in 2000. A paint spot imaging technique was also demonstrated.

The RapidCoater™ will be demonstrated and spot-shaping techniques will be developed in a laser peening work cell, and the laser peening control system will be incorporated into the RapidCoater™.

1.6 Manufacturing Technology for Affordable LSP

FY 98-02

Background: The main activity of this program has been to prepare the facility for the various technical activities. The technical challenges associated with this program are all related to transitioning a prototype production facility into a full manufacturing facility. Additionally, the development and implementation of new (or improved) controls and monitors into the manufacturing facility will present individual technical challenges. This program has three phases.

Phase I: The purpose of Phase I is to mitigate the risks associated with the transition to manufacturing. This phase is divided into three areas:

1. Development and testing of new (or improved) controls and monitors, which will be used to increase the process reliability and reduce processing costs. The primary monitors (energy, temporal profile, and spatial profile) typically used for laser peening have been enhanced. "Secondary" laser monitors, process monitors, and quality control monitors are currently being demonstrated and will be down-selected for implementation into the new manufacturing cell.
2. Development of prototype small-parts and large-parts peening cells. This effort began in the final quarter of calendar year 1998 and is expected to be completed by the end of 1999.
3. Initial commercialization planning and new application development. Market surveys have been conducted and the commercialization plan is currently being drafted.

Phase II: Phase II is the final design and build phase for the laser and a small-parts peening cell. This phase is divided into two areas:

1. Design, fabrication, and integration of a manufacturing cell consisting of the laser system and a small-parts peening cell. This includes the down-selection and integration of the controls and monitors developed in Phase I.
2. Demonstration of the LSP manufacturing cell. The demonstration is currently scheduled for mid-year 2001.

Phase III: Phase III is the commercial development phase. The objective is to identify new applications in several market sectors, including the aerospace, medical, and automotive sectors. This is scheduled to begin in fiscal year 2000.

Recent Progress: Great progress has been made in completing the planned Phase I effort. The primary laser controls, which consist of the laser beam energy, temporal profile, and spatial profile, have been redesigned to be more robust. Additionally, new laser monitors have been developed to monitor the "health" of the laser. These new monitors include: monitoring the flashlamps to ensure that they are operating properly, monitoring energy reflected back from the part being processed (target backscatter), and monitoring critical optical components to ensure that they are not degrading.

A robust off-the-shelf distributed control network has been identified and successfully tested. This distributed control network will be incorporated into the design for the new laser system.

A prototype small-parts peening cell was completed. The peening cell, which was based upon the original peening cell already in place at LSPT, includes an improved beam delivery system, a more robust beam monitoring configuration, and a more robust processing chamber. Lessons learned will be incorporated into the manufacturing cell.

Design of a large-parts peening cell was completed. Fabrication is in progress. The cell should be completed and available for use in early 2000.

Two market surveys were conducted: one by Pratt & Whitney of new applications within gas turbine engines, and one by an independent marketing firm that covered all other markets (excluding gas turbine engines). This information will be included in the commercialization plan that will be developed and delivered to the Air Force in December 1999.

Phase II work began ahead of schedule, which allowed for the following to occur ahead of plan:

- completion of the facility modifications,
- the start of the final manufacturing cell design, and
- acquisition of critical long-lead optical components.

The bulk of the remaining work is related to the assembly and fabrication of the laser and the associated peening cells. Implementation of the commercialization plan and the development of applications also remain to be done.

Participating Organizations: LSP Technologies, Inc.

Points of Contact:

Government
Mr. David W. See
U.S. Air Force
AFRL/MLMP, Bldg. 653
2977 P Street, Suite 6
Wright-Patterson AFB, OH 45433-7739
Phone: (937) 255-3612
Fax: (937) 656-4420
Email: David.See@afrl.af.mil

Contractor
Dr. Jeff L. Dulaney
LSP Technologies, Inc.
6145 Scherers Place
Dublin, OH 43016-1272
Phone: (614) 718-3000 x11
Fax: (614) 718-3007
Email:jeff.dulaney-lspt@worldnet.att.net

1.7 Conclusion

The Component Surface Treatment Action Team demonstrated Laser Shock Peened (LSP'd) damaged turbine engine fan blades that had equal or better high cycle fatigue strength than undamaged unpeened blades; completed testing that showed the ability of the LSP process to stop both HCF crack initiation and propagation in these fan blades; demonstrated the complete LSP system (laser, facility; and more affordable process) with the prototype now available for government and industry use; and successfully transitioned the LSP technique to F101 and F110 engines. This has resulted in 15x increase in FOD tolerance for these engines, and major reduction in inspection man-hour costs, with increased flight safety. Due to the excellent progress to-date, all engine contractors are now pursuing LSP approaches. Further cost reduction of the manufacturing facilities and processes for the LSP technique is now the major focus of this team. Engine manufacturers are currently pursuing LSP on fan and compressor integrally bladed rotors (IBRs) and blisks.

2.0 MATERIALS DAMAGE TOLERANCE

BACKGROUND

The Materials Damage Tolerance Research Action Team (Materials AT) is responsible for fostering collaboration between individual HCF materials damage tolerance research efforts, with the goal of reducing the uncertainty in the capability of damaged components by 50%. The Materials AT will provide technical coordination and communication between active participants involved in HCF life prediction, damage nucleation and propagation modeling, fracture mechanics methodology development, residual fatigue capability modeling, and the evaluation of surface treatment technologies. Annual technical workshops will be organized and summaries of these workshops will be disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Materials AT members will meet as required (estimated quarterly) to review technical activities, develop specific goals for materials damage tolerance research projects, and coordinate with the Technical Planning Team (TPT) and the Industry Advisory Panel (IAP). The Chairman (or Co-Chair) of the Materials AT will keep the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT will include members from government agencies, industry, and universities who are actively involved in materials damage tolerance technologies applicable to turbine engine HCF. The team is intended to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT will change as individuals assume different roles in related programs.

ACTION TEAM CHAIRS

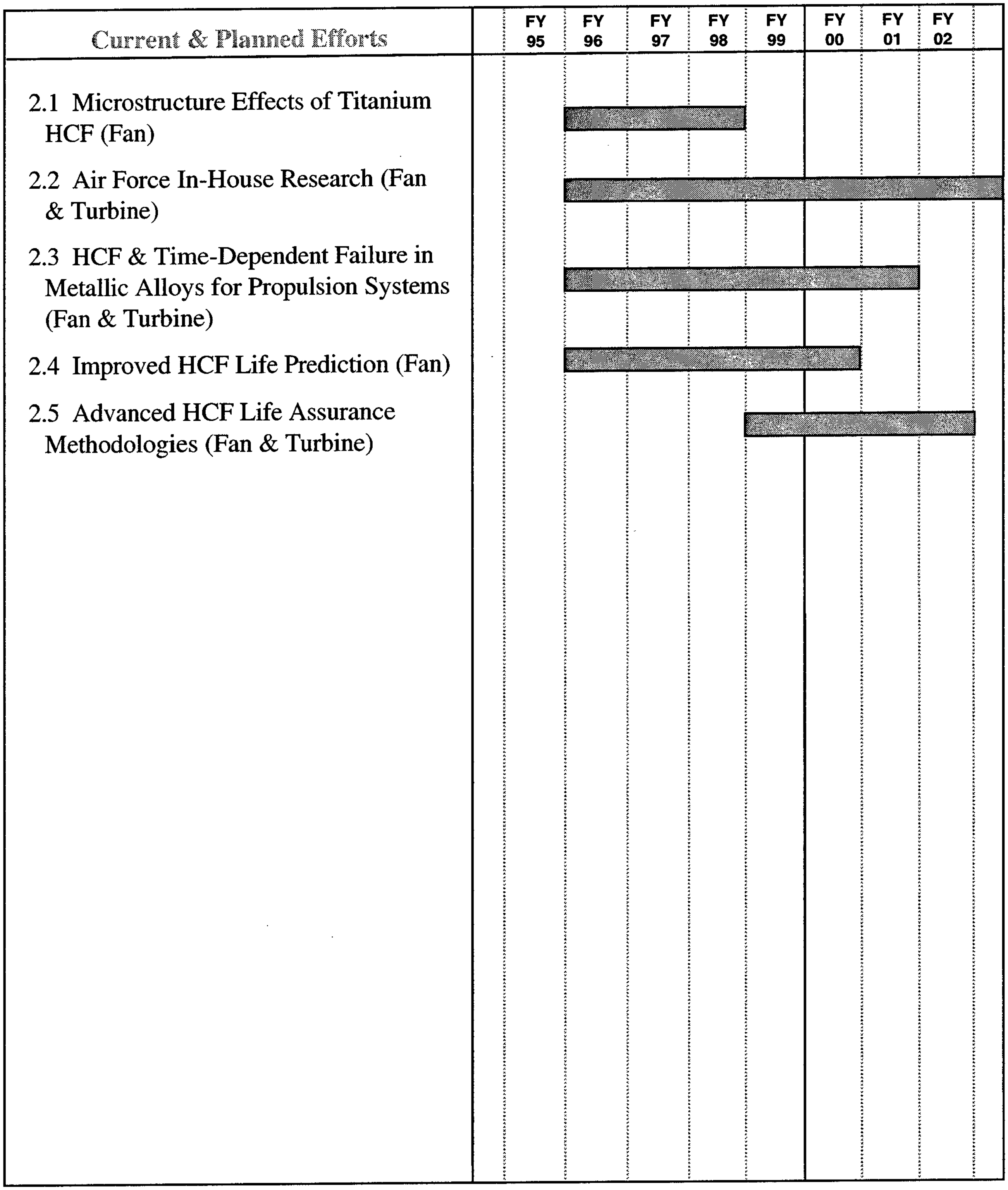
Chair
Mr. Joseph G. Burns
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
Wright-Patterson AFB, OH 45433-7817
Phone: (937) 255-1360
Fax: (937) 656-4840
Email: joseph.burns@afrl.af.mil

Co-Chair
Ms. Kathleen A. Sargent
U.S. Air Force
AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2081
Fax: (937) 255-2660
Email: kathleen.sargent@wpafb.af.mil

INTRODUCTION

Prior to this research program, no accurate techniques were available to determine the capability of materials subjected to variations in manufacturing, component handling, and usage. Such techniques are needed for accurate life prediction and optimized design to assure damage tolerance. The following pages summarize the schedules, backgrounds, and recent progress of the current and planned projects managed by this action team.

Materials Damage Tolerance Research Schedule



2.1 Microstructure Effects of Titanium HCF (Fan)

FY 96-98

Background: The objective of this project was to determine the relationship between mean stresses and high cycle fatigue strength for Ti-6Al-4V by correlating the fatigue crack nucleation process with the cyclic deformation behavior of the alloy for different microstructures and crystallographic texture characteristics.

A workable hypothesis that was investigated was that high mean stress fatigue life sensitivity is associated with cyclic softening of Ti-6Al-4V, which in turn results in the absence of an endurance limit. In addition to establishing such a correlation, the second purpose of the investigation was to study the crystal orientation dependence on, and the microstructural features that affect, the cyclic deformation behavior. The specific factors that control crack nucleation are also being studied. The focus is on the formation of dislocation substructure and the statistical nature of crack formation. Analytical procedures emphasize the use of quantitative physical models that can be used to predict the mean stress sensitivity in this class of titanium alloys. The results should also be useful in the search for the best alloy/process for maximizing fatigue resistance in engineering structures.

Final Results: The findings of the two aspects of the physical behavior of Ti-6Al-4V that were investigated are described below. These findings contributed to the development of a model to predict the mean stress sensitivity of Ti-6Al-4V, which is also described below.

Correlation of Cyclic Softening and the Absence of an Endurance Limit. Cyclic strain tests in strain control mode did not reveal significant differences in cyclic deformation behavior between the investigated microstructures (lamellar cross-rolled, bimodal fine uni-rolled, bimodal coarse cross-rolled, bimodal coarse forged, equiaxed coarse cross-rolled, and equiaxed coarse forged). All six microstructures underwent cyclic softening, and the saturation stresses at all strain levels (and hence, cyclic stress-strain curves) were almost identical for all of these microstructures. However, in the initial condition (monotonic stress-strain curve), the differences in saturation stresses were much greater. Unlike S-N (stress-life) curves, little difference was observed between the ε-N (strain-life) curves generated for each of the investigated microstructures, especially at low strains. Also, relatively little scatter was observed for each curve.

Effect of Crystal Orientation and Microstructural Features on Fatigue Behavior. Of the six microstructure/texture combinations investigated, bimodal fine uni-rolled and lamellar cross-rolled displayed superior fatigue properties to the remaining four microstructures (bimodal coarse cross-rolled, bimodal coarse forged, equiaxed coarse cross-rolled, and equiaxed coarse forged). Bimodal fine uni-rolled and lamellar cross-rolled microstructures exhibited Goodman dependence of fatigue strength, while the other four microstructures had anomalous mean stress dependence, with fatigue strength values at intermediate mean stresses being considerably lower than predicted by the Goodman relation.

Analytical Procedures (Models) to Predict Mean Stress Sensitivity. The fatigue data collected in this project have been statistically analyzed to develop a model to predict the effects of microstructure and texture on the fatigue strength of α/β titanium alloys. This effort resulted in a model that allows the accurate prediction of fatigue curves for titanium alloys from microstructure and texture characteristics at different R ratios ($\sigma_{min}/\sigma_{max}$). Separate models have been developed for low cycle and high cycle fatigue regimes, and for three ranges of R: $R<0$ (tensile-compressive loading), $0\leq R\leq 0.5$ (tensile-tensile loading) and $0.5<R\leq 0.7$ (creep-fatigue interaction). For each of these regimes, fatigue strength

is calculated as a function of alpha grain size d_α, transformed beta volume fraction v_β, texture orientation parallel to test direction X_α, ultimate tensile strength U, and ductility (reduction of area) e_f. Figure 8 demonstrates how the model (presented with solid curves) fits actual data points for three different microstructures at R=0.1. The following equations were used to construct these curves:

1. LCF regime, $0 \le R \le 0.5$

$$\sigma_L = 101.457 + 5.565\, v_\beta + 21.562\sqrt{d_\alpha} - 44.629\, e_f - 1.077\, X_\alpha - 6.227\sqrt{d_\alpha}\,\log N - 0.21U\, R$$

2. HCF regime, $0 \le R \le 0.5$

$$\sigma_H = 91.859 + 10.427\, v_\beta - 8.529\sqrt{d_\alpha} - 5.208\,\log N - (10.684/\sqrt{d_\alpha} + 0.164U)\, R$$

where: d_α = alpha grain size, µm
v_β = transformed beta volume fraction
X_α = texture orientation parallel to test direction (x random)
U = ultimate tensile strength (Ksi)
e_f = ductility (reduction of area)
N = number of cycles
R = stress ratio ($\sigma_{min}/\sigma_{max}$)

The model was tested on the investigated microstructures, and accurately predicted the fatigue strength of α/β titanium alloys for the following range of parameters:

d_α = 3-16 µm
v_β = 0.15-0.80
X_α = 4-13
U = 138-173 Ksi
e_f = 0.30-0.55

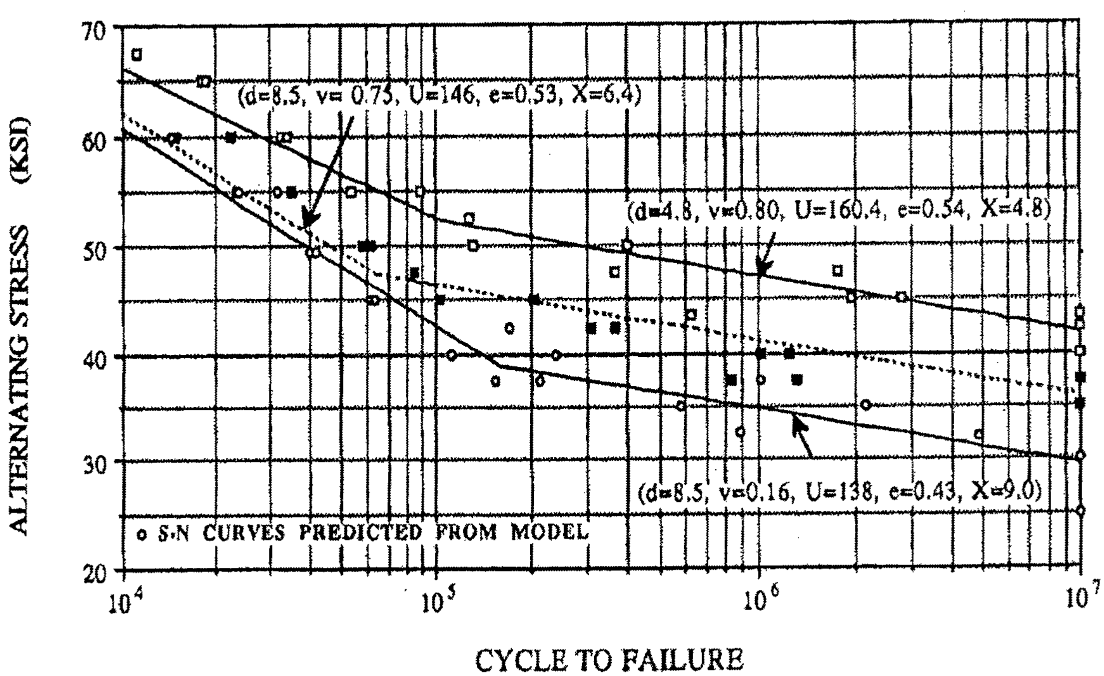


FIGURE 8. S-N Input Data and Fatigue Strength Model Results for Bimodal Fine Uni-Rolled, Bimodal Forged, and Equiaxed Forged Microstructures (Top to Bottom) at R=0.1

Participating Organizations: Air Force Office of Scientific Research (AFOSR), Worcester Polytechnic Institute, Pratt & Whitney

Points of Contact:

Government
Dr. Spencer Wu
U.S. Air Force, AFOSR/NA
110 Duncan Ave., Suite B115
Bolling AFB, DC 20332-8080
Phone: (202) 767-4989
Fax: (202) 767-4988
Email: spencer.wu@afosr.af.mil

Contractor
Prof. Richard D. Sisson, Jr.
Worcester Polytechnic Institute
Mechanical Engineering Department
100 Institute Road
Worcester, MA 01609
Phone: (508) 831-5335
Fax: (508) 831-5178
Email: sisson@wpi.edu

2.2 Air Force In-House Research (Fan & Turbine)

FY 96-03

Background: The objectives of this program are as follows:

(1) Conduct breakout research on titanium and nickel-base superalloys.

(2) Explore high cycle fatigue related damage mechanisms, including the determination of the relative significance of specific damage mechanisms and the identification of specific areas requiring a concentrated research and development effort for incorporation into the HCF design system.

(3) Develop innovative test techniques and modeling concepts to guide the industry research program.

(4) Conduct research and evaluation to demonstrate and validate damage tolerance design methodologies for HCF.

Recent Progress: During the past year, progress has been made in all areas. The following paragraphs highlight specific accomplishments with regard to the approaches being taken in this task.

- ***Material Behavior for Modeling.*** Testing has been accomplished to generate valid data for modeling the damage mechanisms associated with high cycle fatigue interaction with low cycle fatigue (LCF), fretting fatigue, and foreign object damage (FOD).

  - *High Cycle Fatigue / Low Cycle Fatigue Interaction.* A study is currently being performed to determine the influence of load history on the initiation of cracks under LCF loading and its subsequent influence on HCF thresholds for both small and large cracks. This study is being performed on notched fatigue specimens with crack initiation being detected with DC potential difference. In this study, cracks are initiated in LCF loading at $R = -1$ and 0.1, and the HCF thresholds for high cycle fatigue stress ratios of $R=0.1$ and 0.5 are determined from fracture stresses and crack sizes. Heat tinting is used to verify crack size and shape. The step test method is used to apply the HCF loading as described in Figure 9. The HCF load level is ramped up by 5% after 10^7 cycles if no crack growth is detected within the load block. This process is repeated until fracture occurs.

    The HCF crack thresholds determined in the above manner varied with load sequence. However, when specimens were stress relief annealed after LCF pre-cracking (prior to HCF loading), the HCF thresholds were consistent for a given HCF stress ratio as shown in Figure

10. Moreover, the HCF thresholds for small cracks were consistent with the large crack threshold for a given stress ratio. This indicates that the LCF / HCF threshold appears to be dependent on load history. Consistent results also indicate that when LCF cracks are present, there exists an HCF threshold level below which cracks don't grow. Also, preliminary results indicate there is no "small crack" effect down to c = 60mm.

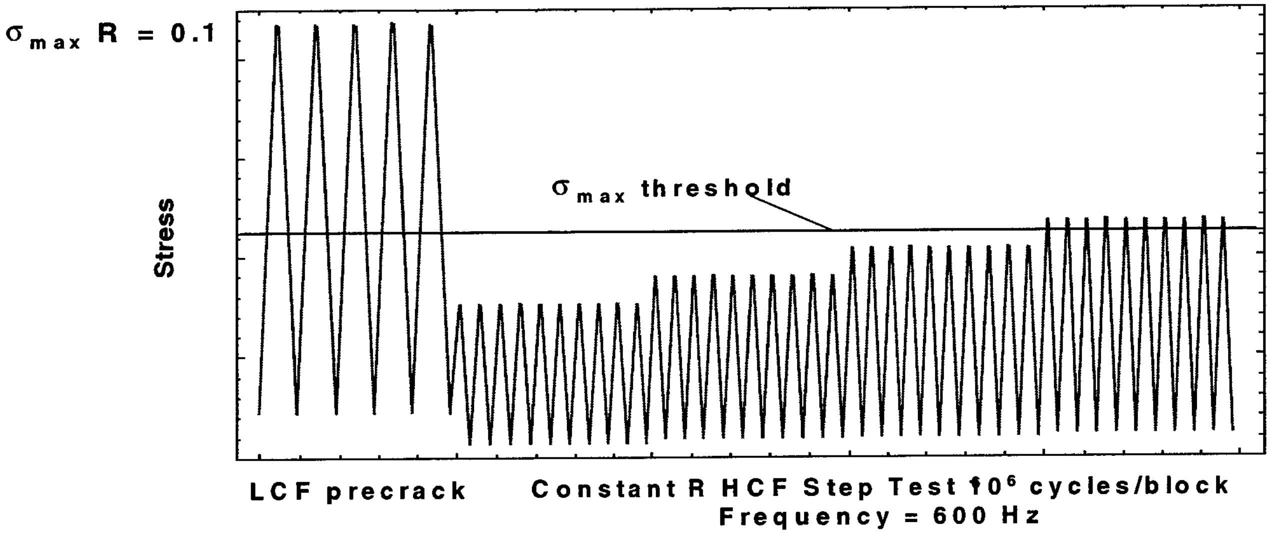


FIGURE 9. Pre-Crack and Step-Test Loading Technique Used to Determine LCF/HCF Thresholds

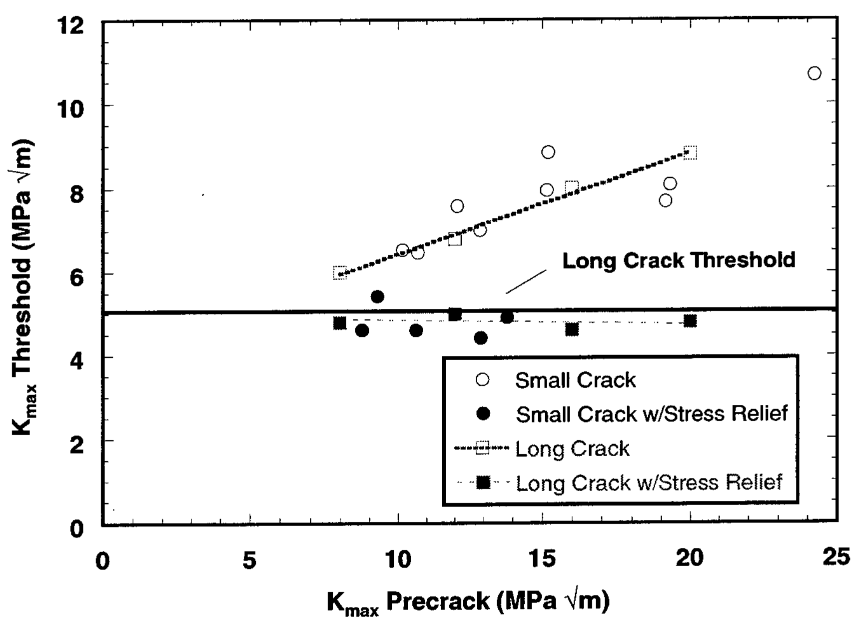


FIGURE 10. LCF/HCF Thresholds for HCF Stress Ratio R=0.1

➢ *HCF Fretting Fatigue.* Four studies and a modeling effort on fretting fatigue are being accomplished in this program:

- The identification of fretting fatigue failure mechanisms and the effect of fretting fatigue damage on residual HCF strength was investigated. The geometry in the test apparatus employed flat fretting pads on either side of a flat uniaxial fatigue specimen with the fretting pads having a radius at the edge of contact. The test configuration, which employs identical gripping at both ends of the specimen, via the fretting pads, produced two nominally identical fretting fatigue tests per specimen. Fretting damage occurred at both ends of the specimen at the edges of contact. All tests were conducted at constant frequency of either 300 or 400 Hz in lab air at room temperature. A range of shear forces (proportional to the axial stress in the specimen), and the resultant shear stress distribution was achieved by varying the contact length and the contact radius using a range of pad geometries, and by varying the normal contact load.

  Test results indicate that for a given condition of contact radius and applied stress ratio, the axial stress in the specimen corresponding to a fatigue life of 10^7 cycles is relatively independent of normal stress. Therefore, for the current study, two normal stresses (140 MPa and 420 MPa) were selected. These stresses represent values that are typical of the upper and lower limit of normal stresses observed in some fan-blade dovetail attachments. A contact radius of 3.2 mm, and a fretting fatigue stress ratio of R=0.5 were chosen because of the similarity to dovetail geometry and loading conditions. Three levels of damage were investigated: 10^4, 10^5, and 10^6 cycles, which correspond to 0.1, 1.0, and 10 percent of the 10^7 cycle life, respectively. Samples tested under uniaxial conditions at R = 0.1 with a normal load of 140Mpa did not result in measurable reduction in residual axial fatigue strength due to fretting fatigue. Additional testing is underway.

- Elastic-plastic finite element analyses (FEA) of a cylinder-on-plate configuration studied in the laboratory were performed to provide an explanation for the decrease in fretting fatigue life with increasing contact pressure. Three values of normal load, namely 1338 N, 2230 N and 3567 N, and three stress ratios (0.1, 0.5 and 0.7) were considered. Based on a previously determined dependency between contact pressure and friction coefficient, the effect of the coefficient of friction was also evaluated. The deformation remained elastic under all the conditions examined. Cyclic, interfacial stresses and slips were analyzed in detail. The amplification of the remotely applied cyclic stress in the contact region was shown to provide a rationale for the effect of contact pressure and stress amplitude on life. Comparisons with previous experiments indicate that the local stress range computed using finite element analysis may be sufficient for predicting fretting fatigue life. Further, results suggest that the slip amplitude and shear tractions may be neglected for this purpose.

- An investigation of fretting fatigue crack initiation behavior in Ti-6Al-4V was performed. Fretting fatigue contact parameters were varied through the modification of the fretting pad geometry which included two different radii of cylindrical contact (50.8mm and 101.6mm) and flat contact with edge radii. The applied tensile loads were also varied to obtain fretting fatigue crack initiation in both the low and high cycle fatigue regimes. The salient features of the fretting fatigue experiments were modeled and analyzed with finite element analysis. The results of the finite element analyses were used to formulate and evaluate several fatigue parameters. The fretting fatigue specimens were examined to determine the crack location and the crack orientation along the contact surface. The fatigue parameters were evaluated on their ability to predict these observations and they were used to compare fretting fatigue with uniaxial (no fretting) fatigue data. The comparison of the analysis and experimental results showed that fretting fatigue crack initiation is dependent on the plane of maximum shear stress amplitude and the slip range at this location.

➢ *HCF and Foreign Object Damage.* Three studies are being performed in this area:

- The effects of notch sizes on HCF capability (10^6 cycles) have been investigated. Three different notch sizes, each with a stress concentration factor of K_t = 2.78, were tested to determine whether or not K_t was a valid parameter for assessing FODed and/or notched material capability. Results demonstrated a definite notch size effect in Ti-6Al-4V that can be influenced by the material product form and microstructure. Also, no single parameter is adequate for characterizing the notch size effect. Important considerations include material condition, notch root radius, local stress field, and notch root plasticity.

- An investigation was performed in which four different methods of simulating FOD (impact by glass spheres and steel spheres, and quasi-static indenting and notch shearing by steel chisels with controlled tip radii) were evaluated to determine their effects on Ti-6Al-4V fan-blade specimen fatigue capability. Finite element methods were also utilized to model the impact events and to build an understanding of the effect of the residual stress state on the capability of damaged specimens and to determine a criterion to predict HCF failure after damage by simulated FOD.

  Results indicate that by calculating the real stress state in Ti-6Al-4V that has been damaged by simulated FOD, the conditions under which it will fail from high cycle fatigue can be predicted. This failure will occur when the stress state in the vicinity of the damage is as severe as the fatigue strength of undamaged Ti-6Al-4V.

  The total depth into a specimen from its edge to the maximum extent of the plastically deformed zone (D_d) was found to be a damage quantification parameter that yielded a simple empirical relationship with the reduction in fatigue strength. It is clearly the size of the notch plus the size of the plastic damage zone that reduces the fatigue strength of Ti-6Al-4V. But when the parameter D_d is used, damage created by all techniques investigated in this study produced identical reductions in fatigue strength, within the statistical variation.

  The smallest amounts of total damage that could be generated were about 500 μm (92 μm notch depth with 400 μm plastic zone). At these levels of damage, the fatigue strength is nearly the same as that of undamaged Ti-6Al-4V. At greater damage depths, all damage mechanisms evaluated in this study show a linear decrease in fatigue strength with increasing damage depth until it reaches 1750 μm. At damage depths larger than 1750 μm, a stress threshold appeared below which no specimen failures occurred. This may be because these notches approach the 'worst case notch' conditions; i.e., notches with initial cracks that will not propagate at stresses below the threshold level.

  It was also found that impacts by glass spheres between 2 mm and 5 mm in diameter and 2 mm diameter steel spheres at realistic FOD velocities can be adequately simulated more economically by indentation techniques that use chisels of various radii to create damage so long as the total damage depth is matched (not just the visible crater dimensions).

- A detailed systematic evaluation of macroscopic and microscopic damage generated by all FOD impact conditions is being performed for the laboratory FODed specimens. Currently, the damage created by the impact by 1-mm-diameter glass spheres (300 m/sec) on the leading edge of simulated fan-blade test specimens is being characterized. Impact from steel spheres and quasi-static indents will be performed in the future.

❖ ***Investigation of Other Damage Mechanisms.*** Two studies are being performed in this area.

➢ The characterization of the effect of laser shock peening (LSP) is important for understanding the increase in fatigue strength and foreign object damage (FOD) tolerance for turbine engine components. These enhanced fatigue properties are a direct result of compressive residual stresses found in the treated regions. This study will seek to explore the effects of power density and pulse repetition on the residual stresses, fatigue crack growth properties, and microstructure / substructure development of a Ti-6Al-4V simulated airfoil.

Little microstructural deformation was found in SEM examinations. TEM studies showed a large increase in dislocation density after laser shock peening. It was found that the residual stress state and percent cold work were a function of both the LSP power density and the number of laser pulses per spot. In addition, there was a strong correlation between the magnitude of residual compressive stresses generated and the percent cold work measured. Fatigue cracks in LSPed blades would frequently arrest until increased loads were applied.

Figure 11 depicts a typical in-depth residual stress profile generated by two sets of LSP parameters. The residual stresses were measured through half the nominal airfoil thickness. It is clear that the higher intensity treatment (9 GW/cm^2 as opposed to 4 GW/cm^2) produced a more intense state of compressive residual stress throughout the thickness.

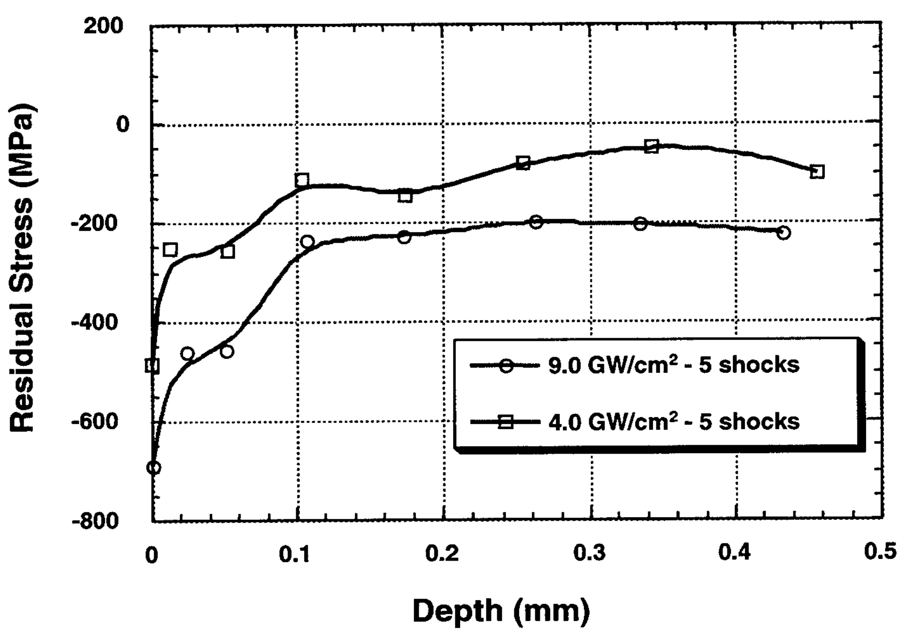


FIGURE 11. Residual Stress vs. Depth for Five Shocks per Spot

➢ A study on the effects of pre-straining on material HCF capability was conducted to evaluate the effect of material pre-straining at FOD impact sites. Bulk material (Ti-6Al-4V) was upset forged to a strain level of 10% at room temperature. Specimens were then machined from the pre-strained material and both "as received" and pre-strained specimens were tested at 400 Hz under pure HCF loading using the step-test method to determine material maximum stress capability (fatigue limit stress) at 10^7 cycles. As shown in Figure 12, pre-strained specimens show a possible slight decrease in fatigue limit stress at R=0.1 and 0.5. Additional testing of pre-strained specimens at a pre-strain level of 15% will be pursued in the next year.

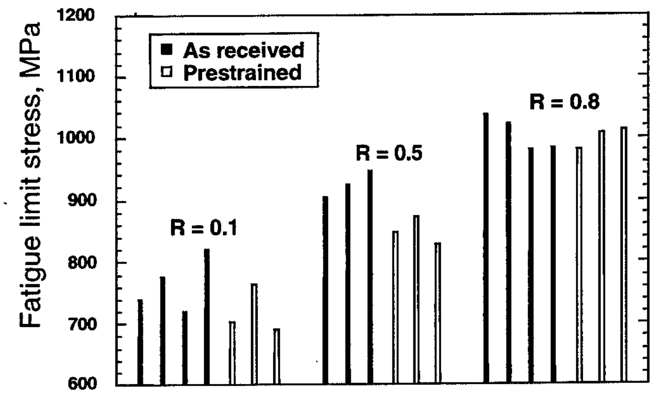


FIGURE 12. Comparison of Pre-Strained and "As Received" Material Fatigue Limit Stress at 10^7 Cycles

❖ ***Innovative Test Technique Development.*** A new fretting fatigue test apparatus has been developed that imparts both LCF and HCF stresses similar to those experienced by fan blades in the dovetail region of the blades. At the contact region, steady-state and temporal normal stresses, shear stresses, torsional stresses, and a moment are imparted on the blade / hub interface. These loads are a result of the centrifugal loads due to engine rotation (low cycle fatigue loading – steady-state), and the (temporal) vibrational loads imparted by aerodynamic loading. The experimental set-up shown in Figure 13 enables both static loading and a dynamic axial load to be applied in the dovetail region.

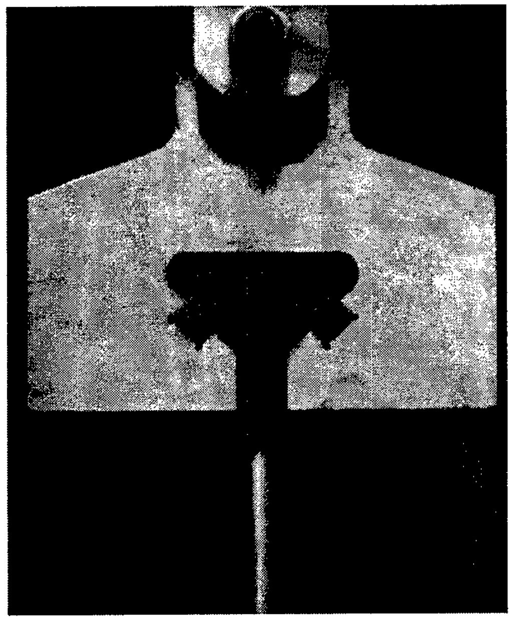


FIGURE 13. New HCF/LCF Fretting Fatigue Test Apparatus

Participating Organizations: Air Force Research Laboratory (AFRL); University of Dayton Research Institute; Systran Corporation; Southern Ohio Council on Higher Education; University of Portsmouth, United Kingdom; Air Force Institute of Technology

Points of Contact:

Government
Dr. Theodore Nicholas
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
Wright-Patterson AFB, OH 45433-7817
Phone: (937) 255-1347
Fax: (937) 656-4840
Email: theodore.nicholas@afrl.af.mil

Government
Mr. Joseph G. Burns
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
Wright-Patterson AFB, OH 45433-7817
Phone: (937) 255-1360
Fax: (937) 656-4840
Email: joseph.burns@afrl.af.mil

2.3 HCF & Time-Dependent Failure in Metallic Alloys for Propulsion Systems (Fan & Turbine)

FY 96-01

Background: This program is focused on the definition, microstructural characterization, and mechanism-based modeling of the limiting states of damage associated with the onset of high cycle fatigue failure in titanium and nickel-base alloys for propulsion systems. The goal of this program is to provide quantitative physical/mechanism based criteria for the evolution of critical states of HCF damage, enabling life prediction schemes to be formulated for fatigue-critical components of the turbine engine. The specific objectives are as follows:

(1) Perform systematic experimental studies to define crack formation and lower-bound fatigue thresholds for the growth of "small" and "large" cracks at high load ratios, high frequencies, and with superimposed low cycle fatigue loading, in the presence of primary tensile and mixed-mode

loading; and analyze the applicability of the threshold stress-intensity factors to characterize crack initiation and growth in engine components subjected to high cycle fatigue.

(2) Define lower-bound fatigue thresholds for crack formation in the presence of notches, fretting, or projectile damage, on surfaces with and without surface treatment (e.g., shot or laser shock peened).

(3) Develop an understanding of the nature of projectile (foreign object) damage and its mechanistic and mechanical effect on initiating fatigue crack growth under high cycle fatigue conditions.

(4) Develop new three-dimensional computational and analytical modeling tools and detailed parametric analyses to identify the key variables responsible for fretting fatigue damage and failure in engine components; compare model predictions with systematic experiments; and identify and optimize microstructural parameters and geometrical factors and surface modification conditions to promote enhanced resistance to fretting fatigue.

(5) Develop mechanistic models of the initiation and early growth of small cracks to characterize their role in HCF failure, with specific emphasis on initiation at microstructural damage sites and on subsequent interaction of the crack with characteristic microstructural barriers; and correlate such models to experimental measurement.

Recent Progress: Considerable progress has been made during the third year of this research program. Specific accomplishments are outlined below:

❖ ***HCF/LCF Interactions.***

➢ Worst-case fatigue threshold stress intensities have been measured in STOA (Solution Treated and Over Aged, $\alpha+\beta$-processed) Ti-6Al-4V using large (> 5 mm) cracks under representative HCF conditions (R > 0.95, 1,000 Hz). A number of different methods were investigated to determine the fatigue threshold stress intensity factors. With constant-K_{max} cycling at 1 kHz, a "worst-case" threshold can be defined in Ti-6Al-4V at $\Delta K_{th} = 1.9$ MPa $\sqrt{m}$ (Fig. 14). To verify this "worst case" approach, the high-load-ratio fatigue crack propagation data are compared to fatigue data from small cracks, which includes both naturally-initiated small cracks (~45–1,000 μm) and to small cracks (< 500 μm) emanating from sites of foreign object damage. In both cases, crack growth is not observed below $\Delta K \sim 2.9$ MPa $\sqrt{m}$, (Fig. 15). Consequently, it is believed that the "worst-case" threshold concept can be used as a practical lower bound for the stress intensity required for the onset of small-crack growth under HCF conditions.

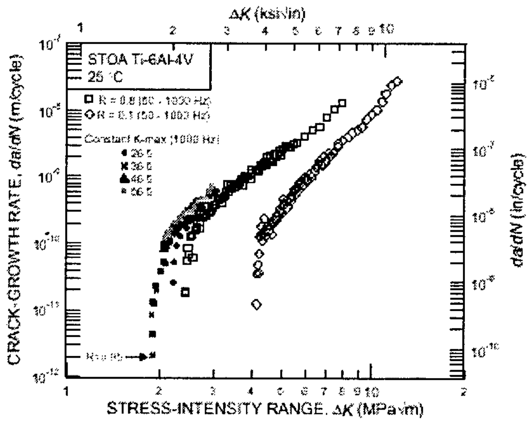


FIGURE 14. Constant-K_{max} fatigue crack propagation behavior at four different K_{max} values: K_{max} = 26.5, 36.5, 46.5, and 56.5 MPa √m (1,000 Hz) compared to constant-R data at R = 0.1 and 0.8 (50-1,000 Hz).

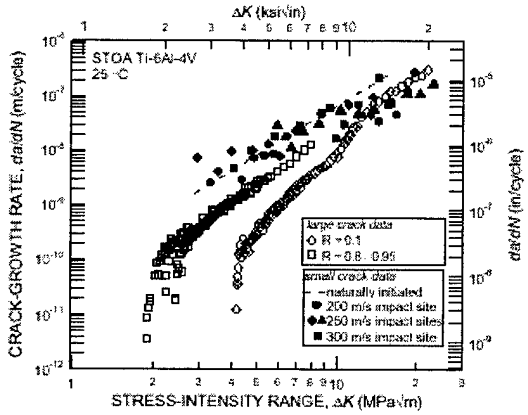


FIGURE 15. Comparison of long-crack propagation data to fatigue data from small cracks (including both naturally-initiated small cracks and those originating from sites of foreign object damage).

- Large-crack threshold behavior in a polycrystalline nickel-base disk alloy has been characterized at 1,000 Hz at 22° and 650-900°C, with respect to the role of microstructure, frequency and load ratio. Two different microstructures of KM4 are being studied. By varying the heat treatment, the grain size is varied from around 6 microns (sub-solvus heat treatment) to 55 microns (super-solvus heat treatment). Room temperature results indicate that coarse-grained material had better fatigue crack propagation resistance and higher thresholds than fine-grained material. Also, higher load ratios led to lower fatigue crack propagation resistance at equivalent ΔK. At 650°C, thresholds at 1,000 Hz are approximately 15-20% higher than those at 100 Hz for both microstructures. Also, thresholds in the fine-grained material are approximately 5-10% higher than in the coarse-grained material at both frequencies.

❖ ***Notches and Foreign Object Damage (FOD).***

- FOD was simulated by high-velocity (200-300 m/s) impacts of 3.2 mm diameter steel spheres on a flat surface at 90° impact angle. At velocities above 250 m/s, pronounced pile-ups at the crater rim with some detached material were formed as is shown for 300 m/s impact in the scanning electron micrograph (Fig. 16). Of critical importance were the observations, shown in Figs. 17, that for the highest velocity impacts at 300 m/s, plastic flow of material at the crater rim causes local notches (Fig. 17a) and even microcracking (Fig. 17b). The microcracks were quite small, i.e., between ~2 to 10 μm in depth, but clearly provided the nucleation sites for subsequent HCF cracking, as shown in Figure 17c. No such microcracking could be detected in this alloy at lower impact velocities.

  To date, no crack growth from FOD impact (or naturally-initiated) sites has been observed at ΔK values below ~2.9 MPa √m. This is over 50% higher than the "closure-free", *worse-case* threshold value of ΔK_{th} = 1.9 MPa √m, defined for large cracks in bimodal Ti-6Al-4V at the highest possible load ratio (R ~ 0.95). Consequently, it is concluded that fatigue-crack propagation thresholds for large cracks, determined under conditions that minimize crack closure, can be used as lower bounds for the threshold stress intensities for naturally-initiated and FOD-initiated small cracks in this alloy.

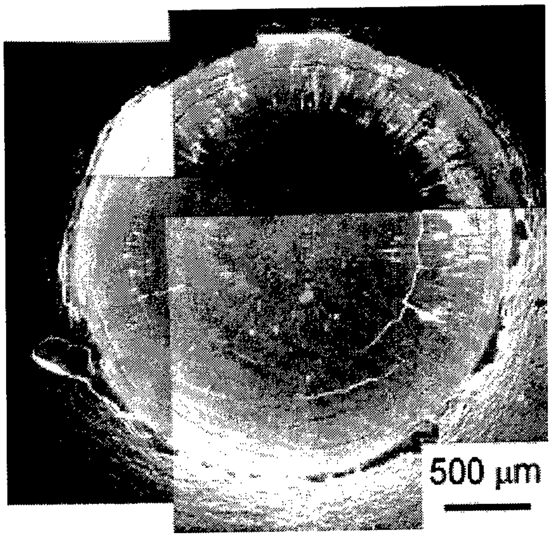


FIGURE 16. Scanning electron micrographs of impact damage sites for a 300 m/s impact velocity, indicating lip formation at crater rim and intense shear band formation emanating at the indent surface.

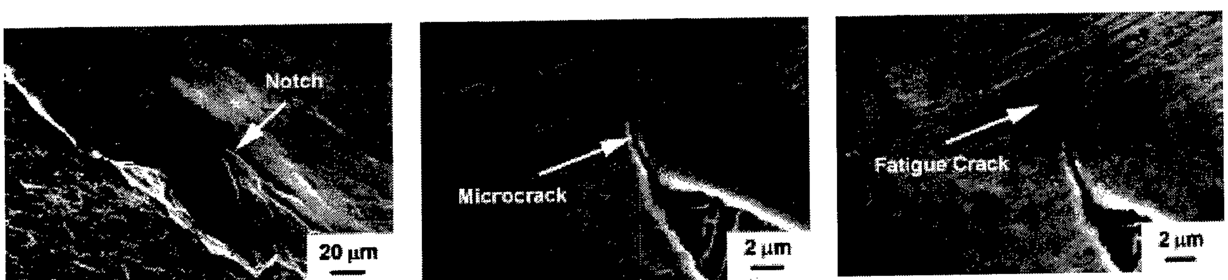


FIGURE 17. Scanning electron micrographs showing the presence of microcracking at crater rim of a FOD indent after the highest velocity (300 m/s) impacts. Micrographs show (a) local notches at crater rim caused by plastic flow of material, (b) microcracks emanating from such notches, and c) subsequent fatigue-crack growth initiated at such microcracks after 5,000 cycles at σ_{max} = 500 MPa (R = 0.1).

➢ Efforts are currently underway to utilize a 300 μm spot size at the Stanford Synchrotron Radiation Laboratory and a 1 μm spot size at the Advanced Light Source at the Lawrence Berkeley National Laboratory to characterize the stress fields surrounding a damage site caused by a hard-body impact. Based on preliminary results, it is evident that synchrotron x-ray diffraction is a useful tool for characterizing the strain distribution associated with foreign object damage; however, further technique refinement is necessary to more completely characterize the damage state.

❖ ***Fretting Fatigue.***

- Mixed-mode crack-growth thresholds were measured in $\alpha+\beta$ processed Ti-6Al-4V using the asymmetric four-point bend geometry at mixities of $K_{II}/K_I \sim 0$ to 7.1. Mixed-mode loading conditions were quantified, both in terms of the ratio of ΔK_{II} to ΔK_I and the phase angle, ß (= tan -1 (ΔK_{II} / ΔK_I)). Results indicate that when fatigue-crack growth in this alloy is characterized in terms of the crack-driving force ΔG (range in strain energy release rate), which incorporates both the applied tensile and shear loading, the mode I fatigue-crack growth threshold is a lower bound (worst case) with respect to mixed-mode (I + II) crack-growth behavior. This result indicates that, for cracks of sufficient length, the presence of mixed-mode loading does not preclude the application of a threshold-based design methodology.

- Stress-intensity solutions have been developed for small, semi-elliptical, surface cracks under mixed-mode loading. Such solutions are being used to experimentally measure (for the first time) small-crack, mixed-mode thresholds in Ti-6Al-4V.

- A continuum level mechanics model (Adhesion Model) that incorporates interfacial adhesion, material properties and contact loads has been developed for predicting contact fatigue crack initiation for a variety of loading states and contact geometries. This model enables the analysis of a variety of contact problems from those due to fretting fatigue in large-scale structures to contact fatigue in micro-scale devices.

- The influence of contact and bulk stresses, contact geometry, material microstructure, and surface finish on the fretting fatigue behavior of Ti-6Al-4V has been investigated through controlled experiments using the MURI-developed fretting fatigue device. The observed fretting damage scars (contact area and the stick-slip zone) correlated well with theoretical predictions. Qualitatively, four different stages (crack initiation, small-crack propagation, long-crack propagation and catastrophic failure) in the fretting fatigue life of a test component were identified. Quantitatively, conditions for crack initiation were analyzed within the context of the adhesion model and a modified Crossland analysis was conducted. By accounting for the steady-state long crack growth life through a Paris law formulation, crack initiation and small crack propagation lives were also identified.

- Work has begun on quantitative analytical and experimental tools for evaluating the effectiveness of different palliatives (e.g., shot peening, laser shock peening, and coatings) for fretting fatigue.

Participating Organizations: Air Force Office of Scientific Research (AFOSR), University of California at Berkeley, Massachusetts Institute of Technology, Michigan Technological University, Harvard University, Southwest Research Institute, Imperial College, London University, Technische Universität Hamburg-Harburg, Universität für Bodenkultur (BOKU)

Points of Contact:

Government
Major Brian Sanders, Ph.D.
U.S. Air Force, AFOSR/NA
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332-0001
Phone: (202) 767-6063
Fax: (202) 767-4988
Email: brian.sanders@afosr.af.mil

Contractor
Prof. Robert O. Ritchie, Ph.D., Sc.D.
University of California at Berkeley
Dept. of Materials Science and Mineral Engineering
Berkeley, CA 94720-1760
Phone: (510) 486-5798
Fax: (510) 486-4995
Email: roritchie@lbl.gov

2.4 Improved HCF Life Prediction (Fan)

FY 96-00

Background: The focus of this program is on the development of damage tolerant design processes for gas turbine engines that substantially reduce the potential occurrence of high cycle fatigue failures in titanium (fan) structures. Specific objectives for this program are: (1) to characterize in-service damage associated with high-cycle fatigue loading of titanium fan blades; (2) to develop techniques to generate damage states in the laboratory that are representative of in-service damage; (3) to model the nucleation and progression of damage in titanium fan blades; and (4) to develop an improved damage tolerant life prediction and design methodology for turbine engine rotating structures subjected to high cycle fatigue (HCF) and combined high and low cycle fatigue (HCF/LCF) loadings.

This program is being accomplished through the development of a better understanding of the three primary damage mechanisms experienced in the fan section, and the transitioning of that understanding into the development of improved damage tolerance life prediction methodologies. All experimental studies are being performed on an $\alpha+\beta$ processed Ti-6Al-4V forged plate, specifically produced to provide a representative titanium alloy with consistent properties that would minimize data scatter due to material inhomogeneities. Specifically, this program is being performed through the accomplishment of research in the following areas:

- *HCF/LCF Interactions* research is aimed at developing a better understanding of the fatigue and crack growth damage accumulation processes due to the load interactions generated in LCF/HCF loading. This includes the study of fatigue crack threshold behavior for both pristine and LCF damaged material (with various surface treatments), as well as the development of baseline material data for comparison with other damage modes.

- *Foreign Object Damage* research is aimed at developing a better understanding of the occurrence and levels of FOD in different sections of turbine engines and characterizing the relevant parameters for modeling FOD damage progression. Techniques for reproducing damage representative of in-service FOD are being investigated, and specimens containing laboratory-induced FOD will be tested to characterize the effects of FOD.

- *Fretting Fatigue* research is aimed at developing a better understanding of the occurrence and levels of fretting fatigue damage at the fan blade root / disk hub interface. Techniques for reproducing damage representative of in-service fretting fatigue are being investigated and specimens containing laboratory-induced fretting and fretting fatigue damage will be tested to characterize the effects of fretting fatigue on the HCF behavior. Criteria for the initiation and propagation of cracks under fatigue in contact regions will be developed.

- *Damage Tolerant Life Prediction Methodologies* research is aimed at utilizing data generated to characterize the damage mechanisms described above to develop new, more accurate methods of modeling the initiation and progression of damage in titanium fan blades. Existing methodologies will be modified where possible, and new methodologies will be developed as necessary. Validation of life prediction methodologies will be accomplished through the comparison of predictions to experimental and service data.

Recent Progress: During the past year, progress has been made in the following areas:

- ***High Cycle Fatigue / Low Cycle Fatigue Interaction.*** Most of the effort performed under HCF/LCF Interaction has been in developing an understanding of baseline material behavior for establishing the effects of other damage mechanisms. The many accomplishments in this area are described below:

- High resolution studies of LCF/HCF crack growth with the SwRI DISMAP system found no significant, systematic effect of periodic LCF unloads on near-threshold fatigue crack growth rates under high-R HCF cycling. This result is consistent with detailed crack-tip micromechanics analyses conducted under another program, which found no significant changes in crack-tip strains or crack closure with the periodic LCF unloads.

- The fatigue crack growth behavior of microstructurally short cracks, which have been known to propagate below conventional long-crack ΔK_{th} values, was evaluated. Naturally-initiated fatigue cracks in smooth specimens (tested at $\Delta\sigma = 80$ ksi, $R = 0.1$, and frequency 60 Hz) were documented via surface replication performed at uniform intervals of 15,000 cycles.

  According to the general trend observed in Figure 18, an initially high crack propagation rate abruptly decreases, reaches certain minimum value, and then gradually increases. This is accompanied by substantial reduction in experimentally observed scatter in crack propagation rate as the crack grows. In Figure 18a, crack size corresponding to the minimum crack propagation rate is also compared to the average primary-alpha grain size. The major trend in crack propagation behavior changes from deceleration to acceleration after the crack tip passes through the first or second primary-alpha grain boundary. At the same time, in one case (specimen 2) an additional crack growth retardation event occurred when the crack size (depth or surface half-length) was five times larger than the average primary-alpha grain. Based on the data presented in Figure 18a, fatigue crack propagation behavior in the present material was divided into two separate regimes with respect to microstructural sensitivity.

  Similar trends in fatigue crack propagation behavior can be seen in Figure 18b. In this graph, the results obtained are plotted as a function of stress intensity factor range, ΔK, and compared to the crack propagation behavior of "long" cracks in both compact tension and surface flaw type specimens. It can be seen that naturally-initiated "small" cracks propagate well below the "long" crack threshold, and that naturally-initiated "small" cracks propagate much faster then "long" cracks for stress intensity range values slightly greater than the "long" crack threshold. The tendency for faster propagation persists up to ΔK ~ 10 at which point both sets of data merge together.

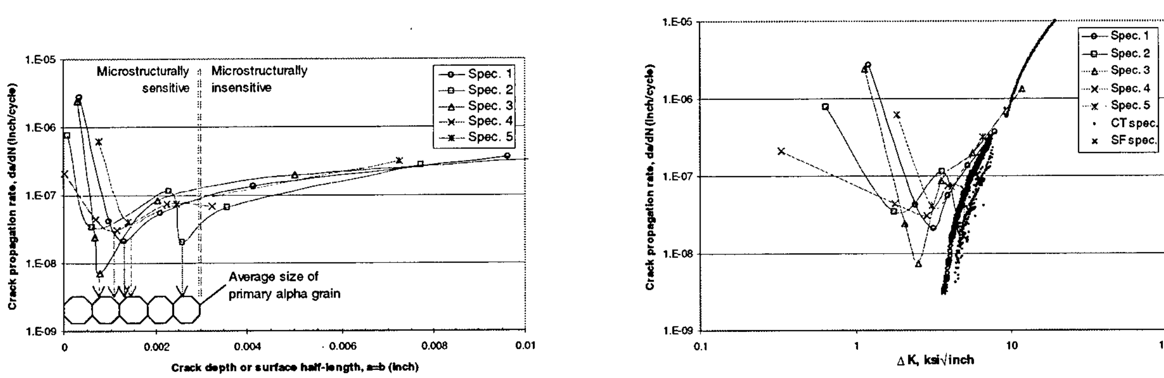


FIGURE 18. Fatigue Crack Propagation Rate of Naturally-Initiated "Small" Cracks as a Function of: (A) Crack Size and (B) Stress Intensity Factor Range.

❖ ***Foreign Object Damage.*** Specific areas of progress are:

- Two geometries were selected for notched testing to estimate the effect of stress gradients and notch volume on initiation life. Each sample was designed to have a nominal K_t of 2.5. The test geometries included both flat notched specimens as well as the unnotched and machined notched tests of winged FOD specimens. All specimens were stress relieved and chem milled. Both stress-invariant and critical plane methods of modeling fatigue life were evaluated. During this evaluation, it became readily apparent that the specimens with small stressed areas had greater HCF capability (higher Walker equivalent stress prior to failure) than the smooth test data. This was especially true for the machined notch FOD test that had the smallest notch length (less than 0.015 inch). It was concluded that this behavior is best modeled by considering the size of the stressed surface area. This was treated quantitatively with the Weibull modified equivalent stress method. A stressed area weighting term was employed for a given specimen geometry and loading condition. Test results indicate that the presence of a large stressed area (unnotched FOD specimen) results in a predicted life similar to those of smooth specimens with a similarly highly stressed area. Yet, a relatively small notch (notched FOD specimens) can result in increased stresses prior to failure if the small area of highly stressed material is not accounted for in the analysis. The Socie stress model seems to correlate the notched data quite well, suggesting that the shear cracking mode might be dominant in the notched specimens. However, use of the Socie stress parameter along with the notch stress state (after accounting for notch-cyclic plasticity) does not adequately correlate with the smooth-data curve-fit. Further development is needed to account for possible material volume effects in notched specimens to allow correlation of smooth and notched data.

- FOD testing was performed on airfoil-shaped tension specimens and winged specimens. Three methods were used to simulate FOD in the winged specimens: machined notches with a 0.021-inch radius, ballistic ball impacts with 0.020 and 0.039-inch radius glass beads, and solenoid gun impacts with a chisel-point indentor (0.005 and 0.025-inch radii tips). Specimens were machined or impacted to simulate FOD nicks at 0° and 30° relative to the centerline of the leading edge region on the specimen. Low damage and high damage target levels were set at depths of 0.005 and 0.020-inch. Figure 19 compares 30° notches in sharp leading edge specimens with ballistic and solenoid gun impacts. Actual notch depths ranged from 0.003 to 0.009-inch and 0.015 to 0.026-inch.

Ballistic Impact with 0.020 Inch Radius Ball | Solenoid Gun with 0.025 Inch Radius Indentor | Solenoid Gun with 0.005 Inch Radius Indentor

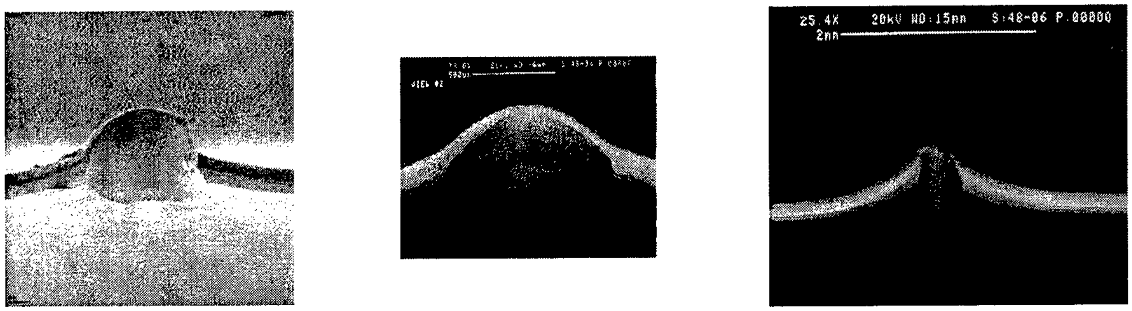


FIGURE 19. Representative FOD from Ballistic and Solenoid Gun Impacts (Sharp Leading Edge Specimens, 30° Impacts, High Damage Levels)

Results from endurance limit testing (10^6 cycles) indicate that the ballistic impact results are not significantly different from the solenoid gun results at equivalent damage depths and impactor radii. The solenoid gun has since been adopted as the simulated FOD impactor of choice for its repeatability.

The airfoil-shaped specimen is based on the Air Force's diamond-like cross-section tension (DCT) specimen. Single FOD impacts were introduced to each specimen side, resulting in two FOD notches per specimen. The indentation from the FOD event was measured using an MTS deflectometer. The non-recoverable energy associated with the FOD impacts was recorded. While some of the results appear to show good repeatability, other results show significantly different energy levels for the same depth of FOD. Additional work is required before this method can be used to calibrate the level of FOD damage imparted to specimens.

Several un-impacted and impacted specimens were tested under axial-load-control HCF conditions for comparison to baseline smooth bar fatigue data. Figure 20 compares the R = -1 and 0.5 diamond cross-section tensile (DCT or airfoil) test data with the smooth-bar baseline data. The data clearly show good agreement with smooth-bar baseline for non-impacted tests, and the negative effect that FOD has on HCF life. The non-recoverable energy showed poor correlation between the energy recorded and the subsequent HCF life of impacted specimens. Additional work is needed to better understand the effect of this parameter and technique. Fractography showed that some of the initiation sites were significantly (e.g., 0.004-inch) below the surface of the FOD impact. From the microstructural deformation observed below the FOD impact, it appears that significant cold work stresses should exist. However, these residual stresses were not measured.

❖ ***Fretting Fatigue.*** Specific areas of progress are:

➢ Multiaxial fatigue tests were performed on solid-round specimens for Ti-6Al-4V. All specimens were stress relieved and chem milled. Tests for torsion, proportional tension-torsion, and non-proportional tension-torsion were evaluated for cases where cyclic plasticity was not an issue and elastic-plastic finite element results were available. The Walker equivalent stress method was evaluated for predicting mean stress effects under uniaxial and multiaxial stress states for both smooth and notched fatigue specimens. The equivalent stress method is a stress invariant method that can be implemented into computationally efficient crack initiation codes such as NASALIFE. A variety of stress invariant multiaxial parameters were evaluated.

The stress invariant model that best predicted the experimental results is based on the effective stress range and a modified Manson-McKnight mean stress. Three different critical plane models, the Smith-Watson-Topper (SWT), the Fatemi and Socie (FS), and the Socie models were also evaluated. The SWT model was found to correlate the data with various stress-ratios quite well. The Socie effective stress parameter was able to collapse all of the data for the different R-conditions reasonably well in both the LCF and HCF regimes. The good correlation of the HCF data using the Socie model also suggests that a shear-cracking mode might be dominant in the HCF regime in general. The FS strain did not correlate the data as well as the Socie stress parameter. Further development is needed to better correlate data at different values of R using the critical plane methods.

- Friction experiments were conducted by Purdue University to study the evolution of the coefficient of friction, μ, with the number of cycles in partial slip experiments in bare Ti-6-4 on Ti-6-4. The pads used were cylindrical, resulting in Hertzian distribution in the contact zone. Loading was stopped after running for a specified number of cycles. Then, without disturbing the pad/specimen contact, a waveform of increasing amplitude was applied to the specimen. The experiment was then stopped when the pad just started sliding (about 50 cycles). The average coefficient of friction was then calculated using the maximum value of the tangential force before the pad started sliding. The friction experiments were conducted with two different sets of pads of radii 5 inches and 7 inches. The maximum bulk stress applied during the experiments was 42 ksi. Figure 20 shows the results of the friction experiments. These results are similar to the results of fretting tests with flat pads performed at GEAE.

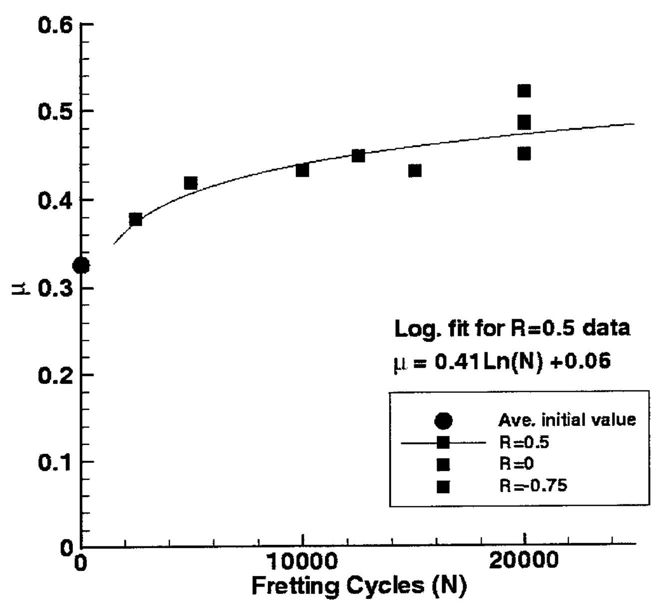


FIGURE 20. Evolution of Coefficient of Friction

- An investigation utilizing both integral equation and finite element methods (FEM) was performed to determine edge-of-contact stresses. The singular integral equation approach is based on the solution representing two-dimensional, plane-strain elastic contact of similar materials with an arbitrary surface profile. The integral equations can be derived from classical theory of elasticity results relating the slope of the contacting surfaces to the resulting interfacial tractions. The boundary conditions for this type of problem are the force and moment equilibrium conditions. In addition, the pressure vanishes at the ends of the pad. The singular integral equation can then be solved using trigonometric variable transformations. The surface normal traction can be obtained from any arbitrarily specified surface profile, normal load, and bending moment. Once the surface tractions are evaluated by this procedure, sub-surface stresses can be obtained using discrete Fourier transformation techniques.

The local edges of contact stresses were also obtained using FEM. However, FEM requires a very fine mesh in order to obtain a fully converged solution. Stress analyses were performed for a relatively simple two-dimensional problem. A mesh size of 0.0625 mil was required to obtain a fully converged solution. Meshing to this level for a complex three-dimensional skewed disk-airfoil attachment would be a very computationally intense problem and is not well suited to an engineering or design environment. For the two-dimensional experiments in the current program, the singular integral equations give a solution that matches very well with the solution obtained from the finite element analysis as shown in Figure 21.

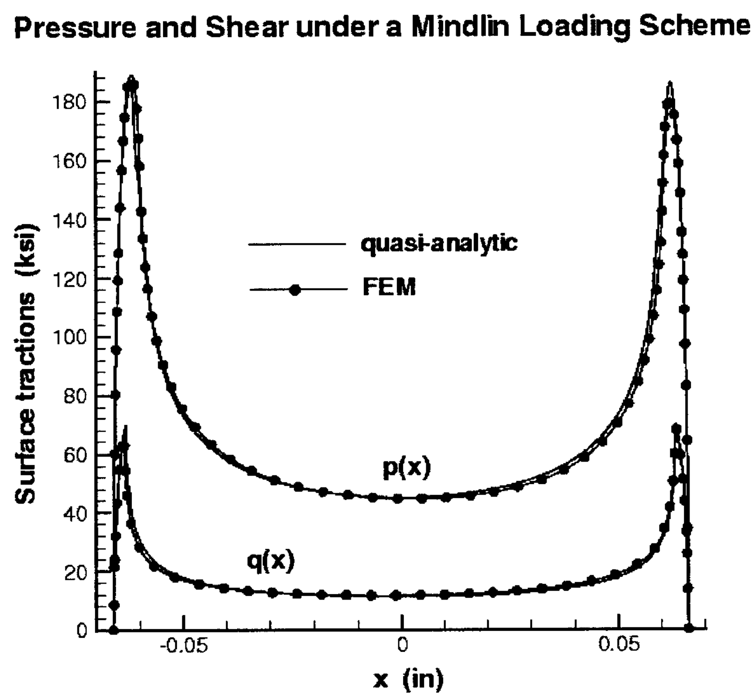


FIGURE 21. Comparison of Surface Normal Tractions Obtained from Integral Equation and FEM Methods

❖ ***Damage Tolerant Life Prediction Methodologies:*** Damage tolerant life prediction methodologies have been developed or utilized as mentioned in the three damage state areas above. In each of the three areas, exit criteria have been developed to ascertain the level of accuracy of the techniques for determining the HCF alternating load capability of damaged materials. The metric for assessing the predictive accuracy is based on the ratio of "actual to predicted" capability where actual capability is determined in bench testing. For the different damage states, exit criteria are based on different limits put on the mean and coefficient of variation (COV) of the "actual-to-predicted" capability, as compared to that for baseline smooth axial fatigue specimens. The exit criteria are listed in Figure 22.

Damage State	Mean Ratio*	COV*
LCF/HCF Interaction	0.95 – 1.05	1.25 X
Foreign Object Damage	0.85 – 1.15	2.50 X
Fretting Fatigue	0.85 – 1.15	2.50 X

; compared to baseline smooth axial fatigue specimens

FIGURE 22. Materials Damage Tolerance Damage State Exit Criteria

Participating Organizations: University of Dayton Research Institute, General Electric Aircraft Engines, Pratt & Whitney, Rolls Royce Allison, Honeywell Engines and Systems, Southwest Research Institute, Purdue University, North Dakota State University, and the University of Illinois.

Points of Contact:

Government
Dr. Theodore Nicholas
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
WPAFB, OH 45433-7817
Phone: (937) 255-1347
Fax: (937) 656-4840
Email:
Theodore.Nicholas@afrl.af.mil

Government
Mr. Joseph G. Burns
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
WPAFB, OH 45433-7817
Phone: (937) 255-1360
Fax: (937) 656-4840
Email: Joseph.Burns@afrl.af.mil

Contractor
Dr. Joseph P. Gallagher
Univ. of Dayton Research Institute
300 College Park
Dayton, OH 45469
Phone: (937) 229-2349
Fax: (937) 229-3712
Email: gallagher@udri.udayton.edu

2.5 Advanced HCF Life Assurance Methodologies (Fan & Turbine)

FY 99-02

Background: This program is a follow-on effort to Effort 2.4, "Improved HCF Life Prediction," and is focused on the extension and validation of the technologies developed in the earlier effort to other titanium alloys for use in the fan section, as well as to single crystal nickel-base superalloys for use in the turbine section. The objectives of this program are: (1) to extend the understanding of damage mechanisms in $\alpha+\beta$ processed Ti-6Al-4V blades and disks to other titanium alloys with varying microstructures, (2) to develop a better understanding of the underlying damage mechanisms to which single crystal nickel-base superalloy blades and disks are subjected, and (3) to extend and validate the damage tolerant life prediction and design methodologies developed for $\alpha+\beta$ processed Ti-6Al-4V to other titanium alloys and to single crystal nickel-base superalloys.

A comprehensive database of test results are being developed to describe all aspects of material HCF behavior for β-processed Ti-17 titanium and PWA 1484 single-crystal nickel-base superalloy. The damage states that increase the potential for HCF failures will then be defined. Finally, improved test methods, improved analytical approaches, and total life prediction software for titanium and single crystal superalloy, will be developed.

Recent Progress: This work has recently started and limited testing has been performed. No results are available at this time.

Participating Organizations: Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), University of Dayton Research Institute, General Electric Aircraft Engines, Pratt & Whitney, Rolls Royce Allison, Honeywell Engines and Systems, Southwest Research Institute, Purdue University, University of Illinois, North Dakota State University, Rensselaer Polytechnic Institute.

Points of Contact:

Government
Maj Brian Sanders, Ph.D.
U.S. Air Force, AFOSR/NA
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332-0001
Phone: (202) 767-6063
Fax: (202) 767-4988
Email: brian.sanders@afosr.af.mil

Government
Mr. Joseph G. Burns
U.S. Air Force
AFRL/MLLN, Bldg. 655
2230 Tenth St., Suite 1
WPAFB, OH 45433-7817
Phone: (937) 255-1360
Fax: (937) 656-4840
Email: joseph.burns@afrl.af.mil

Contractor
Dr. Joseph P. Gallagher
Univ. of Dayton Research Institute
300 College Park
Dayton, OH 45469
Phone: (937) 229-2349
Fax: (937) 229-3712
Email: gallagher@udri.udayton.edu

2.6 Conclusion

The Materials Damage Tolerance Action Team dramatically increased the propulsion community understanding associated with and contributing to turbine engine high cycle fatigue. Specifically, this Team developed a new titanium Foreign Object Damage (FOD) life model: a new FOD baseline for HCF analysis with increased understanding of FOD occurrence, locations and severity. The Materials Team also developed a unique HCF bench test that can simulate both fretting fatigue and contact stresses and improve overall HCF predictive capability, and developed new methods for modeling fretting fatigue life, crack growth in fretting fatigue, and contact stresses. A low cycle / high cycle fatigue interaction model is also being formulated. Currently, fretting of blades is the most difficult failure mode, as there is significant disagreement between predicted and observed data. An effort addressing single crystal blades is also currently underway.

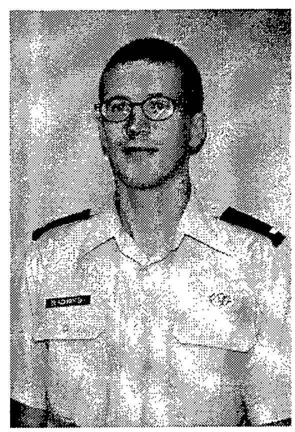
3.0 INSTRUMENTATION

BACKGROUND

The Instrumentation Action Team (Instrumentation AT) has the responsibility of fostering collaboration between individual HCF instrumentation efforts with the overall goal of combining with the Forced Response and Component Analysis ATs to better determine alternating stresses to within 20%. The Instrumentation AT provides technical coordination and communication between active participants involved in HCF measurement, sensor, data processing, and engine health monitoring technologies. Technical workshops have been organized on at least an annual basis and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Instrumentation AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for instrumentation and engine health monitoring programs, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Instrumentation AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in instrumentation technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

ACTION TEAM CHAIRS

Chair
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

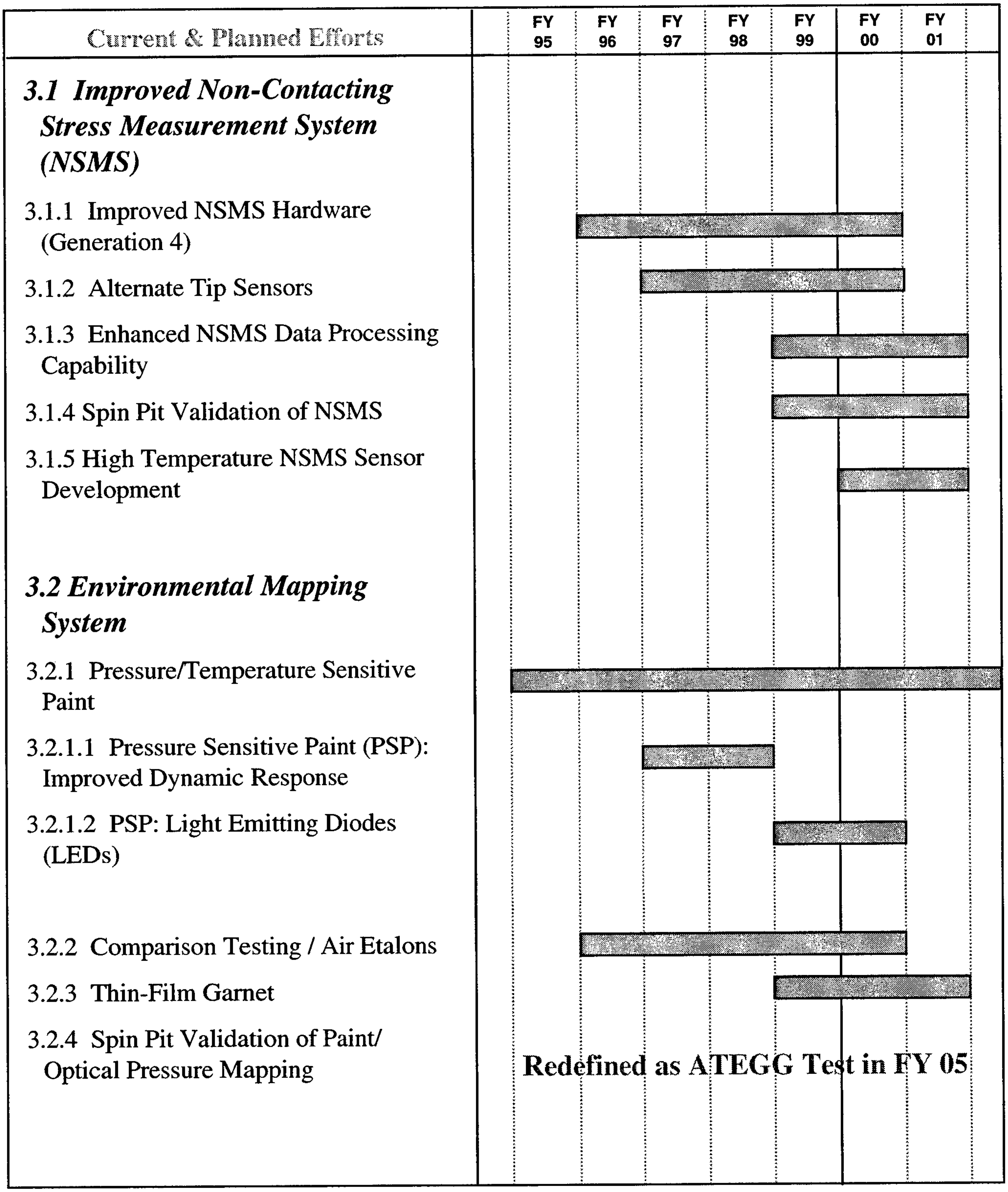


Co-Chair
2Lt Brian Beachkofski
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2326
Fax: (937) 255-2660
Email: brian.beachkofski @wpafb.af.mil

INTRODUCTION

The following pages summarize the schedules, backgrounds, and recent progress of the current and planned projects managed by this action team.

Instrumentation Schedule



Instrumentation Schedule *(Cont.)*

Current & Planned Efforts	FY 95	FY 96	FY 97	FY 98	FY 99	FY 00	FY 01
3.3. Improved Conventional Sensors							
3.3.1 Non-optical NSMS Sensor Development (Eddy Current)							
3.4 Development of Long-Life, Less Intrusive Devices							
3.4.1 Advanced Thin-Film Dynamic Gages							
3.4.2 Advanced High-Temperature Thin-Film Dynamic Gages							
3.4.3 Spin Pit Validation of Strain Gages and Spin Pit Validation of High Temperature Strain Gages			Cancelled				

3.1 Improved Non-Interference Stress Measurement System (NSMS)

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the projects described below is to develop an advanced generation NSMS (Fig. 23) capable of detecting simultaneous integral-order modes with a 5X improvement in accuracy, and to provide the ability to accurately convert the measured tip deflection to a dynamic stress map.

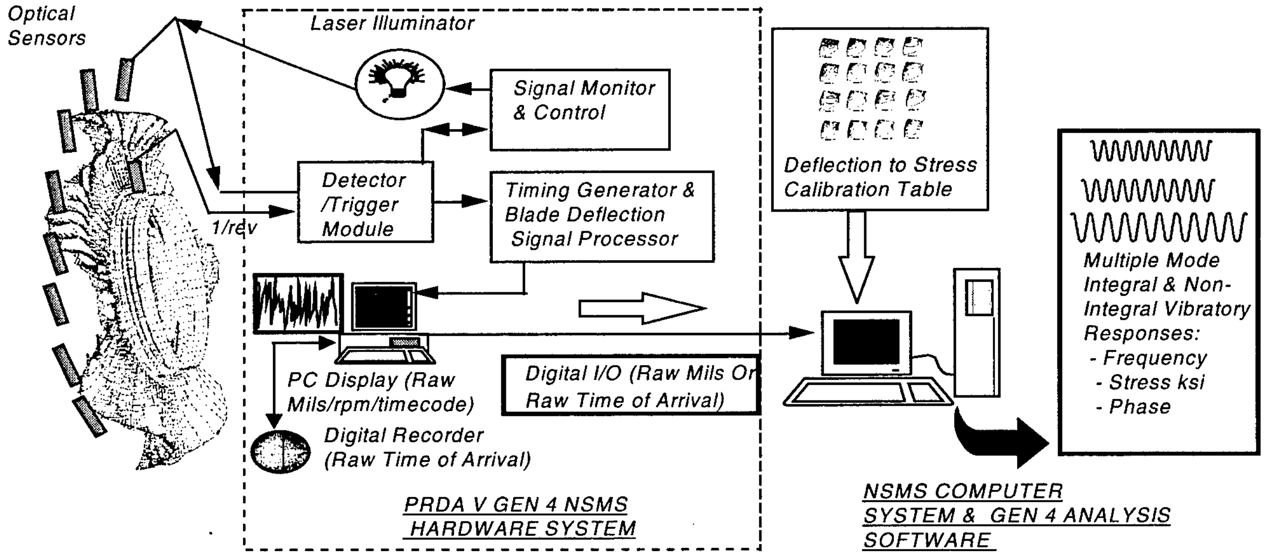


FIGURE 23. Next-Generation NSMS Overview

3.1.1 Improved Non-Interference Stress Measurement System (NSMS) Hardware (Generation 4)

FY 96-00

Recent Progress: Progress has been made on all four major subsystems of the NSMS hardware: Electro-Optics, the Blade-Deflection Signal Processor (BDSP), the Optical Probe, and the Blade Timing Generator. NSMS hardware also fared very well both in conventional simulated altitude testing as well as flight testing.

Electro-Optic Development:

This effort has been subcontracted to Arnold Engineering Development Center (AEDC). A manpower limitation that occurred within the existing project team made this necessary. Existing designs, documentation and materials from the Electro-Optics Task were delivered to AEDC. AEDC personnel are rapidly gaining familiarity with the various aspects of the design and are proceeding.

Blade-Deflection Signal Processing (BDSP):
Design and layout of the enhanced trigger board is complete and the board has been ordered. Nearly every electronic part has been received for 24 channels of detectors, lasers, and trigger boards. Major parts remaining to be ordered are packaging and power supplies. Single-mode lasers have been received and shipped to OZ Optics for installation in fiber-coupling devices. The photosensitivity of the detector has been redefined to match response of current NSMS Generation 4. This will enable our detectors to respond to reflected light signals in the 100nW to 20μW range. Required design changes are complete, but detector board layout must be updated. Also, temperature compensation has been added to the detector bias circuit. Software for interface from BDSP to Electro-Optics has been received and installed.

Optical Probe Development:
A prototype custom-designed connector for coupling the sensor output to the Photo-Detector was fabricated and delivered to AEDC. It will accept an off-the-shelf optical filter. Lab tests will be initiated to determine the minimum size and quantity of receive fibers for the five-lens optical head. Size and quantity (fibers) directly impact the cost of the optical extension cable (fiber core size drives cost).

Blade Timing Generator Development:
To date, we have a Master Clock and seven Timer cards that appear to work as designed. Testing of the prototype Master Clock and Timer cards will be completed 1Q FY00. The circuits will be revised as necessary and new boards procured. If the fixes are minor, the full set of circuit boards (24 channels) will be procured. We expect to receive the Blade Timing Generator chassis by 1Q FY00. Overall, preliminary designs have been completed and prototyping and bench testing of major subsystems are well underway. The high-temperature line-probe technology was demonstrated in F119 high-pressure compressor (HPC) for over 100 hours. The multi-lens configuration (low temperature, shown below) is being used extensively in current JSF, F119 ISR, and ATEGG applications, and was used in the PW2037 (F117) and PW4000 low-pressure compressor (LPC) and HPC NSMS applications at Pratt & Whitney.

The line probe has demonstrated superiority over conventional probes, as it is capable of measuring multiple-occurring synchronous and non-synchronous vibratory modes that yield greater than 1 mil peak-to-peak component deflections. Figure 24 is an artist's conceptualization of the probe. The line is created by five optical lenses. The current configuration is capable of operating at 350 °F continuously and 500 °F for a limited time. Work continues to increase the temperature capability of the system. The Gen 4 probe will be capable of continuous operation at 650 °F.

Five Lens Line Probe

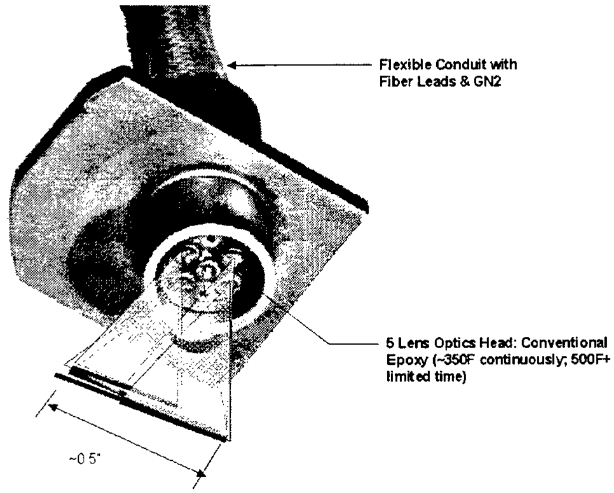


FIGURE 24. Five-Lens Line Probe

NSMS Flight Program:

An NSMS flight program has been conducted on an F100-220 redesigned first-stage high-pressure compressor blade in an F-15 aircraft at Edwards Air Force Base (EAFB). The F100-220 first-stage high-pressure compressor blade was recently redesigned and is currently undergoing design validation substantiation testing. In addition to conventional simulated altitude testing in a laboratory test cell at Arnold Engineering Development Center (AEDC), a flight test program has been conducted to verify flutter-free operation in an F-15 aircraft at Edwards Air Force Base (EAFB).

For testing at AEDC, the first, second and third stages of the high-pressure compressor (HPC) were instrumented with conventional strain gages and NSMS optical sensors. NSMS sensors utilized in the AEDC testing were adaptations of optical line sensors currently being developed under a contract related to the High Cycle Fatigue Program. All three stages were heavily instrumented with NSMS sensors (eight or nine probes per stage) to provide measurement of flutter and multiple-occurring integral-order vibratory modes. NSMS data quality from the AEDC testing was excellent, and comparison with conventional strain-gage data is underway.

Three probes were installed, including one backup and two probes required for full analysis of any flutter events. The optical element of the sensor was a bundle of seven aluminum-jacketed 100-μm-diameter core optical fibers. Figures 25 and 26 show the sensor head and the lead egress from the area of the unison ring. These sensors were capable of continuous operation at 750 °F (up to 900 °F for a limited time) without cooling.

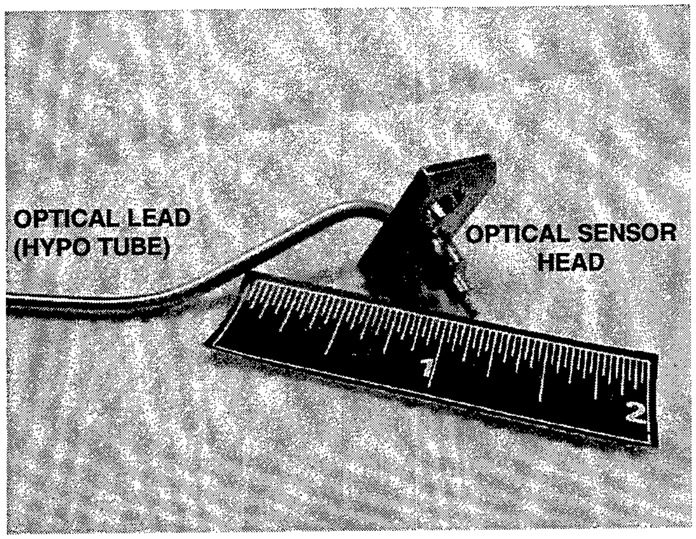


FIGURE 25. F100-220 First-Stage High Compressor NSMS Flight Probe

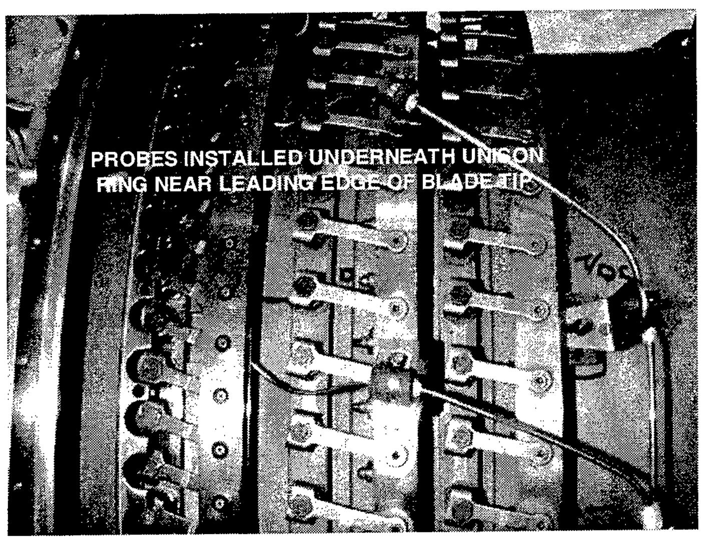


FIGURE 26. F100-220 First-Stage High Compressor NSMS Optical Probe Lead Routing

An existing multichannel custom-designed Electro-Optical signal-conditioning module provided illumination and optical-to-analog electrical signal conversion for the sensors. Illumination was provided by ¼-watt laser diodes (~850nm wavelength), one per sensor. Avalanche photo detectors were used to produce the electrical signals. Additionally, the module provided signal conditioning for the 1/rev variable reluctance sensor. This system was custom designed by the engine manufacturer and built for a previous flight test of the F100-220 third-stage low-pressure compressor conducted on the same aircraft in 1995 and 1997. Aircraft avionics cooling air was used to maintain a safe operating temperature in the Electro-Optics module.

During flight, NSMS data were recorded on the aircraft's special instrumentation magnetic tape recorder. During specific flights designated for NSMS data, the recorder was run at 30 ips to provide a bandwidth of 125KHz for the NSMS sensor signals. Data from the three NSMS optical 1/blade sensors and the 1/rev magnetic sensor were recorded along with other parameters and an IRIG time code signal (for time correlation of data). All three sensors provided high-quality data throughout the flight test program.

Post-flight, data tapes were screened to search for flutter events using the engine manufacturer's Flutter Monitor. Preliminary results indicate the blade was flutter-free under all flight conditions where NSMS data were collected.

More-detailed analysis is planned for the near future at the engine manufacturer's home facility using an NSMS computer-based system. With the high-quality data obtained from all three probes and a good 1/rev signal, the analysis for the presence and characterization of any non-integral vibratory blade responses should be very complete. Additionally, even with only three sensors, it may also be possible to glean a considerable amount of information on the fundamental resonant responses under actual flight conditions.

The ability to validate blade vibratory responses during actual flight reduces the probability that HCF-susceptible blades will be placed into production. Three NSMS flight programs have been conducted in this specially outfitted F-15 aircraft (77-139) over the past several years on F100-220 engines to aid in HCF blade failure investigations and/or to validate blade redesigns. Currently, it is undergoing major overhaul. It is anticipated that the capability to fly and collect NSMS data will be retained in the aircraft when it returns to flight test service.

Participating Organizations: Pratt & Whitney, Honeywell Engines and Systems, Arnold Air Development Center (AEDC)

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Woodrow Robinson
Pratt & Whitney
M/S 723-10, P.O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-4809
Fax: (561) 796-1442
Email: robinsw@pwfl.com

3.1.2 Alternate Tip Sensors

FY 97-00

Background: As part of the Fourth Generation NSMS development effort, a study of alternate (i.e., non-optical) NSMS sensors has been initiated. The motivation for this study arises principally from problems associated with applying optical sensors, namely installation complexity and susceptibility, to optical contamination. These problems are of paramount importance in flight test and engine health monitoring applications (but are of less concern in ground-based engine testing). A sensor capability specification was prepared with input from the members of the Fourth Generation NSMS design team. This sensor specification defines the requisite characteristics of sensors to be used for engine health monitoring and Third and Fourth Generation NSMS applications. This sensor specification was used as a basis for evaluating the suitability of alternative sensor technologies for Fourth Generation NSMS applications.

Recent Progress: Over the past year, the literature search to identify alternate NSMS sensor technologies suitable for NSMS applications has continued. A full report will be written on this subject in fiscal year 2000.

Participating Organizations: Rolls Royce Allison

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Thomas Bonsett
Rolls Royce Allison
Speed Code W03A, P.O. Box 420
Indianapolis, IN 46206-0420
Phone: (317) 230-3448
Fax: (317) 230-4246
Email: tbonsett@iquest.net

3.1.3 Enhanced Data Processing Capability for Generation 4 & 5 NSMS Development

FY 99-01

Recent Progress: A Design Review was conducted on in May 1999 in Albuquerque. All of the tasks were reviewed. However the focus was on software documentation. No major problems were uncovered. Arnold Air Development Center (AEDC) participated in the review. Work on the Blade Timing Generator (BTG) and Blade Deflection Signal Processing (BDSP) is proceeding well. Production version BTG cards are being fabricated. The software documentation is complete, and sign off has occurred.

Participating Organizations: Arnold Air Development Center (AEDC)/Sverdrup, Honeywell Engines and Systems, Rolls Royce Allison

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Henry Jones
Arnold Air Development Center/Sverdrup
1103 Avenue C, M/S 1400
Arnold AFB, TN 37389-1400
Phone: (931) 454-7750
Fax: (931) 454-6187

3.1.4 Spin-Pit Validation of NSMS

FY 99-01

Recent Progress: Discussions with the Navy are underway to incorporate NSMS into its spin-pit test instrumentation. In preparation, NSMS Generation 3 light probes have been loaned to the Naval Postgraduate School (NPS). The research effort is focused on a joint project to evaluate eddy-current excitation and to develop measurement techniques and expertise required in full-scale HCF-related spin tests. Hood Technology Corporation (HTC) will conduct excitation tests in a research-dedicated spin pit facility at NPS. The test article, an F119 integrally bladed rotor (IBR), was received from Pratt & Whitney early in early August. Discussions were held on the design of possible test configurations, and two candidate arrangements will now be detailed.

Effort has concentrated, very successfully, on the development of an HCF measurement capability. The power supplies for a four-channel laser-light probe system were completed, and the probes were installed on and used to observe rotor blade vibrations in a large, low-speed multistage compressor. After verifying the system using an oscilloscope, two probes were used with one HTC "BVM Interface Board" and one National Instruments PCI Counter Board, to record time-of-arrival (NSMS) data. Labview software, also from HTC, was used in the acquisition. Data reduction using Matlab is planned. A second interface board will allow the simultaneous acquisition from all four probes.

Preliminary testing in the spin pit facility is continuing using a larger (M1 turbine) rotor. The goals are to refine shaft orbital displacement measurements to enable in-situ trim balancing, and to demonstrate unsteady strain measurement capability. The order was placed for a 16 (unsteady)/32-channel VXI/PC high-speed data acquisition system for strain gages. The machining of hardware to improve the 1/rev trigger sensor was completed. Also, components of an automatic speed-control system for the facility were delivered from Barbour-Stockwell. Installation of the automatic system will be scheduled when the present test goals are achieved.

Participating Organizations: Air Force Research Laboratory (AFRL), Navy

Points of Contact:

Government
Mr. Raymond Shreeve
Naval Postgraduate School
699 Dyer Rd., Room 137
M/S AA/SF Monterey, CA 93943-5106
Phone: (831) 656-2593
Fax: (831) 656-2864
Email: shreeve@aa.nps.navy.mil

3.1.5 High-Temperature NSMS Sensor Development

FY 00-01

Background and Plans: NSMS sensors do not currently have the high-temperature capability necessary to adequately monitor high-pressure turbine (HPT) blades in the engine environment. The purpose of the project is to develop high-temperature probes to interface with the existing Generation 4 NSMS signal processing hardware. Light probes for ground test applications and Eddy Current probes for Engine Health Monitoring will be investigated. A major emphasis of this project will be balancing the increased temperature capability with sensor life and accuracy.

Participating Organizations: Air Force Research Laboratory (AFRL)

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

3.2 Environmental Mapping System

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, lack of structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the tasks described below is to develop an optical pressure and temperature measurement system to non-intrusively measure the dynamic pressure and temperature distribution over the surface of the blade.

3.2.1 Pressure/Temperature Sensitive Paint (PSP/TSP)

FY 95-02

Recent Progress: Over the past year, extensive work has been done to improve the processing of PSP images. The extremely labor-intensive post processing will soon be completely automated, saving hundreds of man-hours. To improve the paint formula, we re-engineered the binding matrix supporting the luminophores. We also researched other illumination techniques and developed a new reference paint that would remove one time-consuming step from our data acquisition routine. Overall, we estimated a ten-fold improvement was made to the PSP measurement technique.

Over the past year we have experienced significant slippage in our Research Agenda. A year ago, the next major milestone was a compressor test at the Compressor Research Facility (CRF). Unfortunately, the CRF experienced repeated obstacles that caused postponement of the test until late August 1999, over a year behind the original schedule. Details of this test are described below.

Compressor Test

Figure 27 shows a photograph of the test setup. The PSP system consists of a charge-coupled device (CCD) camera, a laser for illumination, a timing circuit to sync and freeze the blade motion, and the painted blades. In the photo you see the reference paint (pink), the pressure paint (yellow), and the temperature paint (white).

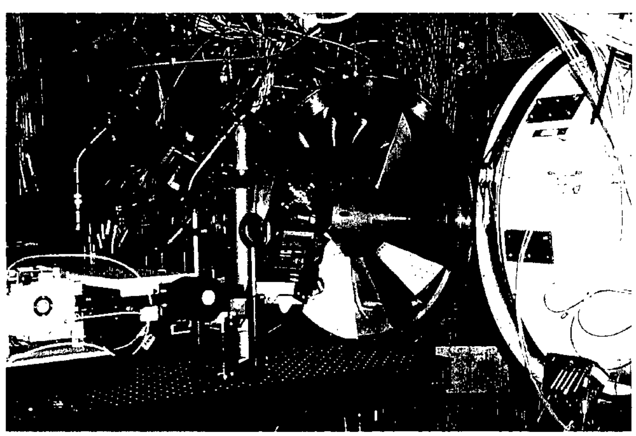


FIGURE 5. PSP Test Setup (ISP – Pink, TSP – White, PSP – Yellow).

Prior to PSP application, the engine-inlet surface was cleaned with alcohol and a lint-free cloth. The surrounding area was masked to prevent overspray. A white basecoat was applied and allowed to dry for about one hour prior to sol-gel deposition. Finally, registration (fiduciary) marks were drawn on the painted surface in a grid formation, and the precise locations were determined using a soldering gun and a coordinate mapping system (CMS). The soldering gun burned the paint locally so it would not luminesce. Hence, these points appeared as black spots in the data images. These control points allow reference images to be registered and accurately ratioed with the spatially distorted images acquired at test conditions. Data were acquired for all paints at 68% Nc and 85% Nc at both the near-stall and peak-efficiency operating conditions. Over-the-rotor kulite data and distortion data were also acquired relative to PSP data. All data is currently being processed and evaluated.

Participating Organizations: ISSI

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Jeffrey Jordan
ISSI
2786 Indian Ripple Rd.
Dayton, OH 45440-3638
Phone: (937) 252-2706
Fax: (937) 656-4652
Email: jordan@ward.appl.wpafb.af.mil

3.2.1.1 Pressure Sensitive Paint (PSP): Improved Dynamic Response

FY 97-98

Background: Characterizing the transient response of PSPs to unsteady pressure flows is a critical aspect in understanding HCF events. A group led by B. Carroll previously developed an apparatus capable of delivering a step change in pressure, and reported response times for proprietary PSP formulations tested on the order of one second. In previous work from our group, a pressure-jump apparatus was constructed and used to measure PSP response times on the order of one millisecond.

Recent Progress: A calibration chamber was constructed to quantify the dynamic-response characteristics of the PSPs. In this approach, continuous wave output (450 nm) from an array of 73-blue photodiodes is used to excite a PSP-coated coupon that is fixed within a calibration cell. The resulting luminescence is detected using a photodiode. Driving a 60-Watt piezoelectric speaker driver at frequencies ranging from 100 Hz to ca. 300 kHz modulates pressure within the cell. Comparison of the intensity modulation to the drive frequency determines the temporal response of the PSP.

Figure 28 presents preliminary high-frequency-response data for a sol-gel-based PSP (- - - -) and the associated speaker-drive function (——). Currently, design-configuration changes are being implemented to allow simultaneous acquisition of transducer and PSP data. This will provide data necessary to probe PSP high-frequency response based on phase-angle delays between drive and response signals. It is clear from these data, however, that the PSP is tracking the 0.2-psi pressure modulation (about ambient) at 5.7 kHz. Current efforts focus on increasing the frequency response of the sol-gel-based PSPs, while maintaining pressure sensitivity suitable for HCF-related applications.

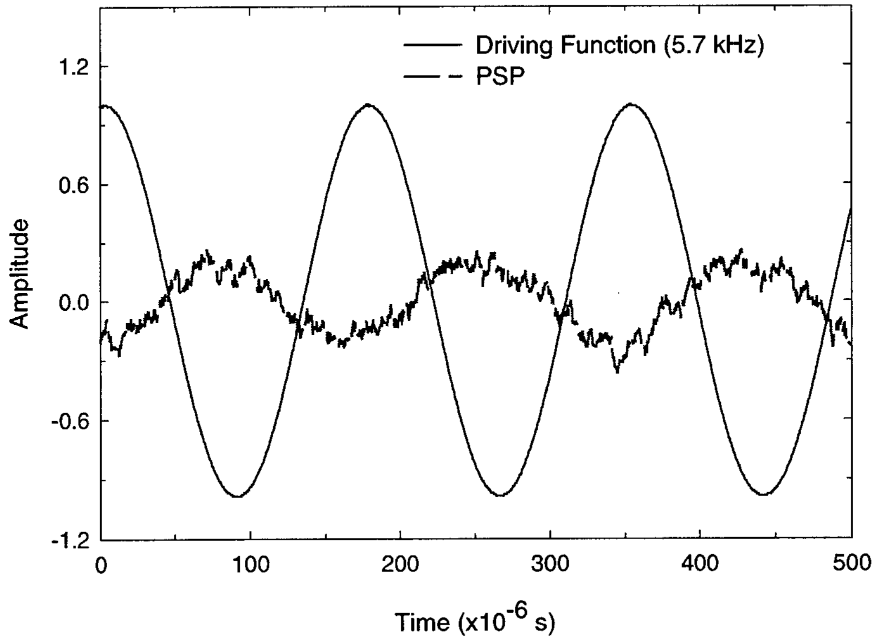


FIGURE 28. PSP Response to a 0.2-psi Pressure Modulation at 5.7 kHz

Future research efforts will focus on the development of an inorganic PSP. Through the synthesis of probe molecules, mechanisms that determine the temperature and pressure capabilities of the oxygen-sensing species used in PSPs can be controlled.

Participating Organizations: ISSI

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Jeffrey Jordan
ISSI
2786 Indian Ripple Rd.
Dayton, OH 45440-3638
Phone: (937) 252-2706
Fax: (937) 656-4652
Email: jordan@ward.appl.wpafb.af.mil

3.2.1.2 Pressure Sensitive Paint: Light Emitting Diodes (PSP-LEDs)

FY 99-00

Background: The objective of this task is to shed light on critical issues required to ensure that pressure-sensitive paints (PSPs) and thermographic phosphors (TPs) can be used in high cycle fatigue studies of turbomachinery. The critical issues to be addressed include probe miniaturization and paint/phosphor improvements.

Probe miniaturization requires the development of compact excitation and detection systems. Current excitation sources are heavier, bulkier, more labor-intensive, and costlier than those desired for certain Advanced Turbine Engine Gas Generator (ATEGG) and Joint Turbine Demonstrator Engine (JTDE) demonstrations. In this project, the use of high-power blue LEDs that hold promise for significant improvements in current methods of excitation for both PSPs and TPs will be investigated.

Pressure sensitive paint improvements in time response, survivability, and sensitivity at higher pressures and temperatures, and the use of thermographic phosphors as a means of temperature correction for the PSPs, are also being investigated.

Recent Progress: A prototype LED illumination system was developed and demonstrated in a recent engine test. This test was conducted with Pratt & Whitney through a Cooperative Research & Development Agreement. The deployment of PSP measurements in an engine test cell required two phases of setup: 1) model preparation and painting and 2) instrumentation installation and alignment. The following subsections summarize the steps taken to deploy PSP measurements within an engine test cell at Pratt & Whitney, East Hartford, Connecticut.

The internal diameter of the bell mouth tested was approximately 75 inches (1.9 m). The circular structure located upstream of the engine inlet (wagon wheel) was used to mount thermocouples. For this test, two symmetrical regions of the upper surface of the bell mouth were painted with a low-speed sol-gel-based PSP. A large quantity of data was acquired from this test, which was considered to be a success. Pratt & Whitney is now processing the data and writing a final report. This effort is scheduled to finish in the summer of 2000.

Participating Organizations: ISSI, Pratt & Whitney

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Jeffrey Jordan
ISSI
2786 Indian Ripple Rd.
Dayton, OH 45440-3638
Phone: (937) 252-2706
Fax: (937) 656-4652
Email: jordan@ward.appl.wpafb.af.mil

3.2.2 Comparison Testing/Air Etalons

FY 96-00

Background: The Air Etalon is a sensing concept based on Fabry-Perot interferometry. In its simplest form, a Fabry-Perot etalon consists of two mirrors separated by a certain distance, or gap. When light is incident upon an etalon, optical interference occurs; at certain optical resonance frequencies, virtually all of the incident light is transmitted through the etalon, while at other frequencies most of the light is reflected. The optical resonance frequency depends on the optical path length between the two mirrors—which of course is dependent upon the index of refraction of the material used in the gap between the two mirrors. This fact can thus be utilized to design a pressure sensor based on a Fabry-Perot etalon where the change in optical resonance is monitored as the optical path length changes as a result of changes in pressure. In this effort, both solid and air-gap etalons have been investigated as pressure sensors.

Recent Progress: In September 1999, we re-initiated our aerogel etalon pressure sensor effort, which had been hampered by funding problems. There are two key components of the program – fabrication of the aerogel sensors and measurement of their pressure sensitivity. For the fabrication component, we have identified a small company (NZ Applied Technologies) that is capable of coating aerogels with the requisite mechanical and geometric properties onto substrates. We have reached an agreement with them whereby they will do the required coating work for us in an iterative manner as we successively redesign the coating properties according to feedback from our measurements.

In order to accomplish rapid screening of the pressure sensitivity of fabricated devices, we have set up two experimental measurement systems. One system is capable of determining the transmission and reflection from an etalon as a function of optical wavelength and static pressure. This will be used for initial screening of etalon optical properties and static pressure sensitivity. The second laser-based system is capable of determining the transmission and reflection from an etalon at a fixed wavelength with fast time response. This will be used to assess the time response of the pressure signal from fabricated etalons that have passed the static pressure sensitivity screening tests.

In the coming months we will fabricate and test etalons according to the procedure outlined above. Task completion is projected for the summer of 2000.

Participating Organizations: Rolls Royce Allison, General Electric Corporate Research & Development

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Thomas Bonsett
Rolls Royce Allison
Speed Code W03A, P.O. Box 420
Indianapolis, IN 46206-0420
Phone: (317) 230-3448
Fax: (317) 230-4246
Email: tbonsett@iquest.net

3.2.3 Thin-Film Garnet

FY 99-01

Background: The objective of this project is twofold: (1) to investigate a new surface pressure-sensing concept, and (2) to develop a compact fluorescence detection system. The concept utilizes forester energy transfer, a process that can occur in conjunction with photoluminescence, and is very sensitive to the distance between an energy donor and an energy acceptor. Because of this spatial sensitivity, it has been exploited as a "molecular caliper." Under this effort, the use of Forester energy transfer to measure the surface pressure of the thin-film garnet is being investigated. In addition, a compact fluorescence detection system will be developed whose ideal application is the acquisition of data from either the thin-film garnet, pressure paint, or thermographic phosphor.

Recent Progress: Over the past year, we have explored the use of electronic energy transfer as a pressure transducer. We are looking for surface measurement capability in the range of 0.6 to 3 atm as an alternative to pressure-sensitive paint. The rate of electronic energy transfer, of the Förster type, is extremely sensitive to the distance between the energy donor and energy acceptor species, and it is this phenomenon that we exploit in the advance of new pressure-sensitive materials. The selection of the energy transfer species and the host matrix is guided by the operational requirements of temperature and pressure inside the engine; inorganic or atomic species embedded in a ceramic or glass-like host was our initial choice. The host material must be selected with care as the material must be reasonably compliant to respond to the operational pressures, yet be robust to withstand the operational temperatures and corrosive environment. Some oxide glasses or sol-gel compounds may be the best option.

A theoretical model has been established to show the relationship between the material properties and the sensor performance. The Cr^{+} - Nd^{3+} energy transfer system was identified as a potential pressure sensor. We continue to investigate host materials for optimal performance. Many host-material requirements have been identified such as acceptable Young's Modulus, and the material structure and orientation. The aerogel host matrix selected for the etalons described in Section 3.2.2 may also be well suited for this energy-transfer concept. Preliminary calculations show that this innovative technique has the potential to measure pressures in the desired range with a resolution of 0.029 atm.

Work continues in this area and is expected to be complete by March 2001.

Participating Organizations: TACAN Corp.

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Brian Sullivan
TACAN Corp.
2330 Faraday Ave.
Carlsbad, CA 92008
Phone: (760) 438-1010 ext. 3340
Fax: (760) 438-2412

3.2.4 Spin-Pit Validation of Paint/Optical Pressure Mapping

Recent Developments: This task has been redefined. An Advanced Turbine Engine Gas Generator (ATEGG) test will be conducted in fiscal year 2005 rather than a spin-pit test. We are currently working on the contract change to accommodate this task with the General Electric / Allison Advanced Development Company team.

Participating Organizations: Rolls Royce Allison, General Electric Corporate Research & Development, ISSI, TACAN

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Thomas Bonsett
Rolls Royce Allison
Speed Code W03A, P.O. Box 420
Indianapolis, IN 46206-0420
Phone: (317) 230-3448
Fax: (317) 230-4246
Email: tbonsett@iquest.net

3.3 *Improved Conventional Sensors*

To date, prediction of aerodynamic forcing functions has been difficult or impossible due to lack of Computational Fluid Dynamics (CFD) fidelity, structural modeling accuracy, instrumentation effects, and insufficient characterization of instrumentation installation effects. The purpose of the projects described below is to improve the lifetime and performance of conventional sensors (eddy current/strain gages) for transition into engine health monitoring applications.

3.3.1 Non-Optical NSMS Sensor Development (Eddy Current)

FY 99-01

Recent Progress: The eddy current sensor (ECS) was tested as part of the JSF Seeded Fault Engine Test Program at Pratt & Whitney in West Palm Beach, Florida in 1999. Under this program, two F100 engines with seeded faults were used to evaluate candidate prognostics and health management technologies (PHM) for future aircraft engines.

The ECS build 3 system was evaluated during this test. This system consisted of seven ECS sensors installed into the engine case over the first-stage fan, test cell based electronics, and personal computer (PC) data acquisition and processing. In the test, the ECS measured blade clearances, deflections, and speed. This data was used to estimate clearance closedown, blade vibration, and foreign object impacts. The testing was successful, and as a result, the ECS has been boarded on two stages of an engine currently under development. Figure 29 shows an example of the ECS vibration estimation for a second torsion mode on the first-stage fan driven by 21E. Figure 30 shows an example of clearance closedown for the same stage for all blades. Last, Figure 31 shows an example of foreign object impact, identified by blade number.

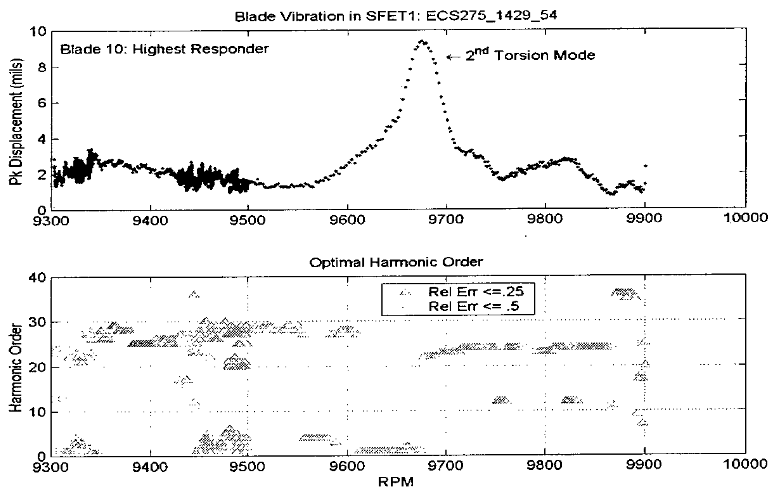


FIGURE 29. Eddy Current Sensor Vibration Estimate, Seeded Fault Engine Test (SFET#1), Blade 10, 2nd Torsion Mode

Later in the year, the ECS build 4 system was completed. This system has real-time processing and a sensor with a higher standoff capability that allows the sensor to be recessed into the engine case, below the rubstrip. This build 4 system will be tested in early 2000.

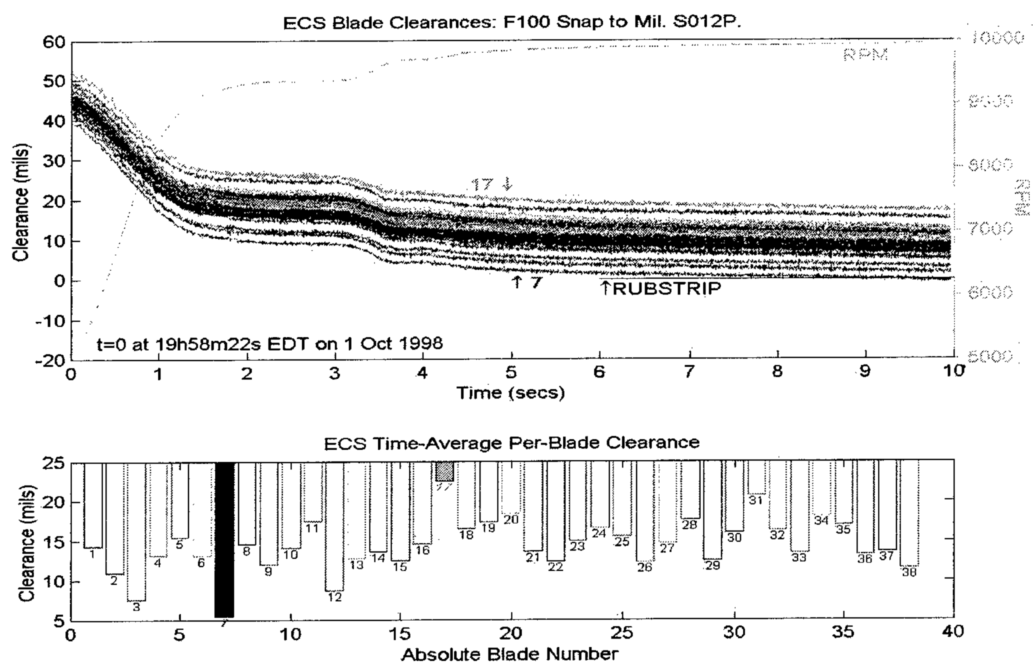


FIGURE 30. Eddy Current Sensor Clearance Closedown, SFET#1, All Blades Shown

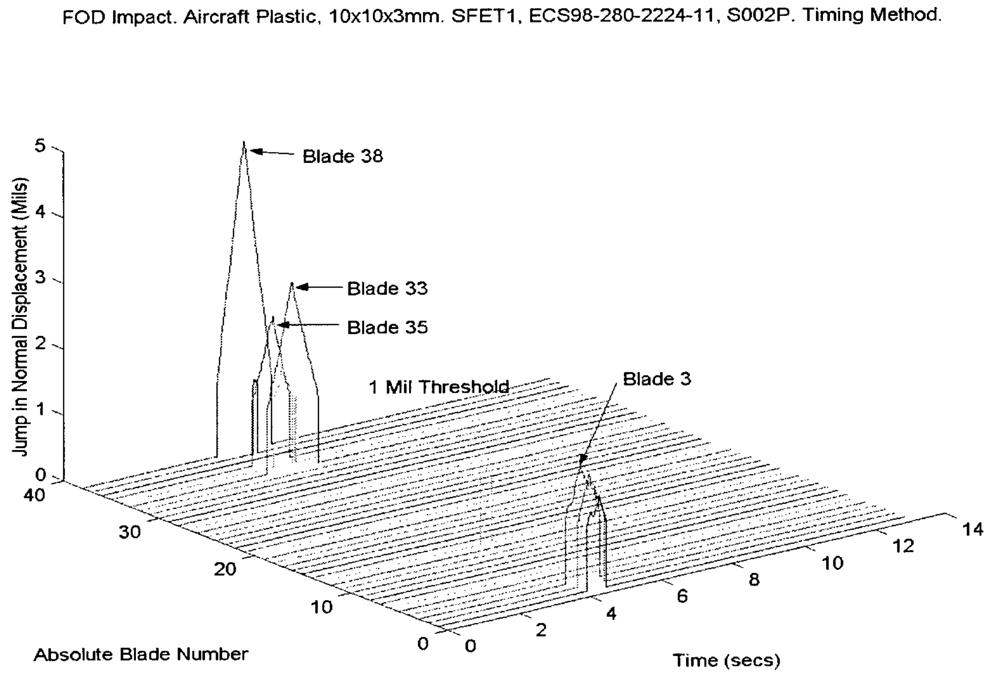


FIGURE 31. Eddy Current Sensor Foreign Object Impact Detection, SFET#1, Composite Material (10mm x 10mm x 3mm)

Participating Organizations: Pratt & Whitney

Points of Contact:

Government
Ms. Kelly Navarra
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: kelly.navarra@wpafb.af.mil

Contractor
Mr. Robert Morris
Pratt & Whitney
M/S 707-22, P.O. Box 109600
West Palm Beach, FL 33410
Phone: (561) 796-5981
Fax: (561) 796-7454
Email: morrisrj@pwfl.com

3.4 Development of Long-Life, Less-Intrusive Strain Gages

The following sections describe NASA's efforts to develop long-life, less-intrusive strain gages.

3.4.1 Advanced Thin-Film Dynamic Gages

FY 95-01

Background: The objective of this program is to develop and utilize the already successful NASA PdCr static strain gages in a thin-film form for dynamic strain measurement. Thin-film sensors are fabricated directly onto the test surface using vapor deposition and lithography techniques. They do not require additional bonding agents such as adhesive or cements, and are in direct contact with the test surface. Thin-film sensors in general have a thickness on the order of a few micrometers (μm) which are much thinner than the commonly-used sensor wires. They have fast response times (in milliseconds), add negligible mass to the test surface, and create minimal disturbance of the gas flow over the surface. Consequently, thin-film sensors have minimal impact on the thermal, strain, and vibration patterns that exist in the operating environment, and provide a minimally intrusive means of accurate measurement of surface parameters.

Recent Progress: During the past year, the PdCr thin-film dynamic strain gages were fabricated on nickel-based superalloy and ceramic based cantilever bars. The dynamic response of these gages was characterized in a newly set up shaker facility under ±2,000 microstrain, 1,000 Hz to 700C. The lifetime of this PdCr-based thin-film gage were compared to the conventional foil strain gages at the room temperature. Only two of the six commercial foil gages (33%) survived after only 3.5 minutes dwell at 1,100 Hz, while all the PdCr gages (4) remained functional after 50 minutes dwell exposure. The test at high temperature was stopped due to the test bar cracking and breaking, although no gage delamination was found. Meanwhile, Honeywell Engines and Systems is applying these PdCr thin-film strain gages to the fourth-stage gamma blades of Pratt & Whitney demonstrator core XTC67/1. The engine test is scheduled for the fall of 2000. (See section 8.2.5.)

Participating Organizations: NASA Glenn Research Center, Honeywell Engines and Systems

Points of Contact:

Government
Dr. Jih-Fen Lei
NASA Glenn
Cleveland, OH
Phone: 216-433-3922
Fax: 216-433-8643
Email: jih-fen.lei@grc.nasa.gov

Contractor
Harvey Niska
Honeywell Engines and Systems
Phoenix, AZ
Phone: 602-231-7584
Fax: 602-231-2018
Email: h.niska@alliedsignal.com

3.4.2 Advanced High-Temperature Thin-Film Dynamic Gages

FY 96-01

Background: The objective of this program is to develop advanced thin-film strain gages with increased temperature capability. This work is proceeding under a grant with the University of Rhode Island (URI) and is based on a ceramic sensing material, Indium Tin Oxide (ITO).

Recent Progress: During the past year, the characteristics of the ITO strain sensor were evaluated up to 1,450°C (2640°F). A reproducible piezoresistive response was measured with a drift rate as low as 0.0018%/hr at 1,450°C. The gage factor of the gage remained relatively constant from room temperature to 1,100°C with a maximum gage factor of 21.8 at 1,190°C (2,170°F). The dynamic response and lifetime of the gages were characterized in a shaker facility under ±300 microstrain, 2,100 Hz, to T=700°C. This ITO-based strain sensor failed after an 18 million cycle test at room temperature, five thermal cycles to 1,100°C, and then 11 million cycles at 700°C. The failure was due to the detachment of lead wires from the thin-film sensor.

Participating Organizations: NASA Glenn Research Center, University of Rhode Island

Points of Contact:

Government
Dr. Jih-Fen Lei
NASA Glenn
Cleveland, OH
Phone: 216-433-3922
Fax: 216-433-8643
Email: jih-fen.lei@grc.nasa.gov

Contractor
Prof. Otto Gregory
University of Rhode Island
Kingston, RI
Phone Number: 401-874-2085
Fax Number: 401-874-1180
Email: gregory@egr.uri.edu

3.4.3 Spin-Pit Validation of Strain Gages and Spin-Pit Validation of High-Temperature Strain Gages

Recent Developments: These two tasks have been eliminated, as the Pratt & Whitney XTC67/1 test will be sufficient to show the gage capability.

3.5 Conclusion

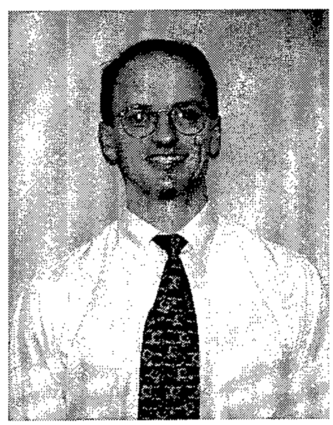
The Instrumentation Action Team demonstrated a 5x improvement in the accuracy of light probes—a major advancement in Non-Interference Stress Measurement System (NSMS) capability—and increased the dynamic response characteristics of Pressure Sensitive Paints (PSPs) by a factor of six. These characteristics are now adequate for many fan component applications. The light probe developed for the Gen IV NSMS outperforms current eddy current and capacitance probe technology. The advanced NSMS has been tested in flight on an F100 engine in an F-15 aircraft. Having the ability to validate vibratory responses during actual flight reduces the probability that HCF-susceptible blades will be placed in production. Out-year efforts are continuing to develop the technology necessary to effectively apply NSMS to small engines. Out-year efforts for PSP include the demonstration of high-response data acquisition.

4.0 COMPONENT ANALYSIS

BACKGROUND

The Component Analysis Action Team (Component Analysis AT) is responsible for fostering collaboration between individual HCF component analysis efforts, with the overall goal of combining with the Instrumentation and Forced Response ATs to better determine alternating stresses to within 20%. The Component Analysis AT provides technical coordination and communication between active participants involved in HCF component analysis technologies. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Component Analysis AT members meet as required (estimated quarterly) to review technical activities, develop specific goals for component analysis projects, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Component Analysis AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in component analysis technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

ACTION TEAM CHAIRS



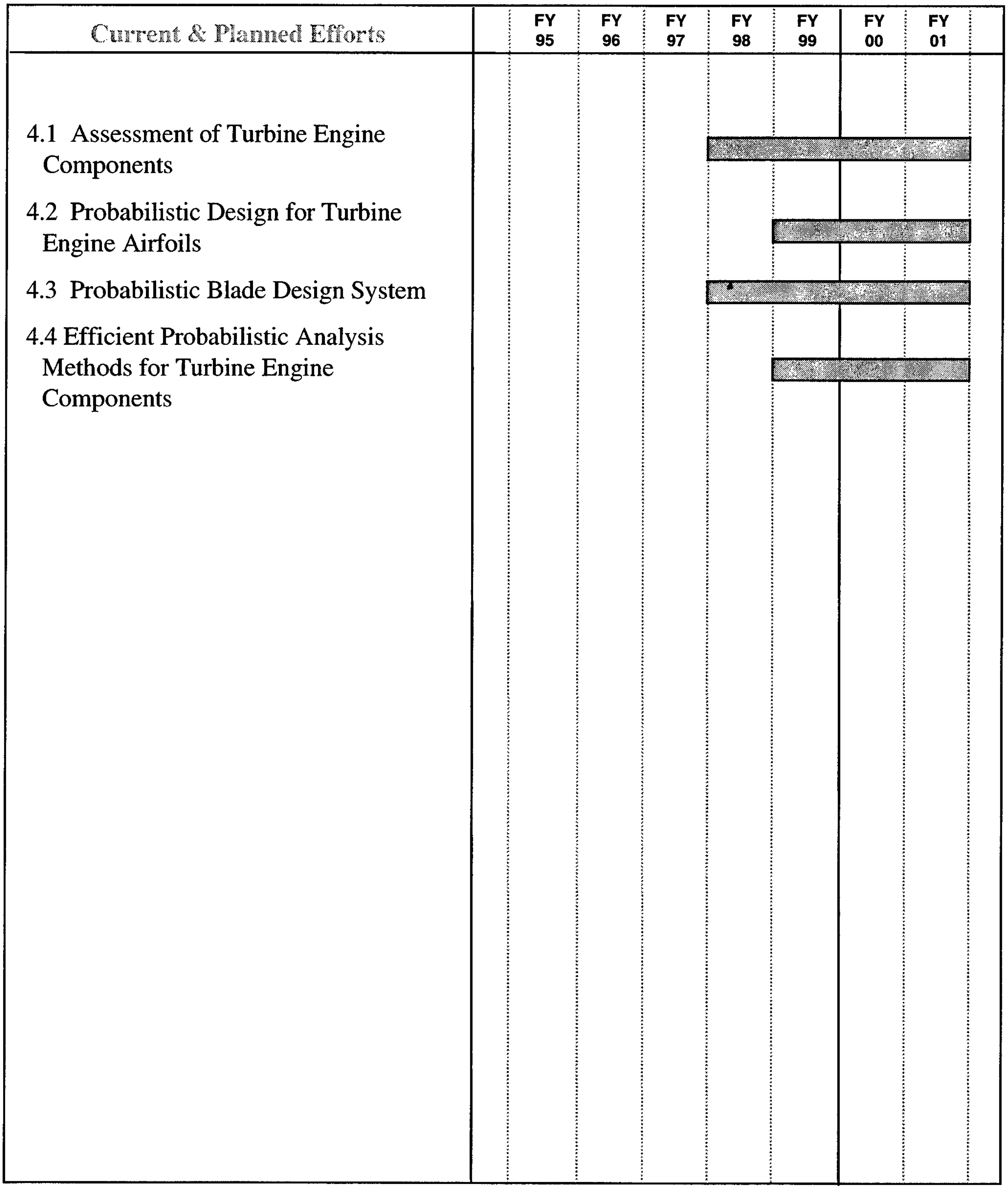
Chair
Mr. Paul J. Zimmerman
Naval Air Systems Command
AIR 4.4.7.2 Bldg. 106
22195 Elmer Road, Unit #4
Patuxent River, MD 20670-1534
Phone: (301) 757-0500
Fax: (301) 757-0562
Email: ZimmermanPJ@navair.navy.mil

Co-Chair
Mr. Jeffrey M. Brown
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: Jeffrey.Brown@wpafb.af.mil

INTRODUCTION

The following pages summarize the schedules, backgrounds, and recent progress of the current and planned projects managed by this action team.

Component Analysis Schedule



4.1 Assessment of Turbine Engine Components

FY 98-01

Background: Current design practice for turbine engine components includes methods for modeling the structural behavior of complicated interfaces, such as bolted connections and snap rings. These interfaces are difficult to integrate into an overall structural model. The objective of this effort is to develop accurate and reliable methods and practices for modeling nonlinear interfaces. Both linear and nonlinear analysis techniques are required. In detailed stress and life prediction analysis, the analyst may need to consider the effects of pretension, contact, and friction, and a reliable nonlinear model of the connection is appropriate. For substructured analyses, and prediction of natural frequencies, the joint model must be linearized to be usable. The linearized model may contain some evidence of the nonlinearity, such as properties that depend upon preload.

To obtain the needed data, detailed finite element analyses (FEAs) of bolted connections are to be performed to determine effective properties, which are then to be used in component-level structural analysis. In general, the process of performing a detailed FEA involves the following steps:

A refined model of the joint is analyzed in detail, including the effect of pretensioning and contact. At several preload levels, several elementary loading conditions are analyzed to obtain effective stiffness characteristics for the joint. The resulting stiffness parameters may be used to define joint properties in a larger model. Once a solution has been obtained in the system-level model, stress information can be obtained for the joint based upon the original analysis of the joint model.

Figure 32 shows a finite element model of a joint between two compressor stages, and the detailed stress field in and around the bolted connection. This model is being used for validation of stress analyses performed using the simplified joint model, which is much smaller and may be analyzed with linear solution techniques.

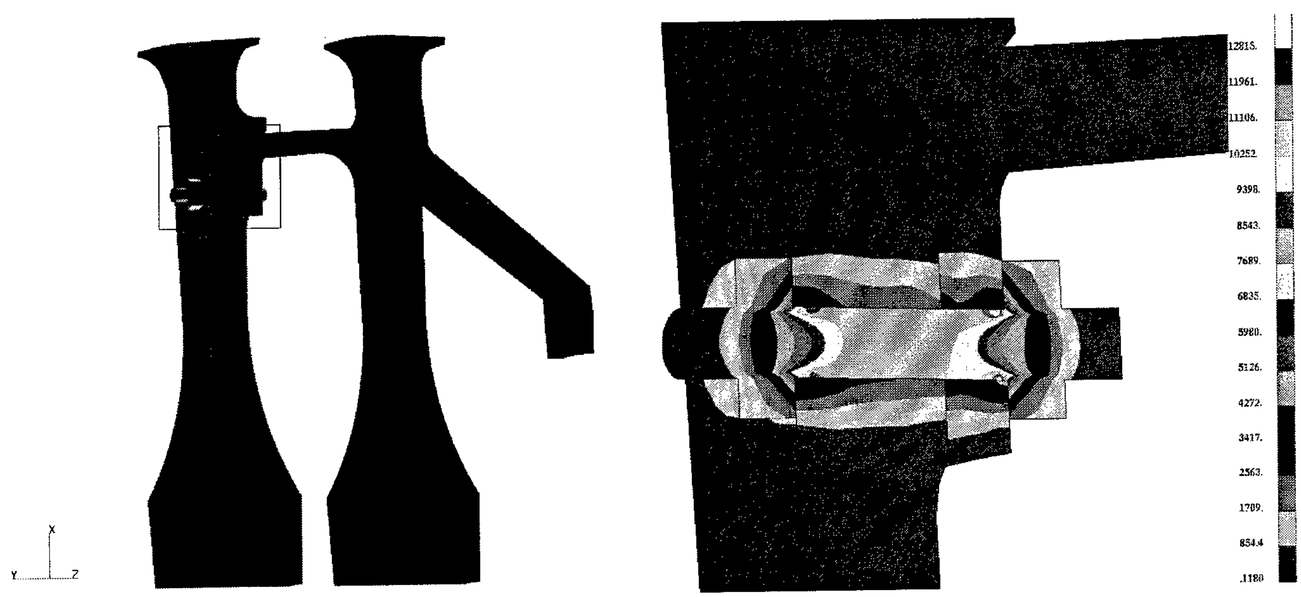


FIGURE 32. Finite Element Model of a Joint Between Two Compressor Stages

Recent Progress: Recent efforts have focused on performing detailed finite element analyses of bolted connections to determine effective properties, which are then used in component-level structural analysis. Investigations into the accuracy of commonly used finite element types for natural frequency prediction have been extended to curved and twisted shapes, for which analytical solutions are not available. An error estimation code has been developed, and presently is being used to correlate several error estimation methods with observed frequency errors in finite element meshes of varying refinement.

Participating Organizations: University of Dayton Research Institute

Points of Contact:

Government
Mr. Jeffrey M. Brown
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: Jeffrey.Brown@wpafb.af.mil

Contractor
Dr. Robert A. Brockman
University of Dayton Research Institute
300 College Park
Dayton, OH 45469-0110
Phone: (937) 229-3484
Fax: (937) 229-4251
Email: brockman@udri.udayton.edu

4.2 Probabilistic Design for Turbine Engine Airfoils

FY 99-01

Background: The objective of this task is to develop a probabilistic design system (Fig. 33) that will integrate all the HCF technical areas and produce rigorous and efficient statistical methods for computational procedures, and that ultimately will improve blade life. Probabilistic models will be developed that incorporate refinements to the design process of gas turbine fan blades by the use of: (1) an efficient probabilistic framework for HCF predictions using advanced stochastic modeling concepts, (2) refined probabilistic modeling for complex space-time phenomena, (3) a probabilistic framework capable of handling highly nonlinear problems with a large number of variables and complex interactions, (4) an adaptive, multilevel, modularly-structured probabilistic implementation suitable for integration into industry's proprietary systems, and (5) an integrated probabilistic framework open to future technological developments.

Recent Progress: A contract with STI Technologies was awarded in May 1999. STI is currently planning for the stochastic modules and preparing for their verification. Preparation for such verification involves collaboration between STI and the four major engine companies, who will investigate the physics behind the stochastic distributions, prepare databases of major parameters, and subsequently undertake the verification studies. The major parameters involved will be selected from the results of a Delphi Study. This study will be conducted early in the project. It is anticipated that arrangements with subcontractors will be completed by mid-December 1999, after which the Delphi Study will follow. In addition, collaboration between STI and ARA has been initiated. Data relating to a bladed-disk arrangement has been provided by STI for the purpose of applying the code ProFES for prediction of failure probability.

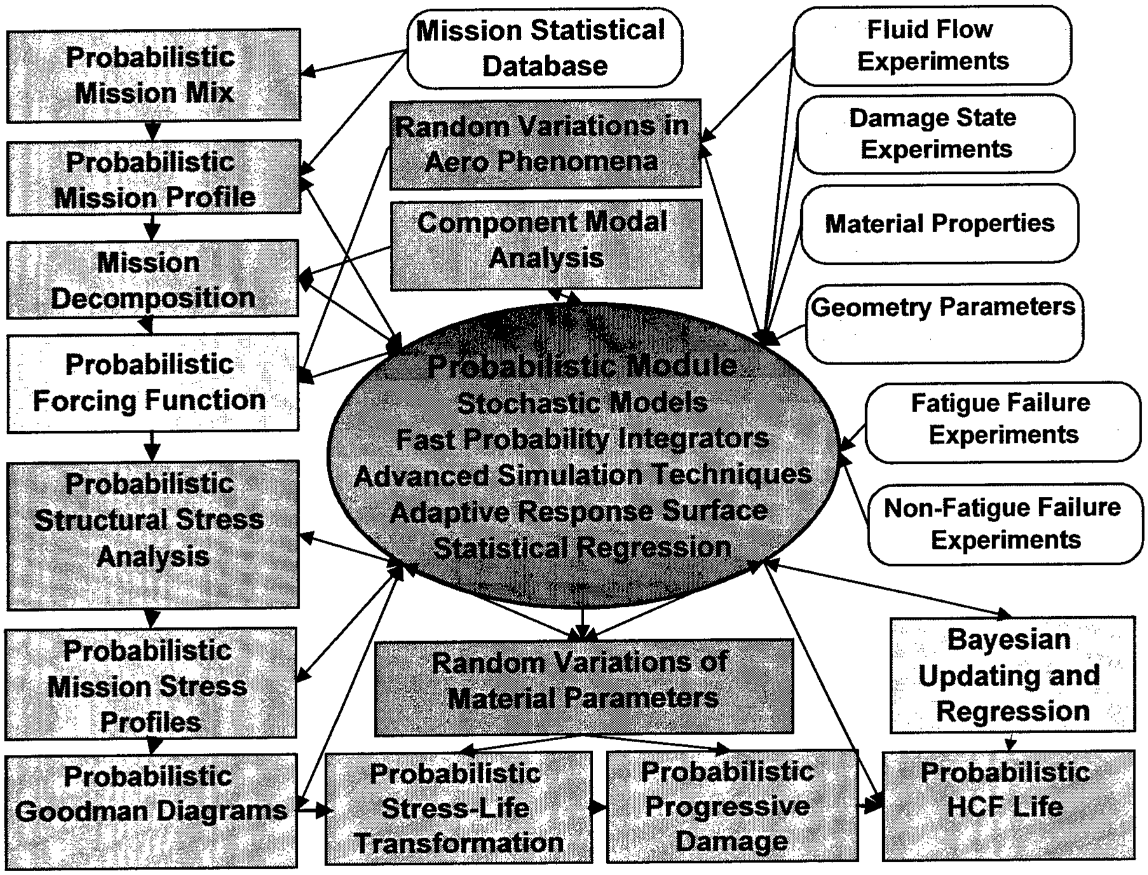


FIGURE 33. Probabilistic HCF Prediction System

Participating Organizations: Stress Technology Incorporated, General Electric, Pratt & Whitney, Allison Engine Co, Honeywell Engines and Systems, Virginia Polytechnic Institute.

Points of Contact:

Government
Mr. Daniel Thomson
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH
45433-7251
Phone: (937) 255-2081
Fax: (937) 255-2660
Email: Daniel.Thomson@wpafb.af.mil

Contractor
Mr. Neville Reiger
Stress Technology Inc.
1880 Brighton-Henrietta Town Line Rd.
Rochester, NY 14623
Phone: (716) 424-2010
Fax: (716) 272-7201
Email: nrieger@STI-Tech.com

4.3 Probabilistic Blade Design System

FY 98-01

Background: Probabilistic analysis capabilities are being investigated in the areas of response variability due to blade mistuning, fracture screening, and the effects of closely spaced modes. Application of these techniques to several blades will provide guidance for the incorporation of such capability into a mainstream blade design system.

Recent Progress: Blade-to-blade response variability due to mistuning is being investigated using the REDUCE computer code. (See Sections 5.1.3 & 5.1.4 for a description of REDUCE). Initial studies for an example bladed disk have shown the sensitivity of resonant response to depend on the type of mode, with the most sensitive being system modes in regions where blade-alone modes cross disk-alone modes. Least sensitive are disk-alone modes with blade-alone modes being medium in sensitivity. Investigations are now proceeding to include analysis of existing military fan blisks and bladed disks. Blade response from light probe and strain gage data from engine tests is being assembled for comparison with the analytical predictions.

Previous work in the area of fracture screening analyzed failure probabilities of internal flaws in rotating parts. This effort extends that work to consider failure probabilities of randomly placed and randomly sized surface flaws caused by foreign object damage (FOD). The existing probabilistic fracture mechanics software is currently being enhanced for these types of damage. Application of the method is focusing on the F110 family of stage-1 fan blades. Previously existing sources of FOD data pertinent to these blades are being examined to provide indicators of FOD frequency of occurrence, its spatial distribution and geometric characterization, and failure consequences of the flaws. These sources include field inspection and failure inspection reports. Assessments of the failure probability will proceed based on these flaw distributions.

Participating Organizations: GE Aircraft Engines / Allison Advanced Development Company

Points of Contact:

Government
Mr. Christopher Lykins
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH
45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: Chrisopher.Lykins@wpafb.af.mil

Contractor
Mr. Bill McAllister
GE Aircraft Engines
1 Neumann Way
Mail Drop A413
Cincinnati, OH 45215
Phone: (513) 243-3337
Fax: (513) 243-8091
Email: Bill.McAllister@ae.ge.com

4.4 Efficient Probabilistic Analysis Methods for Turbine Engine Components

FY 99-01

Background: Efficient and accurate methods for the reliability analysis of large-scale engine component models are the main goals of the project. Response surface methods are applicable when the number of random variables is very small. For practical engine components, there are potentially dozens of uncertain variables, and the designers need to use robust techniques that can accurately predict the failure probability with a minimum number of simulations. Under this research effort, methods are being developed that use function approximations to reduce the computational cost of simulations.

Recent Progress: Recently, methods have been developed based on Fast Fourier Transformation (FFT) techniques for accurately predicting the failure probability for highly nonlinear limit-states and non-normal distributions. To validate the concepts, several highly nonlinear analytical functions and structures modeled with truss and plate members will be considered with normal and lognormal distributions. The results obtained by using FFT will be compared with the Monte Carlo simulations.

Points of Contact:

Government
Mr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 256-5530
Fax: (937) 255-2660
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Ramana Grandhi
Wright State University
3640 Colonel Glenn Hwy
Dayton, OH 45435-0001
Phone: (937) 775-5090
Fax: (937) 775-5147
Email: rgrandhi@cs.wright.edu

4.5 Conclusion

The Component Analysis Action Team established a government/industry/university team to develop an HCF probabilistic design system that will integrate all the HCF technical areas, produce rigorous and efficient statistical methods for computational procedures, and improve blade life. The Team achieved agreement on the basic approach to probabilistic life-prediction system development. Efforts are underway with the lead integrating contractor and multiple engine companies. This team recently recognized successes achieved by the University of Dayton Research Institute in two areas: error estimation for finite element modeling, and interference fit modeling for finite elemental analysis.

5.0 FORCED RESPONSE PREDICTION

BACKGROUND

The responsibility of the Forced Response Prediction Action Team (FRAT) is to foster collaboration between individual HCF forced response efforts and the Instrumentation and Component Analysis ATs in order to determine alternating stresses to within 20%. The Forced Response AT provides a means for technical coordination and communication between active participants involved in HCF unsteady aerodynamics and blade response technologies. Annual technical workshops have been organized and workshop summaries are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Forced Response AT members meet as required to review technical activities, develop specific goals for forced response programs, and coordinate with the TPT and IAP. The Chairman (or Co-Chair) of the Forced Response AT keeps the TPT Secretary informed of AT activities on a frequent basis. This AT includes members from government agencies, industry, and universities who are actively involved in forced response technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate.

ACTION TEAM CHAIRS

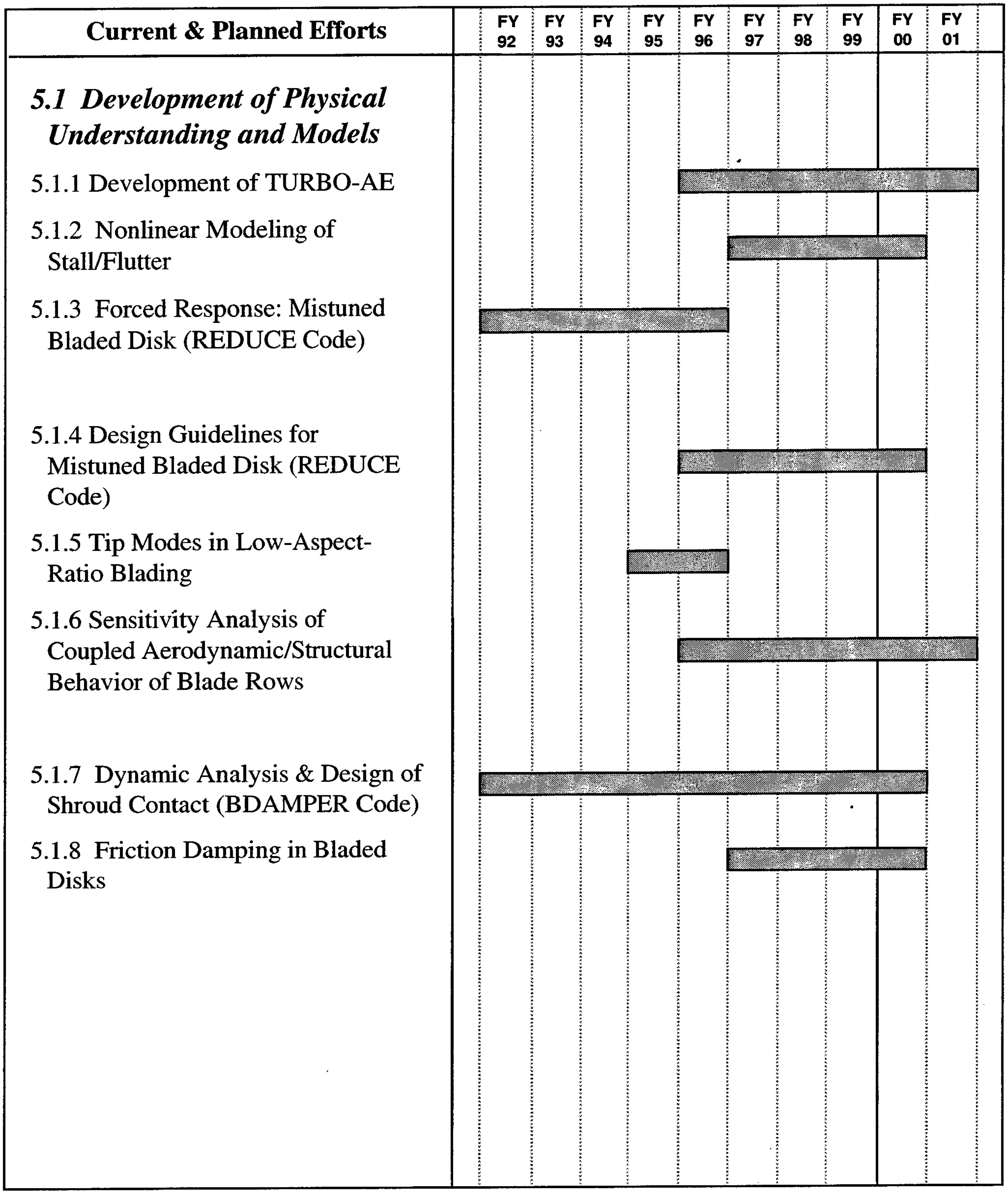
Chair
Dr. Charles J Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Co-Chair
Mr. George Stefko
NASA Glenn Research Center
Mail Stop 49-8
21000 Brookpark Road
Cleveland, OH 44135-3191
Phone: (216) 433-3920
Fax: (216) 977-7051
Email: stefko@lerc.nasa.gov

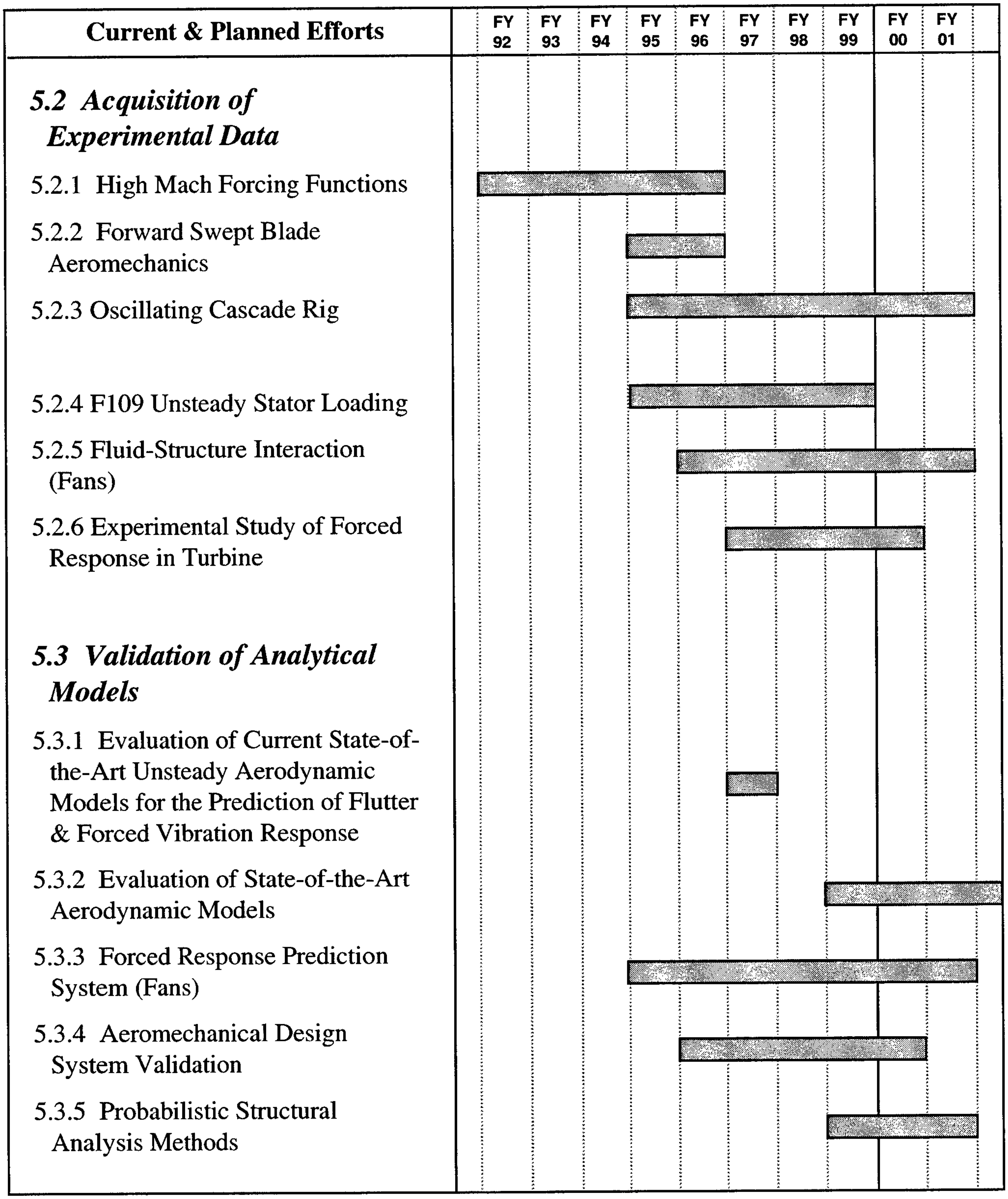
INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Forced Response Prediction Schedule



Forced Response Prediction Schedule (Cont'd)



5.1 Development of Physical Understanding and Models

Predicting forced response is difficult due to the lack of Computational Fluid Dynamics (CFD) fidelity and structural modeling accuracy. The purpose of the following projects is to develop the necessary modules for improved forced response prediction

5.1.1 Development of TURBO-AE

FY 96-01

Background: The TURBO-AE Propulsion Aeroelasticity code is based on a three-dimensional unsteady aerodynamic Euler/Navier-Stokes turbomachinery code called TURBO. The structural dynamics model of the blade in the TURBO-AE code is based on a normal mode representation. In the Flutter version of the TURBO-AE code, a work-per-cycle approach is used to determine flutter stability.

Recent Progress: The development of the Flutter version of the TURBO-AE code has been completed, and validation by industry is ongoing. The development of the Forced Response version of the TURBO-AE code has started. Future planned activities that have not yet been funded include multistage analyses and new turbulence models.

Participating Organizations: NASA Glenn

Points of Contact:

Government
Oral Mehmed
NASA Glenn Research Center
NASA Glenn Research Park
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-6036
Fax: (216) 977-7051
Email: oral.mehmed@lerc.nasa.gov

Contractor
Dr. Miland Bakhle and Dr. Rakesh Srivastava
University of Toledo
NASA Glenn Research Center
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-6037 (Dr. Bakhle)
(216) 433-6045 (Dr. Srivastava)
Fax: (216) 977-7051 (Both)
Email: Miland.Bakhle@lerc.nasa.gov
Rakesh.Srivastava@lerc.nasa.gov

5.1.2 Nonlinear Modeling of Stall/Flutter

FY 97-00

Background: The objective of this project is to investigate the use of reduced-order modeling (ROM) techniques to simulate linear and nonlinear stall flutter in cascades. Research will be conducted in three main areas: (1) the development of a time-domain, linearized Navier-Stokes analysis; (2) the development of an efficient eigenmode extraction code for large systems of equations; and (3) the development of reduced-order modeling techniques to model nonlinear unsteady flows, especially phenomena such as hard flutter boundaries and limit cycle behavior.

Recent Progress: Use of the Harmonic Balance technique for the nonlinear flow solver has been investigated. A frequency domain Proper Orthogonal Decomposition (POD) technique has been developed to compute basis vectors and linear ROMs of unsteady channel flow. These efforts are potentially much faster than conventional time-marching solutions and are computationally efficient. Using the POD technique, a nonlinear ROM will be developed for unsteady viscous flow in cascades. Analysis codes will be transitioned to industry through GUIde Consortium.

Participating Organizations: GUIde*, Air Force Research Laboratory (AFRL), NASA

(*) About GUIde: *The GUIde Consortium was formed in 1991 when a number of companies joined with Carnegie Mellon University and Purdue University to form a partnership that would result in improved technology for understanding the problem of forced response in turbine engines. The acronym GUIde stands for Government, Universities, and Industry working together for a specific goal. The consortium is a precursor to the current national HCF program. The consortium consists of members from USAF (Air Force Research Laboratory (AFRL) and USAFA), NASA, all four major engine manufacturers (GE, Pratt & Whitney, Allison and Honeywell Engines and Systems) and academia (Ohio State, University of California at Davis, Purdue, Carnegie Mellon, University of Michigan, Duke, and Notre Dame). Together, the consortium works to address shortfalls in alternating stress prediction capability with the academic and industrial members developing or validating new codes funded by the government and industry. Some of GUIde's early codes are currently being integrated into the design systems of the engine manufacturers.*

Points of Contact:

Government
Dr. Antole Kurkov
NASA Glenn Research Center
NASA Glenn Research Park
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-5695
Fax: (216) 977-7051
Email: kurkov@lerc.nasa.gov

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
WPAFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656.5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Kenneth C. Hall
Duke University
Dept. of Mechanical
Engineering & Materials Science
School of Engineering
P.O. Box 90300
Duke University
Durham, NC 27708-0300
Phone: (919) 660-5328
Fax: (919) 660-8963
Email: hall@euler.egr.duke.edu

5.1.3 Forced Response: Mistuned Bladed Disk (REDUCE Code)

FY 92-96

Blade mistuning is the small, random, blade-to-blade variation in geometric and material properties that is unavoidable in bladed disks due to manufacturing tolerances and in-operation wear. Mistuning can lead to localization phenomena in which certain blades vibrate with higher amplitudes than other blades. Under this effort, a reduced-order modeling technique for mistuned bladed disks was developed. The resulting code, REDUCE, can calculate natural frequencies and mode shapes for a tuned case and for a prescribed mistuning pattern. REDUCE allows the user to obtain a frequency sweep output for the maximum blade response amplitude or for all blades. A Monte Carlo analysis is performed to determine the blade response amplitude and deviations. Pre- and post-processing capabilities allow for use of NASTRAN and ANSYS files. The REDUCE code version 1.0 has been transitioned to the industrial GUIde members.

Participating Organizations: GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Christophe Pierre
University of Michigan
2250 G. G. Brown Bldg.
2350 Hayward Street
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109-2125
Phone: (734) 936-0401
Fax: (734) 647-7303
Email: pierre@umich.edu

5.1.4 Design Guidelines for Mistuned Bladed Disks (REDUCE Code)

FY 96-00

Background: The objective of this project is to develop a program for analysis and design of mistuned bladed disks based on REDUCE (first developed under GUIde I, with an updated version released each year).

Recent Progress: Version 2.2 of REDUCE has been released to GUIde members. New features in REDUCE 2.2 include an enhanced capability for fine-tuning the reduced order model to match Finite Element Model natural frequencies, the ability to input a complex forcing vector to capture local phase differences in the applied blade forces, a new capability for outputting/inputting the reduced order model to/from a single file, and improved support for post-processing the displacements and stresses in Finite Element coordinates. An experimental investigation has been initiated to generate validation data for mistuned and intentionally mistuned systems. Modifications and improvements will then made to the REDUCE code based on these findings. In addition, a more powerful, accurate, and efficient reduced order modeling technique has recently been developed. The next-generation code (TURBO-REDUCE) that implements this new method is currently being written.

Participating Organizations: GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7253
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Christophe Pierre
University of Michigan
2250 G. G. Brown Bldg.
2350 Hayward Street
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109-2125
Phone: (734) 936-0401
Fax: (734) 647-7303
Email: pierre@umich.edu

5.1.5 Tip Modes in Low-Aspect-Ratio Blading

FY 95-96

The objective of this project was to develop a basic understanding of sources of variability in high-frequency motion in low-aspect ratio blades, and to develop codes based on this research. The two thrusts of the research were: (1) to understand the effect of taper angle and bluntness of the leading edge of the airfoil on the vibratory response of high-frequency tip modes, and (2) to develop an understanding of the manner in which closely-spaced modes interact to produce highly variable response. For the first thrust, using a tapered beam as a first-ordered approximation for a low-aspect ratio blade, it was determined that the magnitude and location of maximum stress were functions of the truncation factor. For small truncation factors, the response of a high-frequency mode was extremely sensitive to variations in the tip thickness. For the second thrust, for an airfoil with two modes of nearly equal frequency, the modes are highly sensitive to minor variations in blade geometry. Codes developed under this effort have been transitioned to GUIde members.

Participating Organizations: GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Jerry Griffin
Carnegie Mellon University
Department of Mechanical Engineering
Room 414 / Scale Hall / 5000 Forbes
Carnegie Mellon University
Pittsburgh, PA 15213
Phone: (412) 268-3860
Fax: (412) 268-3348
Email: jg9h@andrew.cmu.edu

5.1.6 Development of Aeroelastic Capability for the TURBO Code

FY 96-01

Background: TURBO is a three-dimensional unsteady aerodynamic Navier-Stokes turbomachinery code for propulsion applications. Mississippi State University developed the TURBO code under a grant from Glenn Research Center. For aeroelastic calculations with TURBO, the structural dynamics model of the blade is based on a normal mode representation. For flutter calculations, a pre-processor is used to interpolate modal displacements onto the TURBO grid and to generate the deformed grid. Then, a prescribed harmonic blade vibration with a work-per-cycle calculation is used to determine flutter stability. For forced response calculations with TURBO, the aerodynamic interaction between adjacent blade rows is modeled either as (i) a rotor-stator interaction with multiple passages per blade row, (ii) a rotor-stator interaction with phase-lag boundary conditions which requires modeling only one passage per blade row, or (iii) a wake-blade interaction with the influence of the upstream row represented as an unsteady inlet excitation.

Recent Progress: The development of the flutter capability for the TURBO code has been completed, and many validation cases have been run by industry. The development of the forced response capability for the TURBO code is nearly completed, and some validation cases have been run. Planned future activities (subject to funding availability) include extension of TURBO to multistage analyses and analysis of centrifugal machines.

Participating Organizations: NASA Glenn

Points of Contact:

Government
Oral Mehmed
NASA Glenn Research Center MS 49-8
21000 Brookpark Road
Cleveland, OH 45135-3191
Phone: (216) 433-6036
Fax: (216) 977-7051
Email: Oral.Mehmed@grc.nasa.gov

Contractor
Dr. Milind Bakhle and Dr. Rakesh Srivastava
University of Toledo
NASA Glenn Research Center MS 49-8
21000 Brookpark Road
Cleveland, OH 45135-3191
Phone: (216) 433-6037 (Dr. Bakhle)
(216) 433-6045 (Dr. Srivastava)
Fax: (216) 977-7051 (Both)
Email: Milind.A.Bakhle@grc.nasa.gov
Rakesh.Srivastava@grc.nasa.gov

5.1.7 Dynamic Analysis & Design of Shroud Contact

FY 92-00

Background: The objective of this project is to develop a program to predict blade vibration for rotors having shrouds and/or platform dampers (friction dampers). The completed GUIde I effort was instrumental in the development of BDAMPER, which facilitates analysis of blade-to-ground dampers, blade-to-blade dampers, shroud contact interfaces, and wedge dampers. The GUIde II effort focuses on the stick-slip transition for elliptical motion in the shroud contact plane.

Recent Progress: Under the GUIde II effort, development of specific BDAMPER modules is continuing. BDAMPER 6.0 has been delivered, transitioned to GUIde industrial members, and successfully utilized in damper redesign. Analysis of constrained and complex mode shapes and initial 3D kinematics was completed earlier this year. Work in 3D contact kinematics continues, and advanced subroutines for BDAMPER will be transitioned to industry. BDAMPER 7.0 will be transitioned to industry in early 2000.

Participating Organizations: GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656.5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Chia-Hsiang Menq
Ohio State University
Department of Mechanical Engineering
The Ohio State University
Columbus, OH 43210-1107
Phone: (614) 292-4232
Fax: (614) 292-3163
Email: menq.1@osu.edu

5.1.8 Friction Damping in Bladed Disks

FY 97-00

Background: The objective of this project is to investigate the extreme sensitivity of shrouded bladed disk systems to small changes in the input variables. The final result will be a set of design tools and guidelines that can be used to develop robust shrouded bladed disk systems.

Recent Progress: It was shown analytically that shrouded bladed disk systems can be very sensitive to small changes in the friction slip loads. For example, under certain conditions, a perturbation in the slip load of as little as 1% can cause a 30% change in the vibratory response of the blades. The conditions under which high sensitivity can occur and the underlying physics that causes it have been identified.

In addition, a more efficient and accurate reduced order model was developed that uses a subset of nominal modes to represent the response. The new approach makes it relatively easy to include aerodynamic coupling, mistuning, and friction nonlinearities in the analysis. The resulting code is currently undergoing validation evaluation.

Participating Organizations: GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656.5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Jerry Griffin
Carnegie Mellon University
Department of Mechanical Engineering
Room 414/Scale Hall/5000 Forbes
Carnegie Mellon University
Pittsburgh, PA 15213
Phone: (412) 268-3860
Fax: (412) 268-3348
Email: jg9h@andrew.cmu.edu

5.2 *Acquisition of Experimental Data*

To validate advanced prediction models, experimental data is needed. The objective of the following projects is to obtain data necessary to validate modules for improved forced response prediction.

5.2.1 High Mach Forcing Functions

FY 92-96

The objective of this project was to acquire and analyze data defining the forcing functions generated by the wakes from rotor blades operating at high subsonic and transonic Mach numbers. Data for both the near and far wake were obtained in the Purdue High-Speed Compressor Facility (Fig. 34).

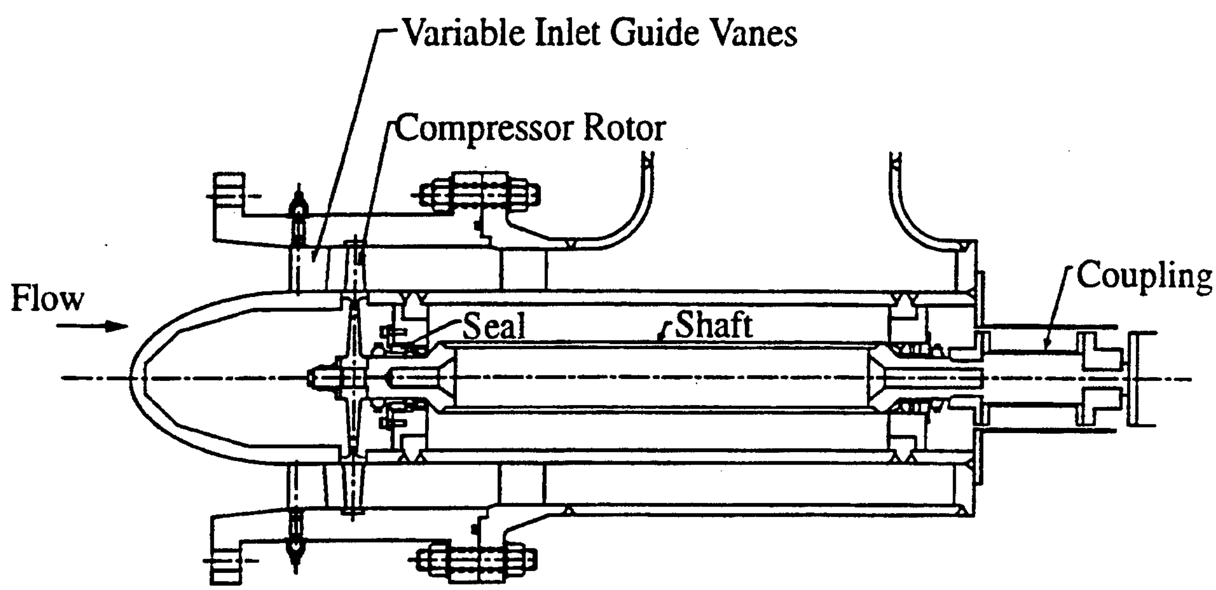


FIGURE 34. Purdue High-Speed Compressor Configuration: Single-Stage, 2/3 Hub-Tip Ratio Design, 18 Variable Inlet Guide Vanes, 19 Rotor Blades, Rotor Diameter 30.48 cm (12 in)

Concurrent to the experimental investigation, fundamental modeling was performed, utilizing current and advanced forced response unsteady aerodynamic models. The experimental data sets were acquired to provide benchmark data for validation of advanced computational fluid dynamic analysis codes. Flow topics which were investigated included rotor wake and potential forcing function blade row interactions, inlet guide vane (IGV) wakes, high-speed rotor wake vortical and potential forcing functions, transonic flow effects on acoustic modes, airfoil row wake interactions, and separated flow effects.

In this study, completed in 1996, the potential gust component of the rotor wakes upstream of the rotor was found to be dominated by the first harmonic component, with small contributions from the second and third harmonics. Higher harmonics of the vortical gust component of the rotor wakes measured both in and out of the IGV wakes are found to be significantly reduced in the IGV wake regions and decay at a uniform rate due to viscous diffusion. Wakes were predominantly vortical for a Mach number near 1.0 and combined vortical-potential for supersonic flows. Interaction of the rotor wake with the IGV wake has a significant effect on the characteristics of both the IGV and rotor wakes. When the rotor blade wakes are in-phase with the IGV wakes, the IGV wake velocity deficit, semiwake width and total pressure losses increase.

Participating Organizations: GUIde, NASA

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7253
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Sanford Fleeter
Purdue University
Thermal Sciences & Propulsion Center
1003 Chafee Hall
West Lafayette, IN 47907-1003
Phone: (317) 494-1504
Fax: (317) 494-0530
Email: fleeter@ecn.purdue.edu

5.2.2 Forward Swept Blade Aeromechanics

FY 95-96

This effort involved application of available design/analysis tools to evaluate and predict the aeromechanical performance of a forward-swept rotor 1 of a two-stage test vehicle with inlet guide vanes. The rotor was tested at the WPAFB Compressor Research Facility (CRF) with instrumentation to measure and monitor the aeromechanical and aerodynamic behavior, both natural and forced. The aeromechanical goal of this effort was to evaluate the current aeromechanical design tools and practices needed to support the successful use of forward-swept blading. Also of interest was identification of unique aeromechanical problems in the design, in current design practice, or in the application of existing design tools.

Based on the testing results and comparison to the analytical predictions, the following conclusions are drawn. Empirical curves of current design practice are inadequate to predict the stability of forward-swept airfoils. The GAP software and analysis process is overly conservative for stability analyses. The NOVAK2D software and analysis process is a good tool but limited to nominal and low operating lines. The SIFOR forced-response analysis process yields fair correlation. Low-order modes have the best comparison. All tools and analysis processes need further development and improvement. Additional tools should be developed that are more accurate and applicable to more operating conditions, especially the high operating line.

This program produced a large amount of detailed data, and much of it was reduced and reviewed/evaluated. The acquired data add considerably to the available aeromechanical database, particularly for forward-swept airfoils. These data are available for, and will be very valuable to, the future improvement of existing analysis tools, design practices, and airfoil designs. Development of new, more powerful tools will benefit from this program and the data acquired. Enabling technology developed by this program will contribute to significant improvement in fan and compressor aerothermodynamics through implementation of forward-swept blade designs with lower development risk and cost.

Participating Organizations: Air Force Research Laboratory (AFRL), General Electric

Points of Contact:

Government
Mr. John Leuke
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB,OH 45433-7251
Phone: (937) 255-8210
Fax: (937) 255-2077
Email: luekeje@wl.wpafb.af.mil

Contractor
Dr. Robert E. Kielb
General Electric Aircraft Engines
One Neumann Way, M/D K105
Cincinnati, OH 45215-1988
Phone: (513) 243-2821
Fax: (513) 243-8091
Email: Robert.Kielb@ae.ge.com

5.2.3 Oscillating Cascade Rig

FY 95-01

Background: The NASA GRC linear oscillating cascade is one of a very few test facilities dedicated to unsteady aerodynamics of oscillating airfoils. The facility is used to investigate unsteady aerodynamic phenomena in an oscillating row of airfoils modeling self-induced cascade flutter. Experimental data acquired in this facility serve as benchmark sets to validate CFD codes for predictions applicable to real turbomachines, so that the data must be of the highest quality and reliability with characteristics sufficiently close to those encountered in annular cascades of real machines. However, achieving flow identity in linear and annular cascades is a very difficult task even for steady flow conditions.

Recent Progress: Lately, the cascade facility has been used to investigate flowfield about airfoils typical for blade tip region of modern high-speed fans. The airfoil has an 'S' shape suction side for flow precompression at transonic inlet Mach numbers. For high subsonic inlet flows and high incidence angles (about 10°), the airfoil suffers a severe flow separation on the first half of the suction side. The initial steady-state investigations showed significant flow pattern variations among the cascade blades. Therefore, the work first focused on improving the steady-state periodicity of the cascade flow pattern. Recently, NASA GRC extensively modernized and refurbished the facility. The boundary layer bleed system was completely overhauled, and it is now possible to monitor its adjustment on line. However, these changes did not improve the flow uniformity and periodicity significantly, particularly for high subsonic and transonic Mach number flows.

The CFD analysis of the blade cascade showed that for the incidence of 10°, the cascade turns the flow for only about 4° due to flow separation on the front portion of the blade suction side. The cascade facility, however, was originally set for flow turning of 10° for the same incidence angle. This resulted in tunnel wall interference with the cascade flow that significantly affected the flow pattern, which explains the tunnel-bleed system inefficiency in improving the flow pattern. The cascade setting was rearranged for a smaller turning angle of 4°, which noticeably improved the pressure uniformity upstream and 'far' down stream of the cascade, but the flow periodicity in the right half of the cascade was still not good enough. Decreasing the tunnel turning angle caused a mismatch between the tunnel wall and the suction side of the last blade on the cascade right-hand side. Consequently, the end blade suffers a massive flow separation over the entire suction surface that affects the flow pattern of the adjacent blades.

Based on the previous experimental results and CFD analysis, a solution was found for shaping the tunnel wall that should prevent flow separation on the last blade and its effect on the cascade flow periodicity. The evaluation work is still in progress, but the results so far demonstrate the careful and meticulous approach to secure the highest possible reliability and repeatability of experimental data acquired in this facility.

Participating Organizations: NASA Glenn, Pratt & Whitney

Points of Contact:

Government
Dr. Jan Lepicovsky
Dynamics Engineering Co. / NASA Glenn
2001 Aerospace Parkway
Brookpark, Ohio 44142-1002
Phone: (216) 977-1402 or (216) 433-6207
Fax: (216) 977-1269
Email: jan.lepicovsky@lerc.nasa.gov

Contractor
Dr. Yehia El-Aini
Pratt & Whitney
P.O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-5911
Fax: (561) 796-3637
Email: elainiye@pwfl.com

5.2.4 F109 Unsteady Stator Loading
FY 95-99

Background: The objectives of the work are to collect, reduce, and analyze unsteady velocity data from the Honeywell F109 turbofan engine at the Air Force Academy in Colorado Springs, Colorado (Fig. 35). The specific areas of interest were upstream of the fan, or "fan forward" region, and upstream and downstream of the stators located behind the fan. All velocity data was taken with a two-wire hot wire, which was phase locked with the rotor.

The conclusions drawn from the analysis of the "fan forward" data are that relatively large, unsteady, velocity disturbances are present in the flow approaching the fan. The unsteady potential field generated by the individual fan blades as they rotate causes these disturbances. The disturbances radiate at acoustic speed into the oncoming flow field in a spiraling helical pattern. The amplitude of the measured unsteady velocity is as high as 50% of the mean-axial-velocity very close to the fan, and is as low as 2-5% of the mean-axial-velocity at 1.0 fan chord (2.61 in) upstream of the fan. The data collected downstream of the fan indicates the presence of a convectively-propagating wake disturbance superimposed on an acoustically-propagating potential disturbance. These results confirm that it was the combination of these two disturbances that produced the unsteady pressure response measured on the surface of the stators in a previous effort.

Recent Progress: Current efforts are focused on the development of a small probe to measure the unsteady surface pressure distribution produced by the large-amplitude velocity fluctuations upstream of the fan. A test probe has been fabricated by Notre Dame for use in their cascade wind tunnel. This probe is scheduled to be tested this summer (1999). Based on the results of this testing, a probe will be designed and built for use in the F109 engine at the Air Force Academy. F109 engine testing is planned for the Aug 99 - May 00 timeframe.

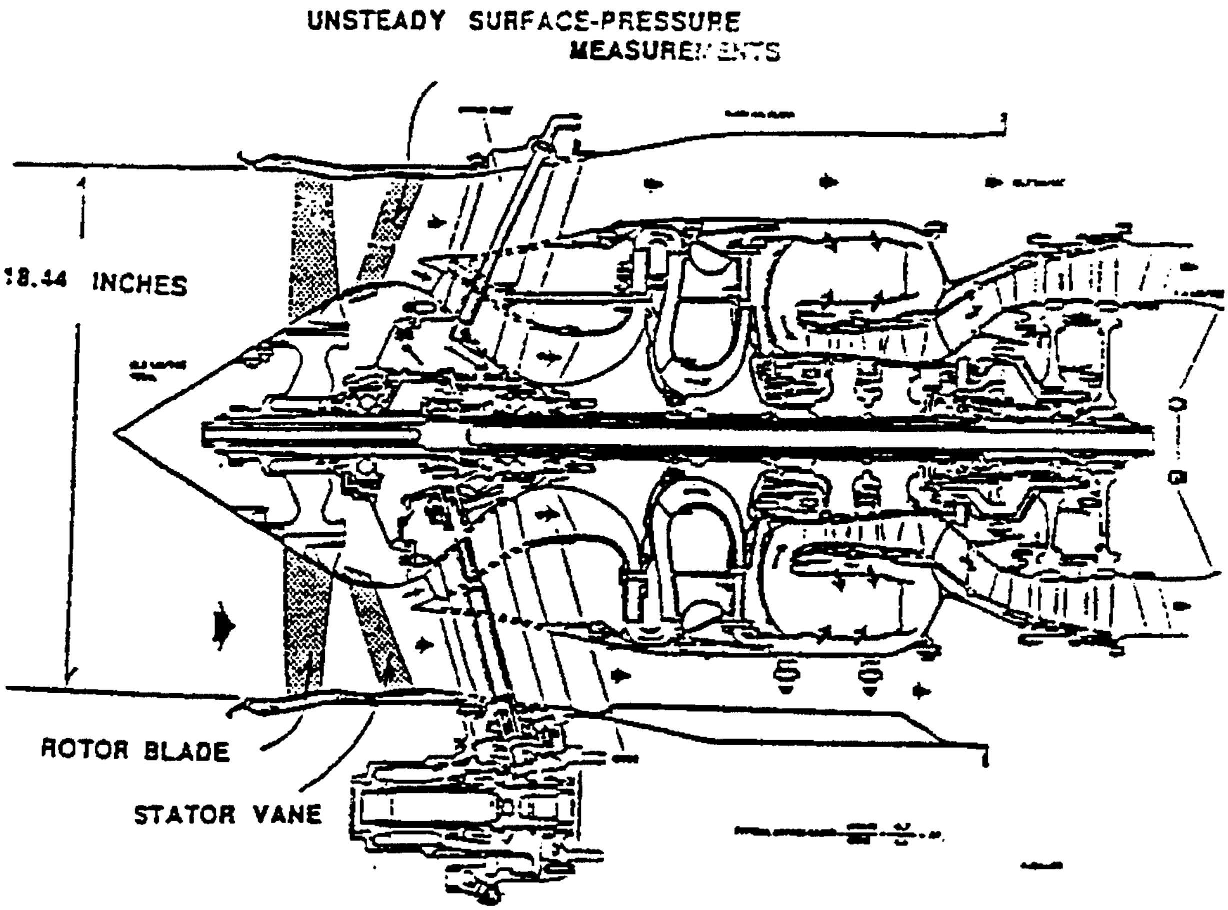


FIGURE 35. Schematic of F109 Engine Showing Location of Pressure-Instrumented Stators

<u>Participating Organizations:</u> U.S. Air Force Academy, Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), University of Notre Dame

<u>Points of Contact:</u>

<u>Government</u>
Maj Brenda A. Haven
U.S. Air Force Academy
Headquarters USAFA/DFAN
2354 Fairchild Dr., Suite 6H22
United States Air Force Academy
Colorado Springs, CO 80840-6222
Phone: (719) 333-3435
Fax: (719) 333-4013
Email: HavenBA.DFAN.USAFA@usafa.af.mil

<u>Contractor</u>
Dr. Eric Jumper
University of Notre Dame
Aerospace and Mechanical Engineering
Hessert Center for Aerospace Research
Notre Dame, IN 46556
Phone: (219) 631-7680
Fax: (219) 631-8355
Email: ejumper@aerosun.aero.nd.edu

5.2.5 Fluid-Structure Interaction (Fans)

FY 96-01

Background: The objective of this effort is to develop the technology needed to accurately predict significant blade row forced response in a multistage environment. Specific objectives include: (1) developing a benchmark standard multistage transonic research compressor; (2) developing a quantitative understanding and predictive capability for multistage blade row forced response; (3) addressing the inherently small damping of complex higher-order modes; (4) investigating techniques to control the flow-induced vibrations; and (5) developing a better understanding of robustness, nonlinearities, and fluid-structure interactions.

The aerodynamic design of the advanced design inlet guide vane (IGV), rotor, and downstream stator rows has been completed. The IGV, rotor, and stator vanes have been fabricated, with the IGV and stators instrumented. Unsteady aerodynamic interactions between the IGV and rotor of an advanced design transonic multistage compressor have been experimentally investigated, with the rotor-generated forcing function and resultant IGV response measured and analyzed at both design and part-speed operating conditions. The effect of aerodynamic blade-to-blade variability on the wake-generated forcing function and its impact on the downstream vane row unsteady aerodynamic response has been experimentally investigated in a high-speed fan stage at both design and off-design rotor operating conditions.

Recent Progress: Investigations into multistage unsteady aerodynamic analysis have been initiated. The following observations have been made. First, the aerodynamic damping of a blade row in a multistage machine can be significantly different from that predicted using an isolated blade row model. This is important since most current models do not account for multistage effects, and thus may significantly over or under predict aerodynamic damping. Second, it may be possible to use the multistage influence on aerodynamic damping to reduce aeroelastic vibrations. For example, the designer may be able to alter the spacing between blade rows to increase aerodynamic damping. Third, using the present method, a good estimate of the aerodynamic damping can be obtained using just a few of the many possible spinning modes. This is fortunate since computational cost grows with the number of spinning modes retained in the model. Finally, the present coupled mode analysis is computationally very efficient, two or more orders of magnitude more efficient than time-marching simulations. The implication is that such multistage computations will be efficient enough for use in design, eliminating potential aeromechanics problems not predicted using isolated blade row models.

Research under this initiative will include continued analytical development of multistage effects. Continued experimental research includes the measurement of the stator response and measurements utilizing the new rotor in the test rig. With the new rotor installed, investigations into rotor-stator and rotor-IGV interactions will be performed, and airfoil response for each blade row will be measured.

Participating Organizations: AFOSR, Purdue University, Duke University, Pratt & Whitney

Points of Contact:

Government
Dr. Thomas Beutner
U.S. Air Force, AFOSR/NA
801 N. Randolph Street
Arlington VA 22203-1977
Phone: (703) 696-6961
Fax: (703) 696-8451
Email: tom.beutner@afosr.af.mil

Contractor
Dr. Sanford Fleeter
Purdue University
Thermal Sciences & Propulsion Center
1003 Chaffee Hall
West Lafayette, IN 47907-1003
Phone: (317) 494-1504
Fax: (317) 494-0530
Email: fleeter@ecn.purdue.edu

5.2.6 Experimental Study of Forced Response in Turbine

FY 97-00

Background: The purpose of this project is to develop an understanding of the forcing function, aerodynamic damping, and structural damping at actual engine conditions for high-frequency vibration of turbine blades. An actual Honeywell TFE731-2 high-pressure turbine will be studied in the Gas Turbine Laboratory at Ohio State University. The original blades, which had a severe high-frequency vibration problem, will be evaluated in conjunction with two other turbine designs. For each configuration, unsteady surface pressures and blade response will be measured at actual operating conditions. The result of this research will be a database that can be used to validate future prediction codes.

Recent Progress: The UNSFLO Computational Fluid Dynamics (CFD) simulation of turbine stage and the ANSYS finite element method (FEM) analysis of blade natural frequency have been completed. Because of reduction in funding, the test plan had to be scaled down, and actual engine conditions were replaced by corrected conditions. All the tests were completed successfully, and the data analysis is in progress. The period of performance on the contract was extended to February 2000.

Participating Organizations: GUIde, NASA

Points of Contact:

Government
Dr. Antole Kurkov
NASA Glenn Research Center
NASA Glenn Research Park
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-5695
Fax: (216) 977-7051
Email: kurkov@grc.nasa.gov

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St, Bldg. 18D
WPAFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Michael Dunn
Ohio State University
328 Bowlz Hall
2036 Neil Ave.
Columbus, OH 43210-1276
Phone: (614) 292-8453
Fax: (614) 292-8290
Email: dunn.129@osu.com

5.3 *Validation of Analytical Models*

The objective of the following projects is to utilize existing experimental data to validate models for improved forced response prediction.

5.3.1 Evaluation of Current State-of-the-Art Unsteady Aerodynamic Models for the Prediction of Flutter & Forced Vibration Response

FY 97

Background: The objective of this project was to evaluate the capabilities of current state-of-the-art unsteady aerodynamic models that attempt to predict the gust and oscillating airfoil response of compressor and turbine airfoils over a range of realistic frequencies and loading levels. Additionally, the effect of the aerodynamic forcing function on gust response, and the effects of three-dimensional flow on airfoil oscillation will be investigated. Codes utilized were primarily NASA Glenn codes, such as Nphase, Sflow, Linflow, and Linflux.

Final Results: This program was terminated when the principal investigator left academia. However, an initial investigation into the capabilities of two state-of-the-art computational models was performed. The unsteady pressure and first harmonic unsteady surface pressure coefficients determined from experiments were correlated with the predictions. The experimental data used was for the NASA/PW fourth standard configuration. Viscous and inviscid flow solutions were generated.

Participating Organizations: Air Force Research Laboratory (AFRL), GUIde

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7253
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

5.3.2 Evaluation of State-of-the-Art Unsteady Aerodynamic Models

FY 99-02

Background: The objective of this project is to evaluate the capabilities of current state-of-the-art unsteady aerodynamic models that attempt to predict the gust and oscillating airfoil response of compressor and turbine airfoils over a range of realistic frequencies and loading levels. Additionally, the effect of the aerodynamic forcing function on gust response and the effects of three-dimensional flow on airfoil oscillation will be investigated. Codes currently under evaluation are TURBO, ADPAC, and 3DVBI.

Recent Progress: This effort officially started in March 99. Research utilizing the 3DVBI and ADPAC codes has been initiated. Efforts utilizing 3DVBI are being lead by WSU, in conjunction with AFRL's CARL facility. Comparisons of the code's prediction capability with experimental data from the CARL facility are being performed. In general, the 3DVBI code has compared quite favorably with the experimental results in the core region of the flow, but the endwall regions need additional investigating before conclusions can be made.

Similar comparisons are being initiated with the NASA ADPAC code through the University of Dayton. Test cases have been run, and steady IGV comparisons to the CARL data have been initiated. The third code under this effort is TURBO. The lead for this effort is the University of Cincinnati. Similar comparisons are planned, but have not been initiated.

Participating Organizations: Air Force Research Laboratory (AFRL), Wright State University

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7253
Phone: (937) 656-5530
Fax: (937) 656-5532
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Mitch Wolff
Wright State University
Department of Mechanical Engineering
123 Russ Center
Dayton OH 45435
Phone: (937) 775-5141
Fax: (937) 775-5009
Email: mwolff@cs.wright.edu

5.3.3 Forced Response Prediction System (Fans)

FY 95-01

Background: The objective of this project is to develop and validate NASA's new Forced Response Prediction System design tools. Three codes are being developed for forced response predictions: FREPS, FREED, and TURBO with aeroelastic capability. FREPS uses two-dimensional linearized potential unsteady aerodynamics and is the fastest running of the codes. The development and validation of FREPS is complete and is being followed by the development of FREED. FREED uses steady Euler aerodynamics from the TURBO code, and linearized three-dimensional unsteady Euler aerodynamics from LINFLUX. LINFLUX is a turbomachinery code developed under a contract from NASA Glenn Research Center (formerly Lewis Research Center). The linearized code FREED and the fully non-linear code TURBO (with aeroelastic capability) are complimentary. Both codes are based on the same algorithm, but each provides a different level of physics modeling and has different computational requirements. The TURBO code, described elsewhere in this report, is the longest running of the three codes. The structural dynamic model of the blade for the three codes is based on a normal mode representation.

Recent Progress: Initial work has focused on installing the LINFLUX code on different computer workstations, and exercising the code to gain familiarity with its operation. An interface code is required to convert the steady TURBO solutions for use with LINFLUX. The interface code is being updated to work with the latest version of TURBO. In addition, the interface code is being modified to work on the Cray C-90, where the steady TURBO solutions are currently being run. The most recent version of LINFLUX includes the capability to model incoming vortical gusts; this capability was not present in prior versions of the code. Future plans include improvement of the steady solver to obtain faster convergence and to obtain solutions with reduced numerical losses. In addition, the FREED code will be validated using configurations that are of current interest to industry.

Participating Organizations: NASA

Points of Contact:

Government
Oral Mehmed
NASA Glenn Research Center
NASA Glenn Research Park
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-6036
Fax: (216) 977-7051
Email: oral.mehmed@lerc.nasa.gov

Contractor
Milind Bakhle and T.S. Reddy
University of Toledo
NASA Glenn Research Park
21000 Brookpark Rd., M/S 49-8
Cleveland, OH 44135-3191
Phone: (216) 433-6083 (Bakhle)
(216) 433-6037 (Reddy)
Fax: (216) 977-7051 (Both)
Email: Milind.A.Bakhle@grc.nasa.gov
Rakesh.Srivastava@grc.nasa.gov

5.3.4 Aeromechanical Design System Validation

FY 96-00

Recent Progress: The response of an existing rotor has been measured, and a full rotor finite element method (FEM) analysis has been performed. Next, the FEM code will be coupled with a model of the inlet flow field, and the resulting vibratory stresses will be predicted. The predictions will be compared with bench data, and recommendations for additional code development will be made.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney

Point of Contact:

Government
John Leuke
U.S. Air Force, AFRL/PRTF
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-8210
Fax: (937) 255-2077
Email: luekeje@wpafb.af.mil

5.3.5 Probabilistic Structural Analysis Methods

99-01

Background: The NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) probabilistic structural analysis computer program combines state-of-the-art probabilistic algorithms with general purpose structural analysis methods to compute the probabilistic response and the reliability of engineering structures. Uncertainty in loading, material properties, geometry, boundary conditions, and initial conditions can be simulated. The structural analysis methods include nonlinear finite element methods, boundary element methods, and user-written subroutines. Several probabilistic algorithms are available, such as the advanced mean value method and the adaptive importance sampling.

Recent Progress: Recently, NESSUS was augmented with the Heat Transfer analysis capability of the EPM backbone computer code CSTEM (Coupled Structural, Thermal, and Electro Magnetic Tailoring)—resulting in NESTEM code. NESTEM can now analyze/assess the complex thermal environment with uncertainties and its effects on the overall component response. Typical output of the code is probabilistic stress distributions at hot spots, probabilistic vibration frequencies and buckling loads. This information allows the designer to make more informed judgments regarding the preliminary design of the components without resorting to overly conservative deterministic approaches with ad-hoc knock-down factors. The information also permits more accurate calculation of the reliability and life of such components. The code also provides information on sensitivities of the various uncertainties and ranks them in the order of importance as a by-product.

Recently, the NESTEM code was enhanced to include the capability to define harmonic excitation parameters. The enhanced capability allows the analysis of three types of harmonic excitations: harmonic nodal forces, harmonic-based accelerations, and harmonic nodal pressures. These improvements will allow us to address some high cycle fatigue (HCF) problems. Furthermore, there is a need to address creep and fatigue-related models as well as lifing-related problems. These methodologies will be ultimately used to computationally simulate and probabilistically evaluate the Department of Defense's disk model, and the methodologies will be verified using the experimental test data from Pratt & Whitney.

Participating Organizations: Modern Technologies Corporation

Points Of Contact

Government
Dr. Shantaram S. Pai
NASA Glenn Research Center
MS 49-8
21000 Brookpark Road
Cleveland, OH 45135-3191
Phone: (216) 433-3255
Fax: (216) 977-7051
Email: Shantaram.S.Pai@grc.nasa.gov

Contractor
Dr. Vinod K. Nagpal
Modern Technologies Corporation
7530 Lucerne Drive
Middleburg Heights, OH 44130
Phone: (440) 234-8488
Fax: (440) 234-8490
Email: vnagpal_mtc@stratos.net

5.4 Conclusion

The Forced Response Action Team has successfully developed models to understand and predict friction and mistuning in gas turbine engine disks. Two models have been transitioned to industry and used to investigate field problems on both the F100 and F110. "BDAMPER," a code developed through the GUIde Forced Response Consortium, is successfully predicting resonant responses of frictionally constrained blades. Applied to the F100 3rd fan blade design, its use has resulted in a 62% reduction in unscheduled maintenance man-hours. "REDUCE," a bladed disk mistuning code, is being utilized by several turbine engine companies, and is successfully predicting response trends in bladed disk assemblies. Additionally, the government and industry are jointly pursuing new codes for flutter and resonant stress prediction. Many efforts have been coordinated and developed through the GUIde consortium of government, engine contractors, and universities, with validation performed through basic research, component rig testing, and production engine operation.

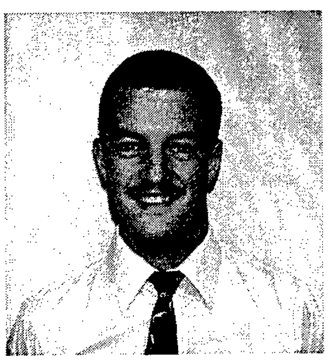
6.0 PASSIVE DAMPING TECHNOLOGY

BACKGROUND

The Passive Damping Technology Action Team (Damping AT) has the responsibility of fostering collaboration between individual HCF passive damping efforts with the overall goal of damping component resonant stress by 60% for fans and 25% for turbines. The Damping AT provides technical coordination and communication between active participants involved in HCF passive damping technology. Annual technical workshops have been organized and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair and selected Damping AT members meet as required (estimated semi-annually) to review damping activities, develop specific goals for passive damping programs, and coordinate with the TPT and IAP. The Chair (or Co-Chair) of the Damping AT keeps the TPT Secretary informed of AT activities on a frequent (at least monthly) basis. This AT includes members from government agencies, industry, and universities who are actively involved in damping technologies applicable to engine HCF. The team is to be multidisciplinary with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT may change in time as individuals assume different roles in related projects.

ACTION TEAM CHAIRS

The following appointments are effective as of 1 Jan 2000.



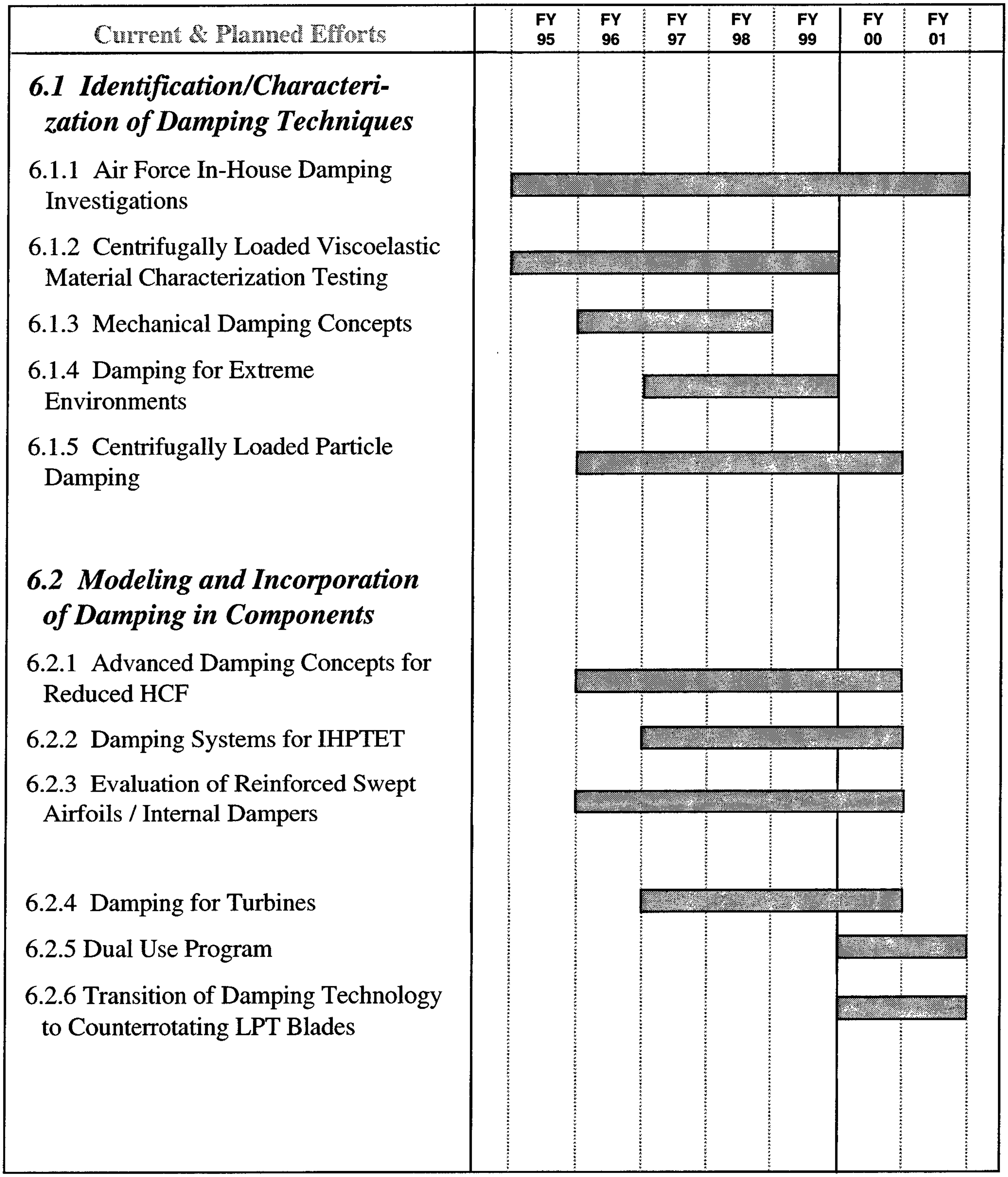
Chair
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
WPAFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Co-Chair
Mr. Ray Pickering
NAVAIR/NAWCAD
Propulsion & Power Engineering
Building 1461
48298 Shaw Road Unit 4
Patuxent River, MD 20670-1900
Phone 301-342-0873
Fax 301-342-4781
Email: pickeringra@navair.navy.mil

To the outgoing chairs, Don Zabierek and Dave Barrett, an enthusiastic "Thank you" for your years of outstanding service to the Passive Damping Action Team and to the National High Cycle Fatigue Science and Technology Program, and best wishes in your future endeavors.

INTRODUCTION: The following pages contain tables, schedules, backgrounds, and summaries of the recent progress of current and planned tasks managed by this action team.

Passive Damping Schedule



6.1 *Identification and Characterization of Damping Techniques*

Four types of passive damping systems, judged to have a reasonable chance of effectively damping rotating engine components, are being investigated: (1) friction damping systems, which have been used in platform and shroud applications and now show promise as devices internal to blades, (2) viscoelastic material systems, which have mature design optimization procedures and are now being designed to function under high centrifugal loads, (3) particle damping systems, which have the potential of providing damping independent of temperature, but require a lot of effort in characterization and design optimization, and (4) powder damping systems, which are an extension of the tribology of dry film lubricants, have temperature independent damping, and require the most work in the development of acceptable systems.

6.1.1 Mechanical Damping Concepts

FY 95-01

Recent Progress: For the past year, researchers at NASA Glenn Research Center (GRC) have been investigating several damping methods for rotating blades. Oral Mehmed, NASA Senior Research Engineer, and Dr. Kirsten Duffy of the Ohio Aerospace Institute have been working with Dr. Ronald Bagley of the University of Texas at San Antonio to study the self-tuning impact damper. Oral Mehmed has also been working with Dr. John Kosmatka at the University of California at San Diego to investigate viscoelastic damping in composite blades.

A self-tuning impact damper was tested in 1999 that significantly reduced resonant vibrations at engine order crossings. The frequency of motion of the damper is proportional to the rotor spin rate, causing it to function along an engine order line. Tests were performed in flat aluminum plates at up to 2600 g's in the NASA Dynamic Spin Facility (Fig. 36). Damping of up to 2.0% critical was obtained at the engine order crossings over a baseline damping of about 0.2%. A follow-up test is being planned for late 1999 to test these dampers at up to 10,000 g's in the same flat plates. In order to show the feasibility of damping for very thin blades, another test will be performed this winter on a miniaturized self-tuning damper. Here, very small impactors will be distributed over an area of a plate. A future goal is to demonstrate the self-tuning impact damper in a blade configuration.

Research is also being conducted in the area of integrally damped composite blades. The objective of this research is to develop technology to passively damp blades made of composite material by designing and fabricating the blades with viscoelastic material built in. Earlier analytical and experimental research with spinning composite plates showed that the concept works and that the damping benefits are significant. New research in 1999 is aimed at demonstrating an integral damping design for a scale model of a modern composite fan blade. The damping design is focused on maximizing the blade damping for a specific rotating speed range and mode, while maintaining the initial structural static and dynamic properties. These scale model fan blades have been fabricated, and spinning structural characterization is planned at the NASA Dynamic Spin Facility in late 1999 or early 2000.

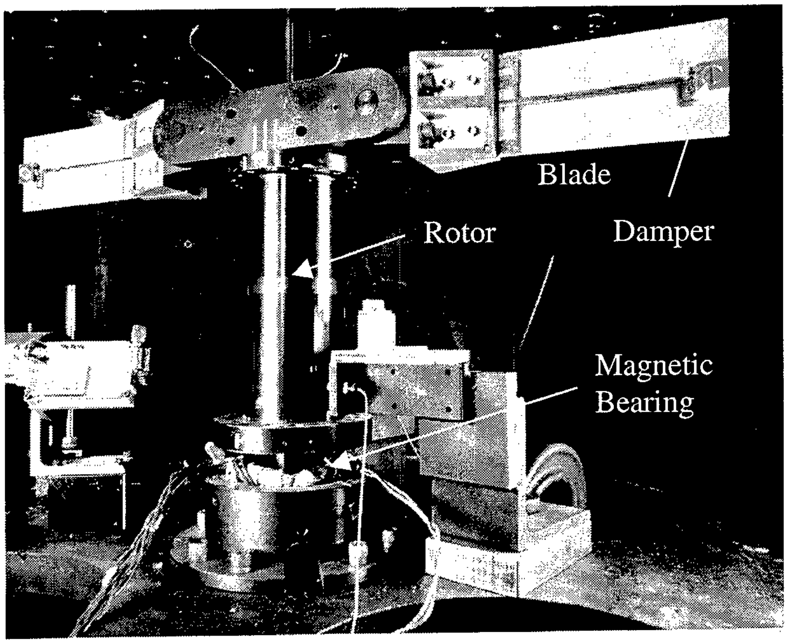


FIGURE 36. Dynamic Spin Facility, NASA Glenn Research Center

Participating Organizations: NASA, University of California, Ohio Aerospace Institute, University of Texas at San Antonio

Points of Contact:

Government
Dr. Kirsten Duffy
Ohio Aerospace Institute
NASA Glenn Research Center MS 49-8
21000 Brookpark Road
Cleveland, OH 45135
Phone: (216) 433-3880
Fax: (216) 977-7051
Email: Kirsten.P.Duffy@grc.nasa.gov

Contractor
Dr. John Kosmatka
University of California at San Diego
Department of Structural Engineering
9500 Gilman Dr.
La Jolla, CA 92093-0085
Phone: (858) 534-1779
Fax: (858) 822-2260
Email: jkosmatka@uscd.edu

6.1.2 Air Force In-House Damping Investigations

FY 95-99

Background: The objective of this task in FY99 was to investigate the use of piezoelectric actuators to increase coupling in an integrally bladed rotor. Mistuning can cause blades to experience much higher operating stresses than would occur in a perfectly tuned system. Increasing blade-to-blade coupling can reduce this non-uniformity. In this task, piezoelectric actuators were attached to an integrally bladed disk and modal tests were conducted to access the amount of additional coupling provided by the actuators.

Ideally, a bladed disk is a periodic system with the substructures and blades all having identical natural frequencies. However, there will be slight variations in the blades. These variations mistune the individual blade natural frequencies and affect the system as a whole. The dynamic behavior of the bladed disk depends on the degree of mistuning and coupling that exists in the system. When the amount of mistuning is small or the coupling is strong, the mode shapes are said to be extended, i.e., they are regular patterns that involve all the blades. As the mistuning is increased or the coupling weakens, the mode shapes tend to become irregular, with amplitude concentrated in a few blades.

Piezoelectric strain actuators have been used to add damping to structures. These actuators have the potential to augment the coupling of engine blades. As a blade deforms during vibration, an electrical charge is induced in a strain actuator located in an area of high modal strain on the blade. The induced charge can then be transferred through an electric circuit to an actuator on another blade causing the second blade to also deform. This sharing of energy between blades is similar to connecting the two blades with a mechanical spring.

Final Results: Experiments were conducted on a model jet engine fan to evaluate the effects of piezoelectric coupling of blades on mode shapes. The model fan, shown in Figure 37, was used as the test article in this study. It is a variant of a model developed under a previous study and is representative of a modern fighter engine's first-stage fan. The model fan had an overall diameter of 18 inches. The blades and hub were fabricated from low-alloy steel. The blades were soft soldered into slots in the hub at a 45° angle to the fan's axis of rotation. The blades were 6 inches long, 4.5 inches wide and 0.063 inches thick. The cylindrical hub had a diameter of 6 inches. The hub wall thickness was 0.325 inches.

The 2-stripe family of modes was chosen for study. Piezoelectric strain actuators were placed on the blades in an area of high modal strain for the local 2-stripe mode shape. Each piezoelectric strain actuator was a sheet of G-1195 lead zirconate titanate (PZT). The dimensions of each actuator were 1.5 inches by 1.5 inches by 10 mils thick. Actuators were bonded to the front and back of each blade. The location of the front actuators are apparent in Figure 37, the back actuators are at the same locations on the other side of the blades. The negative side of each actuator is electrically grounded to the fan using conductive adhesive.

The model fan was inherently mistuned due to small variations in the blades. The natural frequencies of the individual blades (with all sensors, actuators, and wiring in place) were measured to quantify the mistuning. The frequency of each blade was measured, one at a time, by adding small tip masses to the other blades to "detune" them and localize the mode shape to the blade of interest. The average natural frequency measured was 789.4 Hz. The frequency spread from the highest to the lowest frequency blade was 10 Hz or 1.3% of the average frequency.

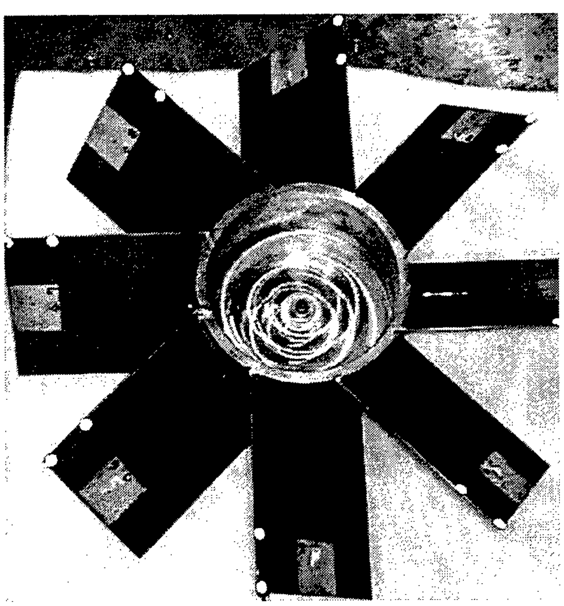


FIGURE 37. Model Fan Test Article

In addition to studying the effects of coupling on the mistuned model, it was desired to test the model in a nearly-tuned configuration. To tune the model, the natural frequencies were altered through the addition of small masses to each blade. A trial and error procedure was used to decrease the frequency spread from 10 Hz to 0.5 Hz. The spread is only 0.06% of the new average frequency of 783.7 Hz. This configuration will be referred to as the "tuned" fan.

The piezoelectric actuators can be electrically connected to achieve many coupling arrangements. In previous work with an analytical model, a single coupling spring was used to couple adjacent blades. The piezoelectric actuators on the model fan were connected to mimic this model. Each front piezoelectric actuator was connected to the back actuator of the next blade as depicted in Figure 38.

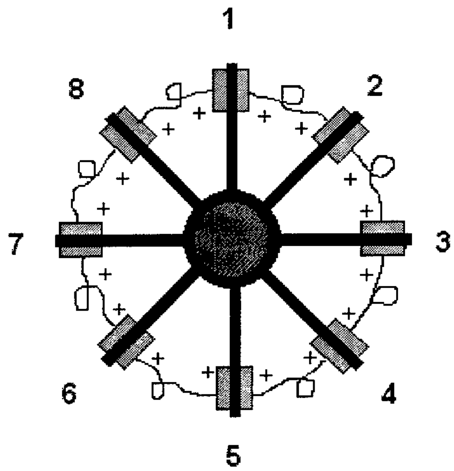


FIGURE 38. The Electrical Connections between Piezoelectric Actuators

The mode shapes for a perfectly tuned system, often called the extended mode shapes, are shown in Figure 39. Extended mode shapes can also occur with a mistuned system if the coupling is strong enough. Achieving extended mode shapes and therefore tuned forced response behavior was the goal of the coupling experiments. For the mode shapes depicted in Figure 39, the length of the radial line in the 12 o'clock position represents the relative modal amplitude of blade 1. The amplitudes of blades 2-8 are represented by the other seven radial lines (numbered clockwise). Solid lines represent blades vibrating in-phase and dotted lines represent blades vibrating out-of-phase. The orientations of the three orthogonal pairs of modes (2-3, 4-5, and 6-7) are arbitrary.

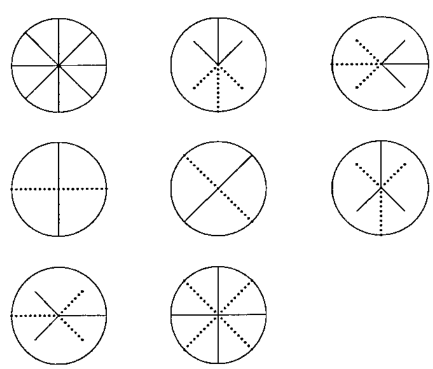


FIGURE 39. Extended Mode Shapes for Eight Blades

Two tests were conducted on the model fan in the mistuned configuration. In the first case, the piezoelectric couplers were not connected and left in the open electrical boundary condition. This case will be referred to as the mistuned, uncoupled case. In the second case, the couplers were connected as shown in Figure 38. This case will be referred to as the mistuned, coupled case.

Modal results for the mistuned, uncoupled case are shown in Figure 40. The mode shapes are generally localized. Modes 1-3, 7, and 8 are mostly localized to a single blade. The other three modes, 4-6, primarily involve blades 2, 3, and 8. These results are readily inferred from the individual blade frequencies. That is, the tendency for two blades to participate in the same mode is directly related to the difference in their individual frequencies.

It is evident from Figure 40 that inter-blade coupling for the 2-stripe mode family is very weak. As discussed previously, extended modes (tuned behavior) can result from either of two conditions—coincident frequencies or large inter-blade coupling. The mode shapes indicate very weak coupling, since the blades that do not have nearly-coincident frequencies are mostly localized. This behavior is to be expected from the 2-stripe mode family since the local mode shape has very little strain energy near the blade root and thus has poor means for coupling through the hub. Therefore, a large increase in coupling of the 2-stripe family is needed to achieve extended behavior.

Modal results for the mistuned, coupled case are shown in Figure 41. A moderate increase in coupling is evident. Generally speaking, each mode shows increased participation from all the blades. The piezoelectric coupling has caused blades 4 and 7, which were previously localized, to strongly interact with blades 2, 3, and 8. Modes 1, 7, and 8 are still mostly localized to blades 6, 5, and 1, respectively, but there is some small participation of adjacent blades. Although the overall coupling has improved, the resulting mode shapes are far from the extended case. The added coupling from the piezoelectric actuators is too weak to have the desired results.

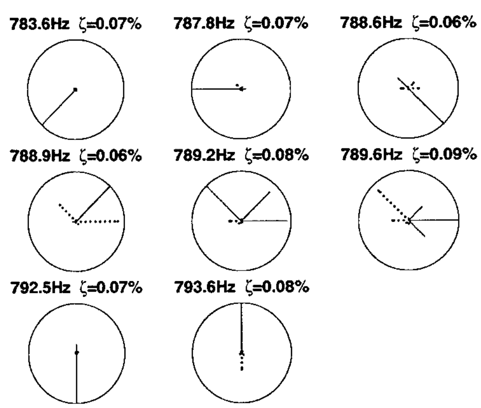


FIGURE 40. Mode Shapes for the Mistuned, Uncoupled Case

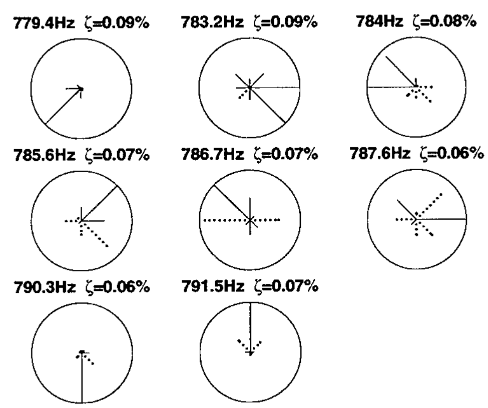


FIGURE 41. Mode Shapes for the Mistuned, Coupled Case

After it was determined that the piezoelectric coupling was not strong enough to achieve extended modes in the mistuned fan, it was decided to see if the coupling could force extended modes in a nearly tuned system. The blades were "tuned" as described previously, and modal tests were conducted for two coupling cases. In the first case, the piezoelectric couplers were not connected and left in the open electrical boundary condition. This case will be referred to as the tuned, uncoupled case (Fig. 42). In the second case, referred to as the tuned, coupled case, the couplers were connected as shown in Figure 43.

The modal results for the tuned, uncoupled case are shown in Figure 42. There is significant participation of most blades in most modes, but only three of the mode shapes (5, 7, and 8) appear to approach the extended mode shapes.

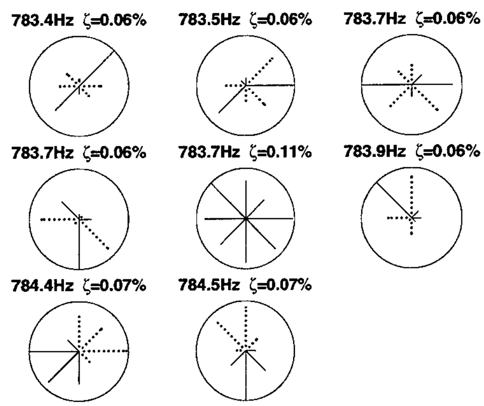


FIGURE 42. Mode Shapes for the Tuned, Uncoupled Case

The modal results for the tuned, coupled case are shown in Figure 43. All the mode shapes closely approximate the extended mode shapes and are in the proper order. With the system nearly tuned, the added coupling from the piezoelectric actuators is sufficient to cause the extended shapes to appear.

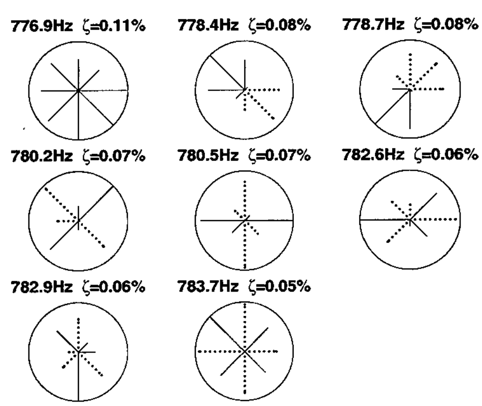


FIGURE 43. Mode Shapes for the Tuned, Coupled Case

The results indicate that the piezoelectric actuators did improve blade-to-blade coupling, but the improvement was weaker than hoped. Only the tuned, coupled configuration was able to achieve the desired extended mode shapes. The disappointing performance of the piezoelectric couplers can be qualitatively attributed to their lack of efficiency. Even though the size and location of each actuator captures a significant portion of the strain in the 2-stripe mode of a blade, conversion of this strain to electrical energy is limited by the inefficiency of the piezoelectric actuator.

The piezoelectric actuators would be much more beneficial at reducing the blade stresses in a mistuned system if they were used to add damping instead of increasing coupling. Results in the literature indicate that the damping of a very lightly damped engine blade could be easily increased by an order of magnitude with a tuned piezoelectric absorber. Increasing the damping by an order of magnitude reduces blade stresses by the same amount. This stress reduction is much more than could be expected from the elimination of rogue behavior in a mistuned system by increasing the blade-to-blade coupling.

Participating Organizations: Air Force Research Laboratory (AFRL)

Point of Contact:

Government
Mr. Robert Gordon
U.S. Air Force, AFRL/VASS
2145 Fifth Street, Suite 2
Wright Patterson AFB, OH 45433-7006
Phone: (937) 255-5200 ext. 402
Fax: (937) 255-6684
Email: robert.gordon@wpafb.af.mil

6.1.3 Centrifugally Loaded Viscoelastic Material Characterization Testing

FY 96-98

CSA Engineering was tasked to characterize the behavior of viscoelastic material under centrifugal loads. While a great deal of work was done characterizing and measuring the Poisson's ratio of representative viscoelastic material in the laboratory environment, only the results of exposing viscoelastic material to centrifugal loads in a spin test are discussed here. Two types of blades were spun. The purpose of the first type of blade (shown in Fig. 44) was solely to study the effect of quasi-static centrifugal loading on viscoelastic material. The material, cast in a pocket, was subjected to up to 25,000 g's. The predicted strain over the pocket compared well with measured strain.

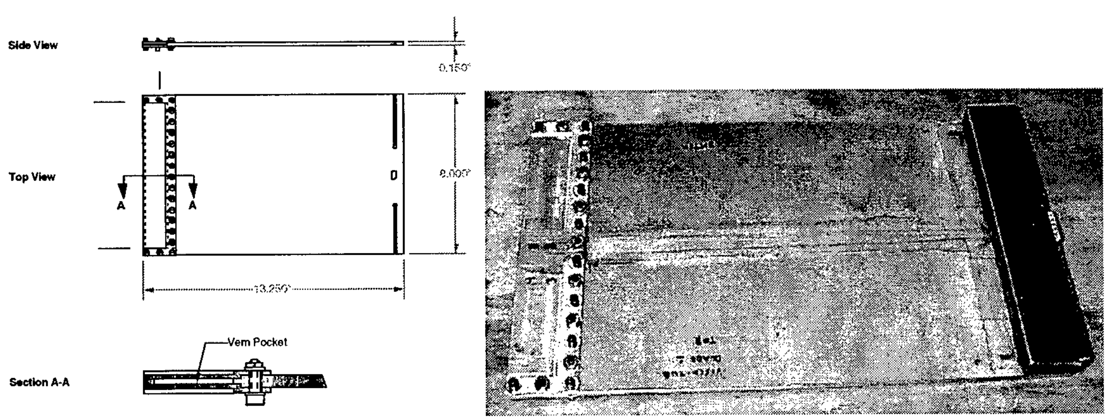


FIGURE 44. Viscoelastic Tub Blade Hardware

The second type of blade was designed to study the issues involved with damping fan blades cost effectively. The developed blade, shown in Figure 45, had a 1.5 aspect ratio. The blade consisted of two face sheets, the thicker of which had two 0.050-inch deep cavities that could be left empty or filled with viscoelastics. The sheets were held together with bolts and epoxy. The blade was instrumented with strain gages and piezoelectric patch (PZT) actuators.

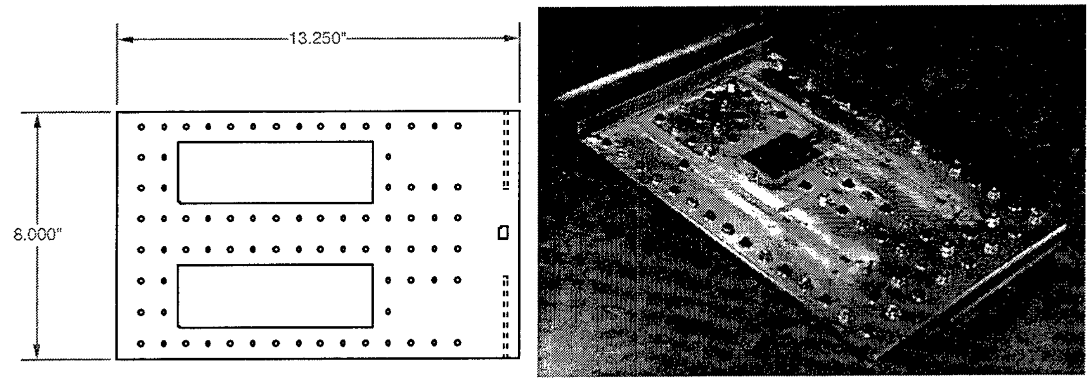


FIGURE 45. Damping Study Blade

The spun blade had one cavity filled with viscoelastic material and one empty cavity. This allowed further study of the effects of quasi-static stress on face sheets containing viscoelastics. A comparison of measured vs. predicted strain is shown in Figure 46. The measured strains for the full cavity are consistently higher than those for the empty one, as predicted. This blade was also exposed to 7,500 RPM, or the equivalent to 22,000 g's at the outmost location of the viscoelastic. The effectiveness of the damping design is seen in laboratory measurements comparing the damped blade and another completely empty but otherwise identical blade (see Fig. 47). The targeted higher-order modes, such as those near 400 and 700 Hz, were well damped. Damping would have been even more significant if both pockets had been full.

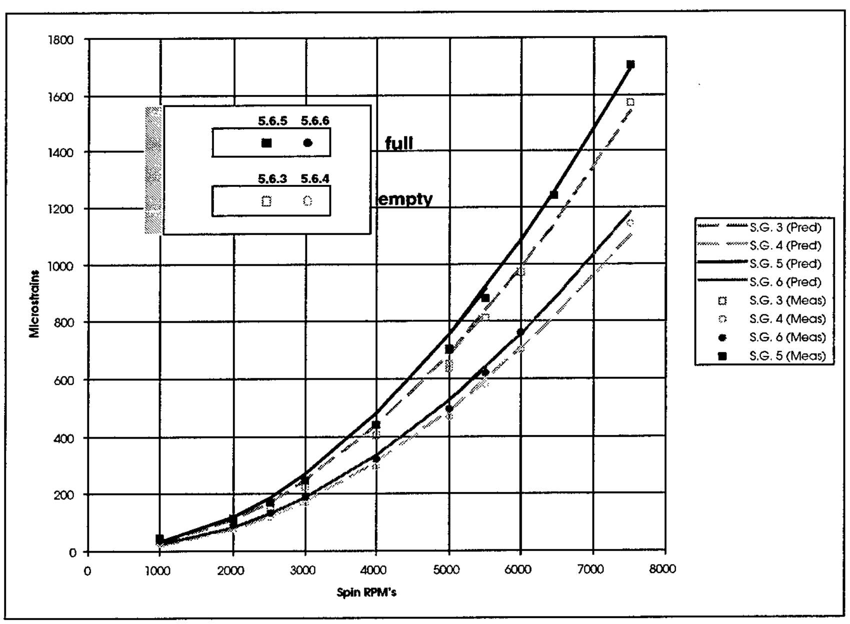


FIGURE 46. Comparison of Measured and Predicted Static Strain Over Cavity Locations for Various RPM Levels Where 7,500 RPM Corresponds to a Maximum of 22,000 g's

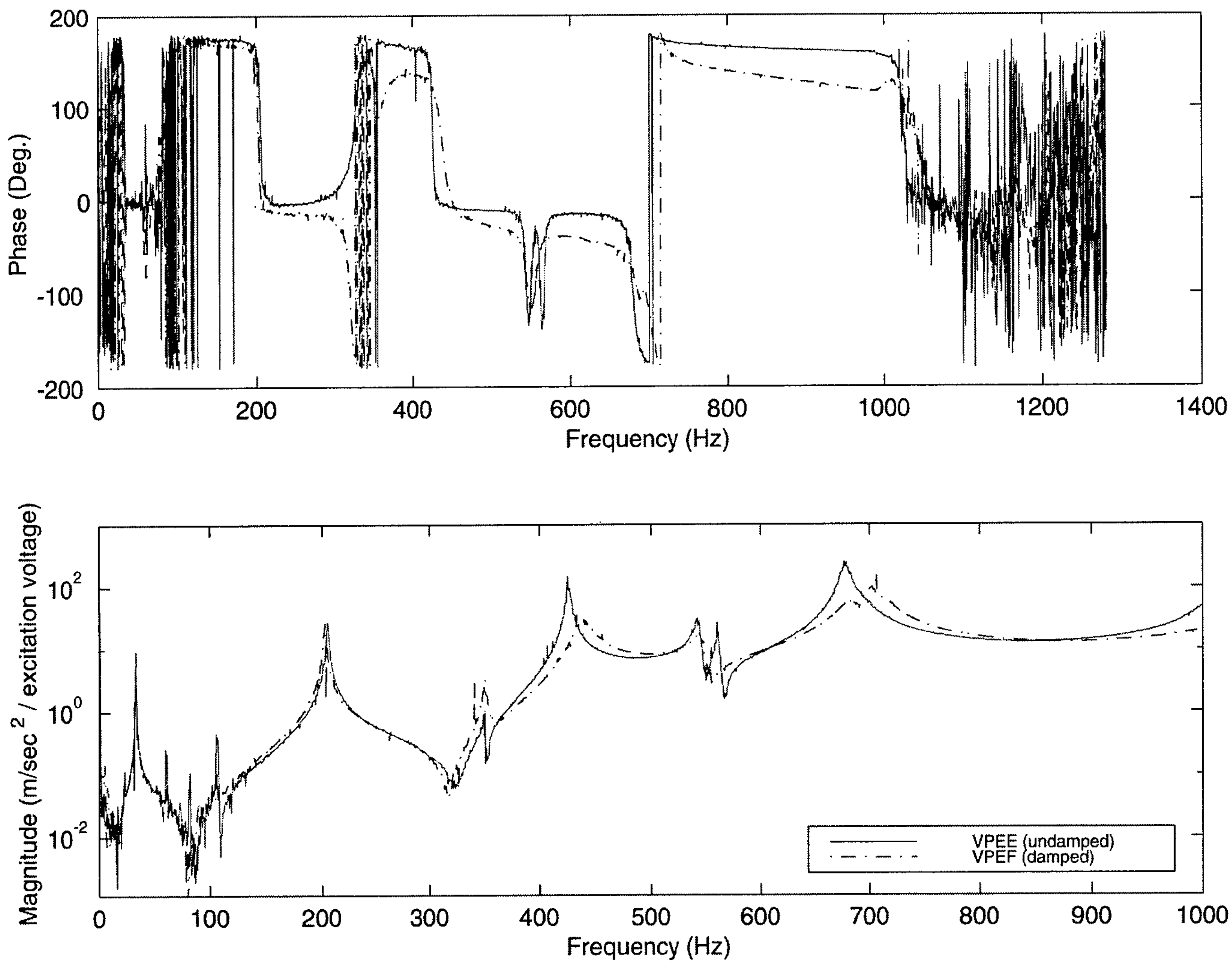


FIGURE 47. Comparison of Undamped and Damped Blade Response (One Pocket) to PZT Excitation in the Laboratory

Participating Organizations: CSA Engineering, Inc.

Points of Contact:

Government
Mr. Robert Gordon
U.S. Air Force, AFRL/VASS
2145 Fifth Street, Suite 2
Wright Patterson AFB, OH 45433-7006
Phone: (937) 255-5200 ext. 402
Fax: (937) 255-6684
Email: robert.gordon@wpafb.af.mil

Contractor
Mr. Eric Flint
CSA Engineering, Inc.
2565 Leghorn Street
Mountain View, CA 94043-1613
Phone: (650) 210-9000
Fax: (650) 210-9001
Email: eflint@csaengr.com

6.1.4 Damping for Extreme Environments

FY 97-99

Background: Multi-particle impact damping (MPID) consists of many small metallic or ceramic particles contained in a cavity that, when excited by vibrations, cause the base structural motion to be damped. Basically, the impact of particles on each other and on the cavity walls, friction between particles, and friction between particles and the cavity walls cause energy dissipation, which reduces the amplitude of the base structure vibration. Since the particles can be metallic or ceramic, they can be used at high temperatures, and since they can be designed to be temperature insensitive, the damping mechanisms are fairly temperature insensitive over wide temperature ranges.

Recent Progress: During the past year, much progress has been made in the analytical understanding of MPID. Early in the program, simple single degree-of-freedom (SDOF) models were developed. More sophisticated multiple degree-of-freedom (MDOF) models are currently being developed. The particle damper simulation code is based on X3D, an explicit finite element code typically used for impact analyses. The code contains various contact algorithms and bookkeeping routines and provides an appropriate framework for simulating particle damping through the use of the particle dynamics method. Force-displacement relations for both the normal and shear forces have been implemented. Preliminary simulation models are being developed, and the most appropriate method to estimate damping is being determined. Figure 48 shows simulated multiple-particle interactions.

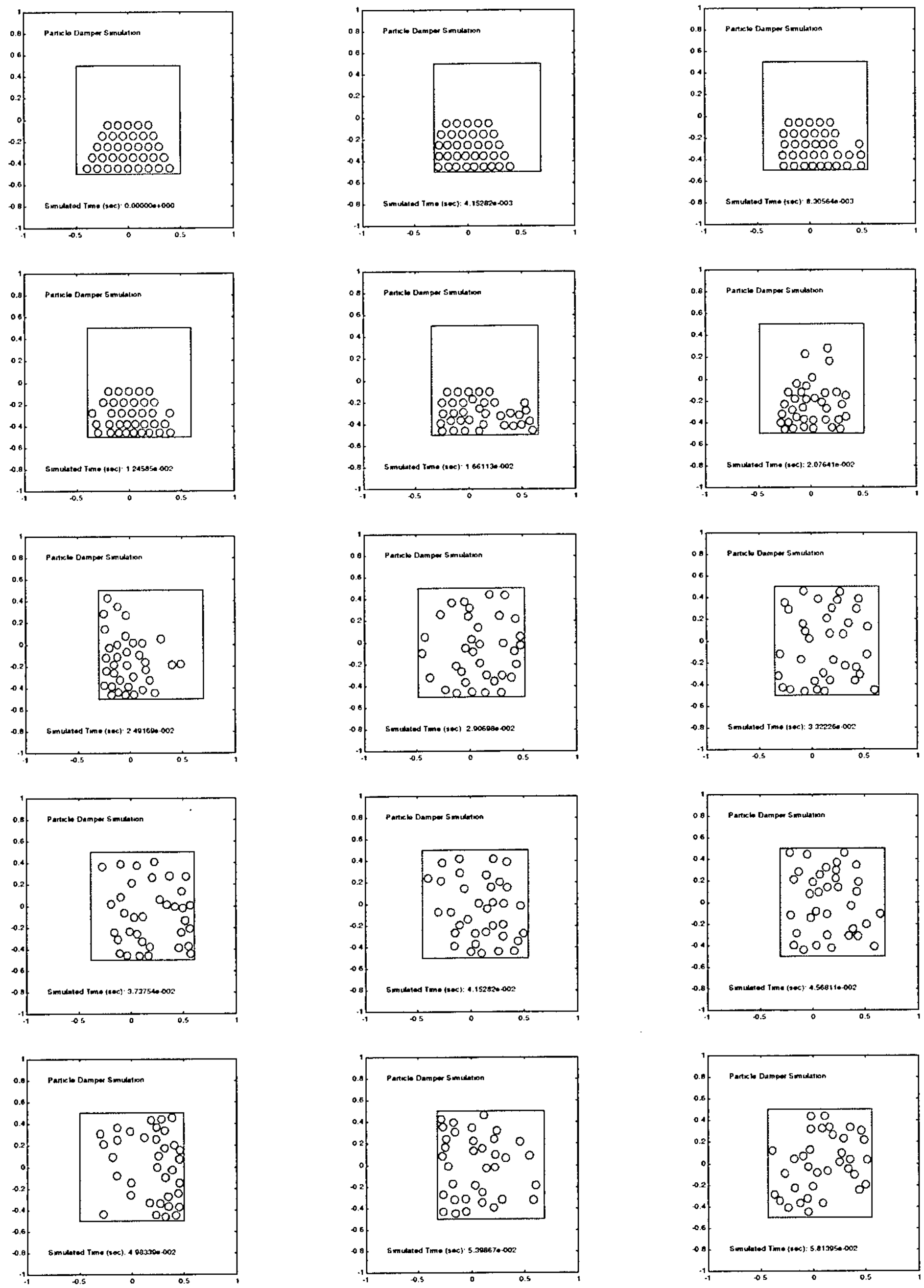


FIGURE 48. Selected Frames from Particle Damper Simulation

A high-temperature test system has been designed that is based on a cantilever beam. A freely-supported shaker is used to drive the beam. Response is transduced with an accelerometer. Since MPID is non-linear, sine-dwell testing is performed. A comparison of frequency response function (FRF) amplitude for damped and undamped systems at multiple excitation amplitudes is shown in Figure 49. Note that the test with a single particle shows high levels of damping until a "particle resonance" occurred. The second plot is much more representative of the amplitude reduction from multiple particles. Test data is currently being cataloged and compared to analytic predictions. High-temperature test articles with cavities of various sizes are shown in Figure 50.

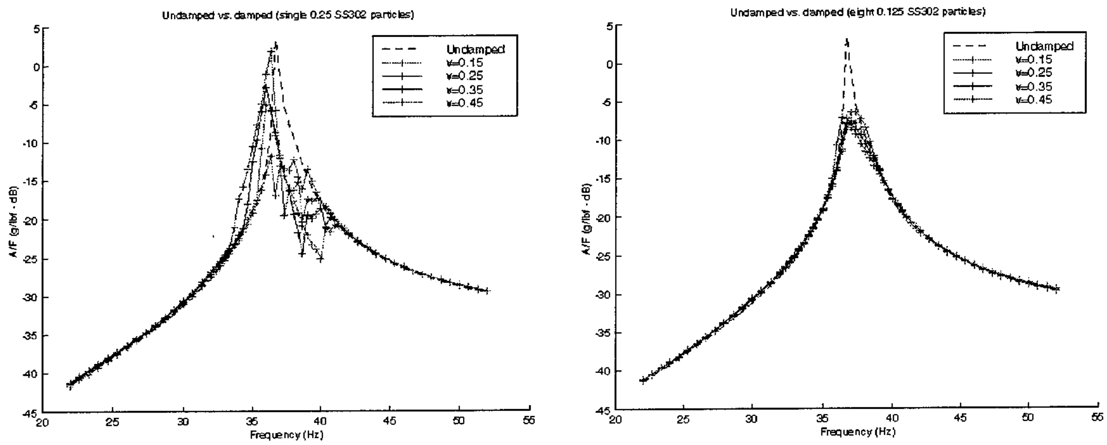


FIGURE 49. Undamped to Damped Comparison for Single and Multiple-Particle Tests

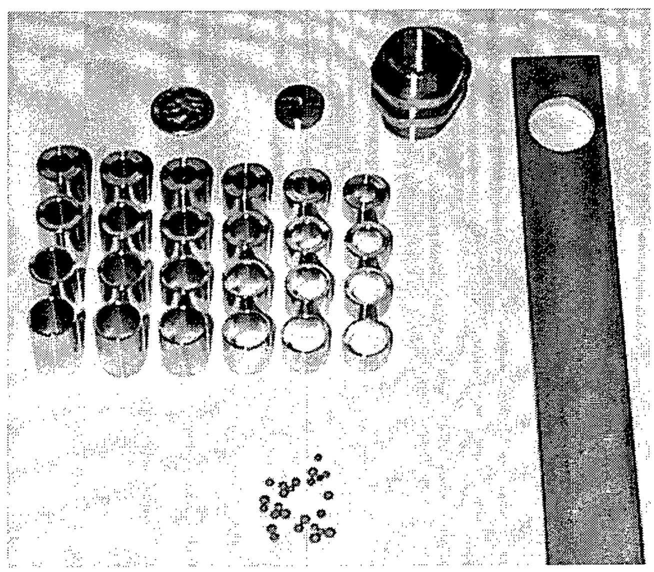


FIGURE 50. High-Temperature Test Articles

Participating Organizations: CSA Engineering, Inc., University of Dayton Research Institute

Points Of Contact.

Government
Mr. Robert Gordon
U.S. Air Force, AFRL/VASS
2145 Fifth Street, Suite 2
Wright Patterson AFB, OH 45433-7006
Phone: (937) 255-5200 ext. 402
Fax: (937) 255-6684
Email: robert.gordon@wpafb.af.mil

Contractor
Mr. Eric Flint
CSA Engineering, Inc.
2565 Leghorn Street
Mountain View, CA 94043-1613
Phone: (650) 210-9000
Fax: (650) 210-9001
Email: eflint@csaengr.com

6.1.5 Centrifugally Loaded Particle Damping

FY 96-00

Recent Progress: During the past year, significant progress was made in several areas critical to understanding particle damping and its potential for use in the rotating engine components, including:

- Characterization of the relevant dynamic disturbance environment
- Development of explicit analytical modeling/predictions tools
- Expanded experimental test methods and systems
- Improved data analysis and extraction tools

Particle damping is dependent on the motion of particles inside a cavity. If the disturbance levels are low, the particles cannot overcome friction and will not move. While experimental results clearly show damping effectiveness in the laboratory, it was not well understood how much dynamic acceleration occurred in engine blades. Without this information it was impossible to determine if particle damping treatments had a chance of overcoming the high friction forces caused by the centrifugal loads. The issue of actual disturbance levels has been resolved. Examination of the achieved disturbance levels in various centrifugally loaded tests performed by us and others revealed that actual achieved levels were lower than what would be experienced in an engine. An effort to experimentally identify the "turn-off" ratio has begun for a wide range of particle and cavity types relevant to the rotating engine components and temperature extremes, thus enabling more focused centrifugally-loaded spin testing. Preliminary results have shown that the treatments that give the best damping tend to "turn off" sooner than treatments that give slightly lower but still very acceptable damping.

Analytically, the capability to explicitly model the behavior of multiple particles, taking into account impact and frictional loss mechanisms was further developed. Methodologies were also developed to generate estimates of a blade's maximum allowable acceleration at any given point based on the blade's allowable fatigue limits. In the area of data extraction and analysis, improved methods for estimating amplitude dependent damping were developed based on the Hilbert transform. An example is shown in Figure 51.

Experimentally, efforts have concentrated on developing new test capabilities that will safely allow rapid testing of various particle damping concepts in the laboratory. The developed test system, which is currently being integrated (see Fig. 52 for some of the hardware) will allow particle damping treatments to be exposed to over 75,000 g's while being dynamically excited by piezoelectric patches. High g tolerant accelerometers will provide data up to 10,000 g's load, after which other piezoelectric-based sensors will be used. Additionally, experimental tests of limited scope were performed at low centrifugal loads for three capsule configurations.

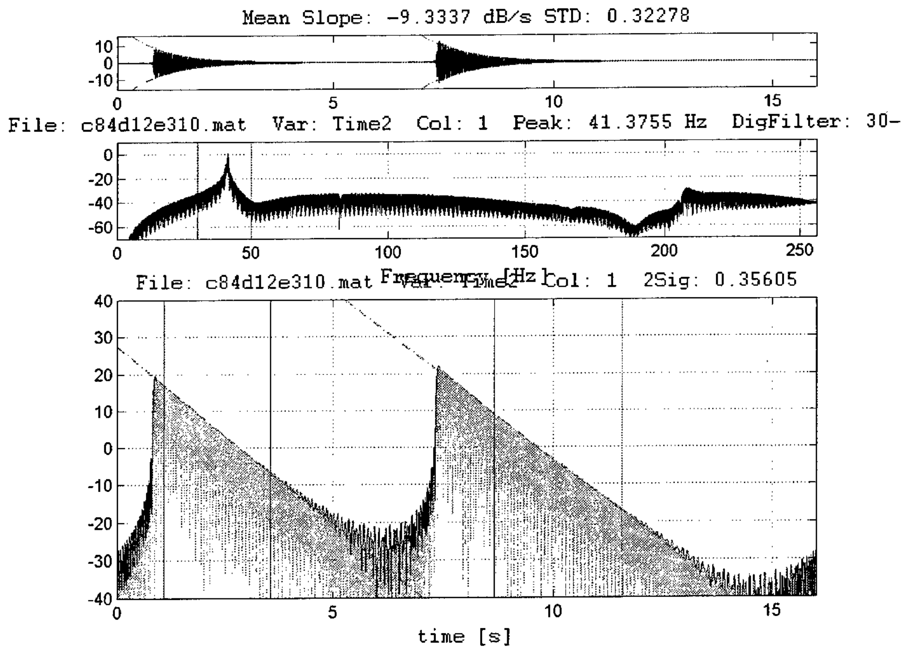


FIGURE 51. Example Time Domain Ring Down and Extracted Hilbert Transform Profile with Linear Fits for a Baseline Non-Damped Test Object

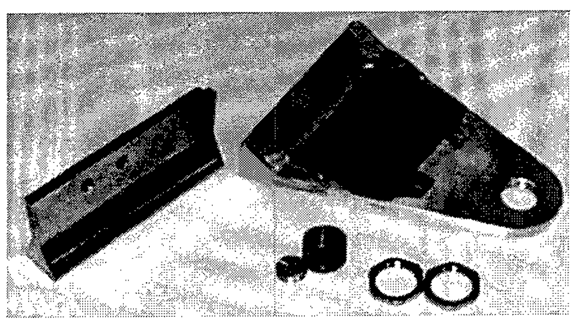


FIGURE 52. Phase II Blade, Counterbalance, and Test Capsules Prior to Blade Wiring and Encapsulation

Participating Organizations: **CSA** Engineering, Inc., University of Dayton Research Institute (UDRI)

Points of Contact:

Government
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
WPAFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Contractor
Mr. Eric Flint
CSA Engineering, Inc.
9500 Gilman Dr 0085
Palo Alto, CA 94303-3843
Phone: (650) 210-9000
Fax: (650) 210-9001
Email: eflint@csaengr.com

6.2 Modeling and Incorporation of Damping in Components

Of the four types of damping systems (friction dampers, viscoelastic damping systems, particle dampers, and powder damping systems), two were ready for use in the design of rotating components: friction and viscoelastic damping systems. A program was initiated to use friction dampers for lower-order modes and to establish their ability to damp higher-order modes. Although there were some concerns with using viscoelastic materials, it was decided that a design program should be started while final characterization of viscoelastic materials was pursued. Component design work for particle and powder damping systems was considered premature, due to a lack of knowledge and a lack of confidence as to the likely performance of either system in a centrifugal environment. Design and testing of components with these systems will occur in the future.

6.2.1 Advanced Damping Concepts for Reduced HCF

FY 96-00

Background: The objective of this task is to design damping into integrally bladed rotors. The new damped design will then be validated with a spin test. Although the original focus of this program was hollow fan blades, the program has been redirected toward concepts applicable to both hollow and solid blades. This change has occurred because of the increasing reliance of the manufacturers on rotors with solid blades.

Information has been gathered to define damping level requirements and the operational environment for a damping system. Team members Pratt & Whitney (P&W) and Honeywell Engines and Systems have provided environmental definition information including operating speeds, temperatures, and frequency ranges to the University of Dayton Research Institute (UDRI). They also have provided documentation regarding current and future blade systems and finite element models of typical blade designs.

Based on discussions with the Air Force, the UDRI/P&W/Honeywell team developed a list of damping concepts applicable to rotating bladed turbine engine hardware. A Delphi analysis was used to rate each of the damping concepts with respect to each of the evaluation criteria. The criteria were selected by the team to fairly address the effectiveness, reliability, and manufacturability of each of the concepts. All the evaluation factors were weighted evenly. The results of the Delphi analysis are indicated in Figure 53. Based on the assessment, the team and the Air Force decided to pursue detailed design and demonstration of a constraining layer rim damping (CLD) concept.

The rim damping concept will be demonstrated on a P&W Fan integrally bladed rotor (IBR). The target mode is the third leading edge (3LE) bending in the blade coupled with the nine nodal diameter bending of the rim. Several leading edge and trailing rim damping design concepts were developed by UDRI and reviewed by P&W with regard to manufacturability and clearance issues. Based on technical review among the team members, specific changes to the leading edge of the IBR were selected that will allow the damping concept to be applied to a surface that is cylindrical. For this particular IBR, the trailing edge rim is cylindrical and no changes are required for attaching the damping concept.

A finite element analysis (FEA) model of the IBR, which had previously been validated by P&W, was modified by UDRI to simulate the addition of a damping system. The FEA was used to evaluate two general conditions: expected effectiveness in damping vibrations and expected ability to withstand centrifugal loads. First, resonant frequency computations were performed over a range of viscoelastic material shear stiffness values. These analyses were used to optimize the strain energy ratio as a function of viscoelastic material shear stiffness for the 3LE bending mode.

Time and temperature data provided by P&W indicates that the optimal damping temperature should be 225°F for this IBR, and the survival temperature is 600°F. Because of the 375°F difference between operating temperature and survival temperature, a material like silicone will be needed to handle the temperature range. Unfortunately, silicone has a relatively low inherent material loss factor, on the order of 0.1. To obtain a significant damping level for the 3LE bend mode, the stiffness of the viscoelastic in the CLD system has been optimized to range where the CLD operates as a tuned damper, resulting in a large portion of the system strain energy being transferred into the viscoelastic. Efforts are ongoing to formulate a silicone that has the desired stiffness, temperature capabilities, and creep resistance.

Another issue is the stresses under centrifugal loading. The FEA indicates that steady stress levels in the most highly loaded areas are nearly unaffected by the addition of the damping system. However, the analysis indicates that a damping system with many segments is required to ensure acceptable strain levels in the viscoelastic due to radial growth of the rim under centrifugal loads. To reduce strain in the viscoelastic material under centrifugal loading, the titanium cover, which is acting as a mass for a tuned damper rather than as a typical constraining layer, will be segmented into pieces around the circumference of the rim.

During the next year, an IBR will be modified and a damping system installed. Bench testing will be used to assess the damping characteristics over a temperature range from 75°F to 300°F, which is the temperature range in which this IBR typically operates. A spin test will be performed at temperatures up to 600°F to assess survivability at high temperatures under centrifugal loading.

Damping Concept	Existing Technology Knowledge	Ease of Manufacture	Reliability	Transitionability to Existing Designs	Solves Mistuning Problems	Solves High-Frequency Resonance Problems	Solves Flutter and Surge Problems	No Performance Impact	Capability to Meet Environ. Conditions	Raw Score	Ranking
Constraining Layer Rim Damping	4	4	4	4	3	1	4	5	3	32	1
Rim Friction Damping	3	4	3	4	3	1	4	5	5	32	1
Damping Pocket With Cover Plate	4	3	3	3	3	2	4	4	3	29	2
Cast Damping Into Airfoil Cavities	4	2	3	1	4	4	4	5	3	29	2
Leading/Trailing Edge Sheathing	3	2	2	3	4	4	4	3	3	28	2
Rim Piezoelectric Damping	2	4	2	4	3	1	4	5	3	28	2
Particle Damping	2	3	3	3	3	1	4	4	5	28	2
Surface Coatings	2	3	2	3	3	4	4	2	3	26	3

Scale: 5=Excellent to 0=Bad

FIGURE 53. Delphi Analysis of Damping Concepts

Participating Organizations: University of Dayton Research Institute, Pratt & Whitney, Honeywell Engines and Systems

Points of Contact:

Government
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Contractor
Mr. Michael Drake
University of Dayton Research Institute, Inc.
300 College Park Av.
Dayton, OH 45469-4251
Phone: (937) 229-2654
Fax: (937) 229-4251
Email: drakeml@udri.udayton.edu

6.2.2 Damping System for Integrated High Performance Turbine Engine Technology (IHPTET) Program

FY 97-00

Background: The Damping Systems for the IHPTET Components program is a thirty-six month technical effort that was initiated in January 1997. The purpose of this program is the design, fabrication, instrumentation, bench testing, and spin testing of two damping systems, one for each of two blisk components. The specific objective of the design is to achieve effective magnification factors (Q) of approximately 50 or less for the targeted modes of vibration. The testing will demonstrate damping effectiveness and validate that the damping systems can reliably work under static and dynamic loads produced in a simulated turbine engine environment. Mr. Frank Lieghley, Jr., USAF Project Engineer, is administering this contract within the USAF.

Fabrication and inspection of the viscoelastic constrained layer damping system in all 16 airfoils of the Advanced Core Compression System (ACCS) blisk was completed (Fig. 54). Bench test results showed that significant damping was achieved, but damping was somewhat short of the goal. X-ray inspection revealed that the laser welds of the titanium coversheets did not achieve the desired 100% penetration. It was judged that the welds were adequate, but that we should conduct an overspeed proof test. Instrumentation was completed, and the damped blisk was shipped to Test Devices for spin testing. The proof spin test of the Allison ACCS damped blisk was conducted. During the attempt to attain the proof spin speed of 20,000 rpm, a shift in rotor vibrations was noticed at 15,000 rpm. The rig was shut down and inspected. It was found that three (of 32) titanium coversheets had partially failed in the region of laser weld (Fig. 56). In addition, two of the stainless steel constraining layers were released from the rotor. The blisk was sent to AADC for further inspection. The inspection revealed that an additional eight coversheets had visible weld cracks. The failure analysis concluded that a radial shift of the constraining layer caused a "wedging" load that failed the coversheet weld. As a result, testing of this design was suspended and Phase II of the contract is being replanned.

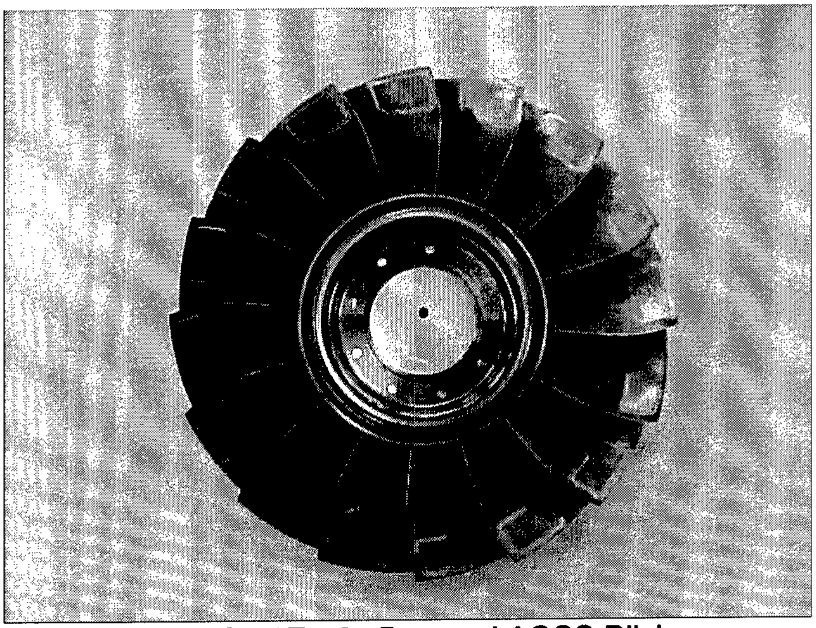


FIGURE 54. Damped ACCS Blisk

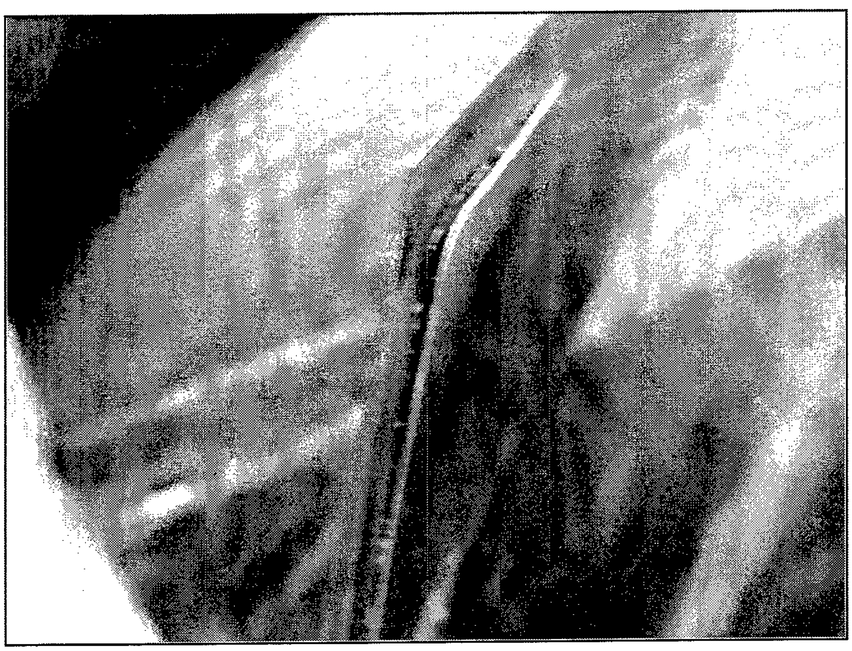


FIGURE 55. Weld Failure

Participating Organizations: General Electric Aircraft Engines, Rolls Royce Allison, Roush Anatrol

Points of Contact:

Government
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Contractor
Dr. Robert E. Kielb
General Electric Aircraft Engines
One Neumann Way, M/D K105
Cincinnati, OH 45215-1988
Phone: (513) 243-2821
Fax: (513) 243-8091
Email: Robert.Kielb@ae.ge.com

6.2.3 Evaluation of Reinforced Swept Airfoils / Internal Dampers

FY 96-00

Background: The objective of this project was to develop and spin test a friction damper for fans. The internal friction damper was designed and analyzed to maximize the damping characteristics of this damping system. The primary function of this design was to demonstrate its effectiveness in reducing the vibratory responses of selected high-order modes. A finite element design utilizing the friction damper was completed, a damping prediction analysis was performed on the component, and the analytical model was verified with static bench test data.

Recent Developments: The spin test was cancelled when it was determined that the likelihood of this component ever being placed into production was very limited. It was decided to redirect the program to address damping of integrally bladed rotors (IBRs). It has been aligned with the UDRI task on "Advanced Damping Concepts to Reduce HCF of Hollow Fan Blades" (see Section 6.2.1). The selected approach has been narrowed down to under-rim viscoelastic damping treatment.

Preliminary testing of this approach on a solid fan IBR has demonstrated good potential for modes with sufficient rim strain energy contribution. Concept demonstration of bench testing of the IBR in a 3rd LE bending mode resulted in a 20% reduction in response. This approach will be optimized for the real engine environment. Damping assessments will be demonstrated using bench testing only since the centrifugal loading will be designed to be perpendicular to the damping treatment. Survivability testing, however, will be demonstrated in a heated spin test facility. Upon completion of the spin tests, a repeat of the bench damping tests will be conducted to ensure that damping effectiveness still exists after exposure to the elevated temperature spin test.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney

Points of Contact:

Government
Mr. Jeffrey M. Brown
U.S. Air Force, AFRL/PRTC
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2734
Fax: (937) 255-2660
Email: jeffrey.brown@wpafb.af.mil

Contractor
Dr. Yehia El-Aini
Pratt & Whitney
P.O. Box 109600, West Palm Beach, FL 33410
Phone: (561) 796-5911
Fax: (561) 796-3637
Email: elainiye@pwfl.com

6.2.4 Damping for Turbines

FY 97-00

Background: The objective of this project is to develop new damping systems for turbines verified with spin-pit tests.

Damping improvements will provide increased design space for more-optimal blade and turbine stage designs. This will reduce aeromechanical risk for turbines and potentially, for other aeromechanical structures. Allowing simultaneously reduced weight and increased durability.

Recent Developments: A unique damping system has demonstrated stress reductions of up to 80% (damped/undamped x 100) alternating stress. This damping technology will enable new configuration designs to become viable by lowering blade stress response in expectedly harsher environments. With additional development and predictive modeling, the damping technology may routinely be used to enable even further reduced-weight rotors and engine systems.

Damper performance data has been obtained by spin testing in a unique HCF-driver spin-rig to generate information on several vibration modes of a blade. The variations of the experiments were designed to depend totally on the damping process under development without the involvement of other damping processes. Additionally, the approaches used to obtaining this data are innovative, while also providing repeatable and controlled drivers and responses above 20,000 Hz frequency.

Future Navy plans for FY00 involve the re-characterization of the damper's performance after exposure in a demonstrator engine. This will validate the durability of a particular design and add further to predictive models.

Participating Organizations: Pratt & Whitney

Points of Contact:

Government
Mr. Lewis Schmidt
NAVAIR, CODE 4.4.7.1
Bldg. 106, Unit #4
22195 Elmer Rd.
Patuxent River, MD 20670-1534
Phone: (301) 757-0465
Fax: (301) 757-0562
Email: schmidtlr@navair.navy.mil

Contractor
Mr. Al Stoner
Pratt & Whitney
M/S Ave. C
1306 Ave. C
Arnold AFB, TN 37389-4700
Phone: (931) 454-7591
Fax: (931) 454-0504
Email: stonera@pwfl.com

6.2.5 Dual Use Program

FY 00-01

Background and Plans: This program will provide damping improvements required to support advanced engine configurations. This will be accomplished by using rapid casting hardware fabrication techniques to generate rig hardware. The development of a verification method relying on rapid prototyping will reduce technology development cycle times. By providing designs rapidly, technology and innovation can be more readily proved out. This will allow marked progress toward improving damping, and delivering designs that meet program goals or requirements. It is not enough to develop new concepts, but these must be fully integrated into advanced cooled turbine blades. The key to developing advanced damping approaches is marrying the damper and blade design to the manufacturing process.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney Aircraft

Points of Contact:

Government
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Contractor
Mr. Al Stoner
Pratt & Whitney
M/S Ave. C
1306 Ave. C
Arnold AFB, TN 37389-4700
Phone: (931) 454-7591
Fax: (931) 454-0504
Email: stonera@pwfl.com

6.2.6 Transition of Damping Technology to Counterrotating Low-Pressure Turbine Blades

FY 00-01

Counterrotating turbine designs subject the low-pressure turbine (LPT) blades to high-frequency excitation from the high-pressure turbine blades immediately upstream. The vibratory response of the LPT blades is in a high-order airfoil mode for which typical platform friction dampers used for lower modes are less effective. This contract addresses innovative damping concepts to provide damping for higher-order LPT turbine blade airfoil modes.

The Contract consists of two Tasks. In Task 1, GE Aircraft Engines, working with subcontractors, Roush Anatrol Division of Roush Industries and Allison Advanced Development Company, will design and provide simple test specimens with two different damping treatments to the USAF for elevated temperature testing. The Turbine Engine Fatigue Facility (TEFF) at the U.S. Air Force Research Laboratory will contrast damping performance of the two treatments for selected airfoil modes of vibration with untreated baseline specimens. In Task 2, a preferred damping treatment will be selected, based on the Task 1 test results, and applied to prototype LPT blades. These blades will then be tested at elevated temperature at the U.S. Air Force TEFF.

Participating Organizations: General Electric Aircraft Engines, Rolls Royce Allison & Roush Anatrol

Points of Contact:

Government
Mr. Frank Lieghley, Jr.
U.S. Air Force, AFRL/PRTC
1950 Fifth Street, Bldg. 18D
Wright Patterson AFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: frank.lieghley@wpafb.af.mil

Contractor
Mr. James A. Griffiths
General Electric Aircraft Engines
One Neumann Way, M/D A413
Cincinnati, OH 45215-1988
Phone: (513) 243-2770
Fax: (513) 243-8091
Email: james.griffiths@ae.ge.com

6.3 Conclusion

By conducting rig, component, and engine tests, and by developing very successful modeling techniques, the Passive Damping Technology Action Team has evaluated numerous damping schemes with great potential. The Team has demonstrated that the historically-based "rainbow" or mixed wheel concept is not an acceptable test protocol for HCF modal damping investigation, and that designing a viscoelastic damping system insertion into a mechanically sound rotating blade may be more difficult than it appears. This team has also demonstrated the feasibility of applying viscoelastic damping to the rim of a bladed rotor rather than to the blade surface. Doing so could effect an 80% reduction in blade stresses. Completed initial tests of an internal "dip stick" friction damper for turbine blades also demonstrated up to 80% stress reduction. The turbine friction damping effort has been a major success, with test results showing vibratory reductions much greater than predicted. The turbine damper is currently being applied in an advanced engine development program. Manufacturability of damping solutions is being evaluated as a major area of future emphasis.

7.0 AEROMECHANICAL CHARACTERIZATION

BACKGROUND

The Aeromechanical Characterization Action Team (Aeromechanical AT) is responsible for fostering collaboration between individual HCF programs and test opportunities with the goal of providing the required design and test verification focus for the entire HCF S&T program. The Aeromechanical AT provides technical coordination and communication between active participants involved in HCF testing technologies and the Test and Evaluation Plan under development at Arnold Engineering Development Center (AEDC). Annual technical workshops have been organized, and summaries of these workshops are disseminated to appropriate individuals and organizations. The Chair, Co-Chair, and selected Aeromechanical AT members meet annually to review technical activities, develop specific goals for test and evaluation programs, and review technical accomplishments. The Chair (or Co-Chair) reports to the Technical Plan Team (TPT) and National Coordinating Committee (NCC) on an annual basis. The secretary of the TPT is informed of AT activities as needed. This AT includes members from government agencies, industry, and universities who are actively involved in technologies applicable to turbine engine HCF. The team is to be multidisciplinary, with representatives from multiple organizations representing several component technologies as appropriate. The actual membership of the AT will change as individuals assume different roles in related programs.

ACTION TEAM CHAIRS

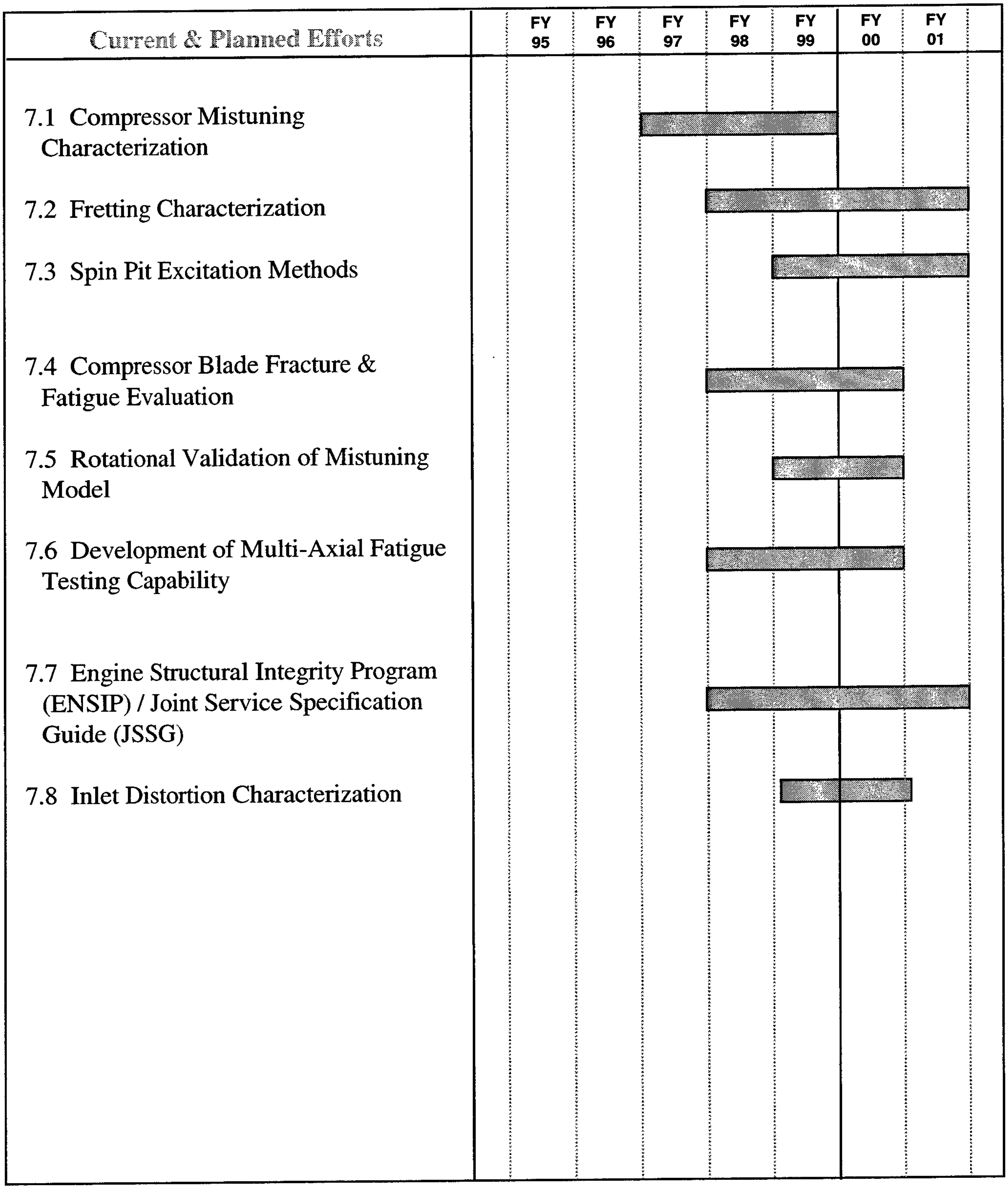
Chair
Dr. Douglas C. Rabe
U.S. Air Force, AFRL/PRTE
1950 Fifth Street, Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-6802 x231
Fax: (937) 255-0898
Email: douglas.rabe@wpafb.af.mil

Co-Chair
Mr. Joseph Babilon
U.S. Air Force, Arnold Air Development Center
AEDC/DOT, M/S 9011
1099 Avenue C
Arnold AFB, TN 37389-9011
Phone: (931) 454-4330
Fax: (937) 454-3559
Email: babilon@hap.arnold.af.mil

INTRODUCTION

The following pages summarize the schedules, descriptions, and progress of the current and planned projects managed by this action team.

Aeromechanical Characterization Schedule



7.1 Compressor Mistuning Characterization

FY 97-99

Background: The objectives of this task are to characterize mistuned response at speed in an integrally bladed disk, or blisk, and to compare experimental results to mistuning code predictions. The findings can be used to evaluate and improve mistuning prediction codes for more accurate prediction of stresses and stress variations. Research is currently applied to fans but may also be extended to compressors and turbines. Structural variations in turbomachine blades cause variations in the natural frequencies of the blades, known as mistuning. Mistuning leads to mode localization, which can cause dangerously high resonant stresses in a single blade or group of blades. Various factors including manufacturing tolerances, wear, and unsteady aerodynamics can affect the mistuned response. Measurement of the mistuned response and characterization of the factors influencing the response is necessary to develop accurate stress prediction models that account for the effects of mistuning.

Recent Progress: Testing of the rotor has been completed, and the mistuned response of the blisk has been characterized for the modes of interest. Mistuned response was affected by different factors for different modes. Aerodynamic coupling dominated the mistuned response at the first blade mode. Comparison to the model yielded significant qualitative insight but indicated a need for improved modeling of aerodynamic effects. The second and third modes occurred at nearly the same frequency, resulting in mode interaction as shown in Figure 56. Because of this, these modes were difficult to characterize, both experimentally and analytically. Results have indicated a need for additional modeling of mode interaction and unsteady aerodynamics, as well as improved physics-based modeling of the fundamental structural mistuning problem. Experimental characterization efforts for this project are now concluded until further developments in modeling are achieved.

$\omega = 1224$ Hz $\qquad\qquad \omega = 1225$ Hz

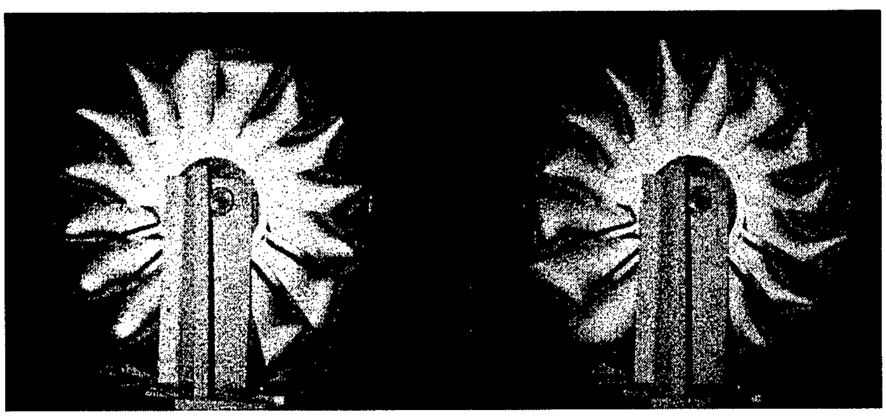


FIGURE 56. 2B/1T Mode Interaction.

Participating Organizations: Air Force Research Laboratory

Point Of Contact

Government
Dr. James Kenyon
U.S. Air Force, AFRL/PRTE
1950 Fifth Street, Building 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-6802
Fax: (937) 255-0898
E-mail: james.kenyon@wpafb.af.mil

7.2 Fretting Characterization

FY 98-01

Background: The objective of this task is to develop an understanding of the mechanical drivers in fretting fatigue and develop techniques to minimize their impact on material behavior. In particular the metal-to-metal dovetail attachment of blade and disk attachments will be studied. Fretting fatigue is approximately 6 percent of all HCF failures. The elimination of this problem correlates to six million dollars ($6,000,000) per annum saved in maintenance costs.

The primary mechanical life drivers will be established through a systematic variation of various contacting bodies, the first of which will be "dog bone" specimens placed into contact by cylindrical pads. Different contact loads will be applied to determine the effect of the applied loads on fretting fatigue. Fatigue parameters will be evaluated as to their ability to predict the number of cycles to crack initiation, crack location, and crack orientation along the contact surface. The evaluation process will provide the basic mechanisms for fretting fatigue crack initiation for metal to metal contact. The second phase of the program will concentrate on real blade-disk geometry. Simulated contact surfaces will be loaded in a manner similar to those experienced in a turbine engine environment. The fatigue parameters developed for fundamental surfaces will be evaluated and modified as necessary to predict fretting fatigue on the real blade-disk geometry. Subsequent programs will then explore techniques to minimize the detrimental effects of fretting fatigue in turbine engines.

Recent Progress: To date, 96 "dog bone" specimens have been fabricated and tested to failure. Fatigue parameter evaluation has been completed on the simplified geometry. A single fir tree specimen, which is symbolic of the real part, is currently being modeled via finite element analysis. A fretting fatigue parameter has been developed based on the interaction between a plain fatigue specimen and a simplified pad geometry. It has been determined that fretting fatigue crack initiation occurs on the plane of maximum shear stress amplitude and that it is dependent on the amount of slip at the crack location. A simulated blade dovetail and disk slot (single fir tree component) have been modeled and CAD drawings have been developed for machining.

The simulated blade-dovetail and disk slot will be tested in order to assess the accuracy of the fretting fatigue mechanisms determined through the simplified geometry approach. The robustness of the predictive model will be evaluated by considering the crack initiation behavior on the single fir tree component. The final phase of fretting fatigue research will involve employing methods such as coatings and compressive residual stresses in order to alleviate the fretting damage induced at the blade disk interface. The estimated completion date is September 2001.

Participating Organizations: Air Force Research Laboratory, Air Force Institute of Technology, Pratt & Whitney

Point Of Contact

Government
Mr. Christopher Lykins
U.S. Air Force, AFRL/PRTC
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 255-2660
Email: christopher.lykins@wpafb.af.mil

7.3 Spin-Pit Excitation Methods

FY 99-01

Background: The objective of this task is to develop a reliable and controlled method for exciting and measuring blade and rotor resonance modes of interest using a spin-pit test. Steady-state blade excitation in a spin pit will enable potential HCF problems and fixes to be addressed early in the development cycle of a rotor. This capability will provide a low-cost alternative to the expensive verification tools (rig and engine testing) currently in use.

Recent Progress: A contract with Test Devices was awarded in June 1999, and the kick-off meeting was held at their facility in July. The meeting was attended by Pratt & Whitney, General Electric, Rolls-Royce Allison, the Navy, and the Air Force, who all have interest in the technology and are involved to some degree in the effort.

Several methods of blade excitation were considered in the initial phase of this contract. A ranking of these methods was accomplished based on their likelihood of success and practical considerations for implementation. The result was a down-select to four methods, including low density air jets, liquid jets, fog jets, and condensing jets.

These four methods will now go through a series of analyses and experiments to select the most promising concept(s). A small four-bladed rotor is being designed with removable instrumented blades to further evaluate the concept(s). A full-scale rotor spin test will then be performed at the end of the contract to demonstrate the steady-state blade/rotor excitation system.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Warfare Center (NAWCAD), Test Devices Incorporated

Points of Contact:

Government
Mr. Frank Lieghley
U.S. Air Force, AFRL/PRTC
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-1867
Fax: (937) 255-2660
Email: Frank.Lieghley@wpafb.af.mil

Contractor
Mr. Paul Wawrzonek
Test Devices Incorporated
6 Loring St.
Hudson, MA 01749
Phone: (978)562-6017 ext. 246
Fax: (978)562-7939
Email: pwawrzonek@testdevices.com

7.4 Compressor Blade Fracture and Fatigue Evaluation

FY 98-00

Background: The objective of this effort is to determine the enhancement capabilities of Laser Shock Peening (LSP) on Foreign Object Damage (FOD) tolerance and HCF resistance when applied to real gas turbine engine compressor blades. A series of F100-PW-229 fourth-stage compressor blades will be evaluated. LSP-treated and untreated blades will be driven to failure at a resonance condition on a shaker table. FOD damage will be simulated on some of the LSP-treated and untreated blades by machining a notch at the leading edge of the blade. The fatigue life of the LSP-treated and untreated blades with and without the simulated FOD will be compared to determine the damage tolerance enhancement of LSP.

Recent Developments: All airfoils to be evaluated have been delivered to the Turbine Engine Fatigue Facility (TEFF) at Wright-Patterson AFB. Testing of the airfoils began in 1999 with approximately 12 airfoils fatigued before experimental problems developed. The shaker system will be back on-line in early 2000 and testing will resume. Testing will be completed on the F100-PW-229 fourth-stage airfoils in FY00.

Participating Organizations: Air Force Research Laboratory (AFRL)

Point of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 255-2660
Email: charles.cross@wpafb.af.mil

7.5 Rotational Validation of Mistuning Model

FY 99-00

Background: The objective of this task is to validate the REDUCE reduced ordered mistuning model developed at the University of Michigan under the GUIde Forced Response Consortium. Initial evaluation using engine hardware (see Section 7.1 above) has been performed, and the reduced order modeling code has shown promise in predicting mistuning response in full engine hardware. However, full validation of the model in needed and will allow for more complete understanding of structural mistuning and application of this code in the HCF test protocol.

In this study, a simulated bladed disk assembly (Fig. 57) will be intentionally mistuned based on the reduced order model predictions, and then experimentally evaluated. Validation data will be obtained from bladed disks under stationary and rotational conditions. Stationary data will be obtained through laser vibrometry at the University of Michigan. Additional stationary and rotational test data will be acquired using strain gages, holography, and SPATE in the vacuum chamber of the Turbine Engine Fatigue Facility of AFRL. The experimental results from the mistuned disks will be compared to the reduced ordered modeling predictions.

Experimental equipment is in place at both the Air Force Research Laboratory and the University of Michigan. Design of final test articles is complete and the disks are currently being machined. Testing of the components should begin in early 2000.

Recent Progress: No activity was reported in 1999.

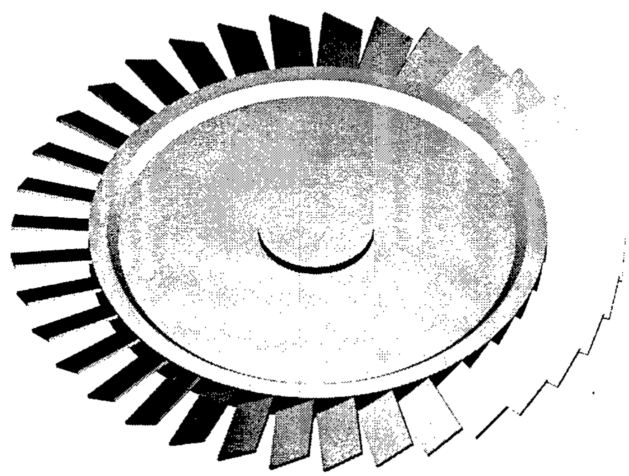


FIGURE 57. Mistuning Validation Simulated Bladed Disk

Participating Organizations: Air Force Research Laboratory (AFRL)

Points of Contact:

Government
Dr. Charles Cross
U.S. Air Force, AFRL/PRTC
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 255-2660
Email: charles.cross@wpafb.af.mil

Contractor
Dr. Christophe Pierre
University of Michigan
2250 G. G. Brown Bldg.
2350 Hayward Street
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109-2125
Phone: (734) 936-0401
Fax: (734) 647-7303
Email: pierre@umich.edu

7.6 Development of Multi-Axial Fatigue Testing Capability

FY 98-00

Background: The objective of this task is to develop the capability to test turbine engine components in a bench-test environment that simulates vibrational loading effects experienced during engine operation. Research goals are to develop a test system that simulates operational blade loading and to develop a data acquisition system that will accurately monitor critical test parameters. This test capability will provide a low-cost method to evaluate turbine engine blades for HCF.

A test fixture (Fig. 58) was designed and constructed to test gas turbine blades under biaxial loading conditions. A load cell on the primary axis was employed to simulate the centrifugal loading experienced by the blade. A ram on a second axis allowed for vibrational loads simulating bending to be induced in the airfoil. Combined, the loading allows for fatigue testing under simulated operational environments. In Phase II, the concept is being extended for multi-axial fatigue. Two rams are positioned on the second axis, and depending on their relative position, either bending or torsion can be induced in the airfoil.

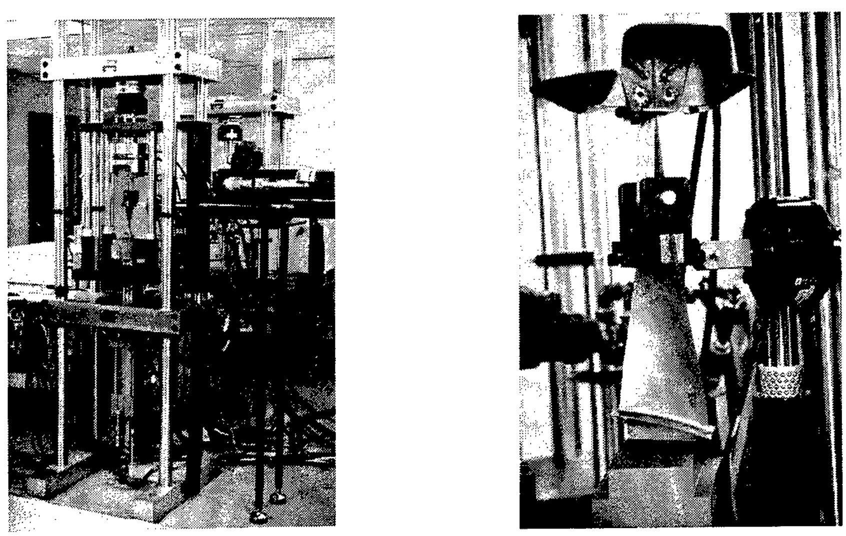


FIGURE 58. Proof of Concept Biaxial Fatigue Fixture

Recent Progress: The design of the multi-axial fatigue frame (Figure 59) was completed in early 1999. Installation in the Turbine Engine Fatigue Facility (TEFF) began in August 1999 an is now complete. Shakedown of the system and initial testing is underway. Testing of fan blades will begin in early 2000.

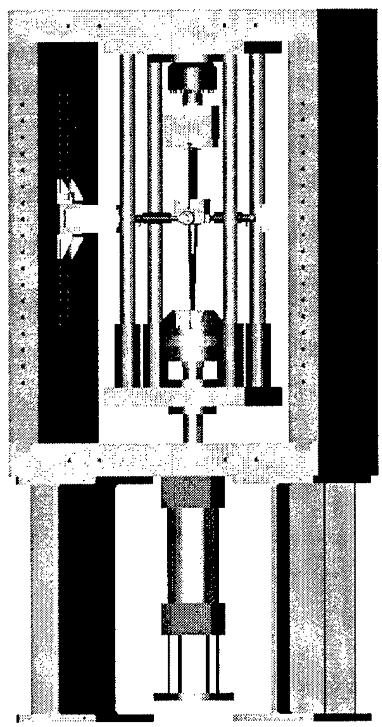


FIGURE 59. Multi-Axial Fatigue Model

Participating Organizations: Air Force Research Laboratory (AFRL)

Points of Contact:

Government
Mr. Gary Terborg
U.S. Air Force, AFRL/PRTC
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 656-5530
Fax: (937) 255-2660
Email: Gary.Terborg@wpafb.af.mil

Contractor
Dr. Ming Xie
AdTech Systems Research
1342 N. Fairfield Rd.
Dayton, OH 45432
Phone: (937) 426-3329
Fax: (937) 426-8087
Email: mingxie@compuserve.com

7.7 Inlet Distortion Characterization

FY 99-00

Background: The objective of this project is to develop a technique to produce inlet flows that simulate conditions experienced in-flight. This will improve the fan system development process for aeromechanical evaluation of blade vibrations due to inlet flow distortions. As a result of this effort, aeromechanical risks to fan systems will be reduced by implementing a proper test and evaluation technique to simulate appropriate inlet flow field conditions, which are similar to those experienced in flight. The outcome of this program will be incorporated in the HCF test protocol. The technical challenge is to accurately predict the inlet flow distortion and the resulting unsteady forces experienced by a fan. In particular, key modeling requirements need to be determined for defining the excitation types on the fan's vibratory response. The approach is use data analysis and computational analysis methods of flight, ground, and model tests of the F-16/F110, and the model test data of an Advanced Compact Inlet System (ACIS).

Recent Progress: The initial data analysis of roughly 50 conditions from the flight tests of the F-16/F110 flight data has given a correlation of vibe stress versus excitation strength, defined by a Modal Excitation Index (MEI), as shown in Figure 60. This stress versus MEI correlation is based on the use of the two rings of total pressure measurements obtained during the flight test. It does NOT include the effects of distortions in other flow variables, namely static pressure and flow angularity.

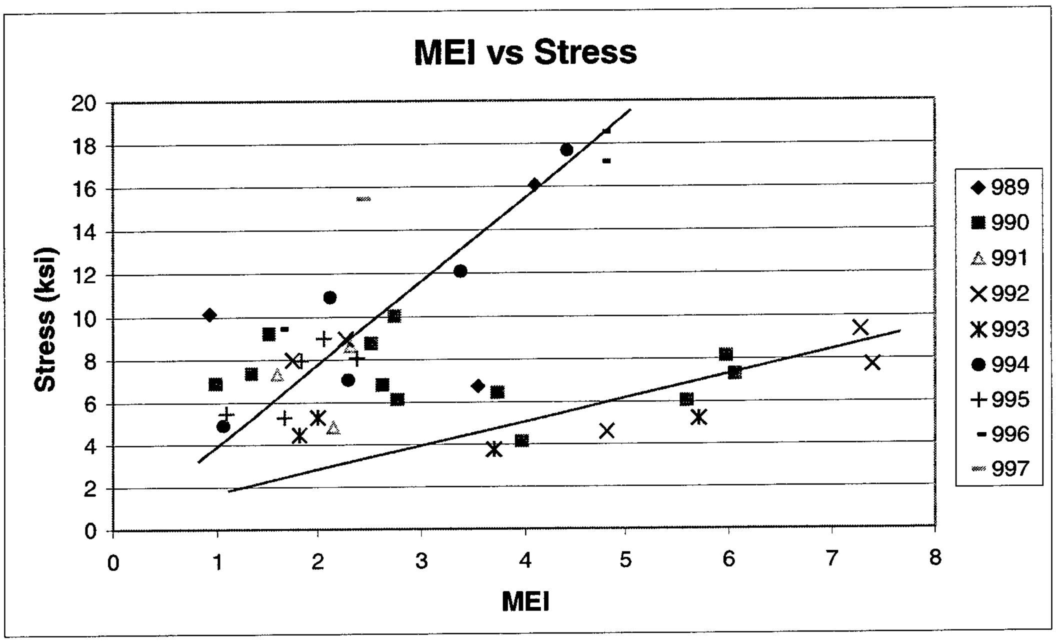


FIGURE 60. Initial Correlation between Vibratory Stresses and Modal Excitation Index (MEI)

This initial attempt shows the potential of being able to use the MEI method to correlate with vibratory stress. However, two distinct, linear curves are shown in the correlation. Further analysis was performed to determine if the source of the different correlations is from the inability to accurately resolve the distortions radially with only using two rings of information. To help demonstrate this, Figure 61 shows the comparison between predictions obtained from computational fluid dynamics (CFD) predictions and the measurements for the supersonic, deceleration condition. This is one of the highest vibe stress cases in the above correlation, Figure 60. As can be seen the excitation (distortion) increases dramatically at roughly 85% span which is further outward in radius than the outer of the two measurement locations.

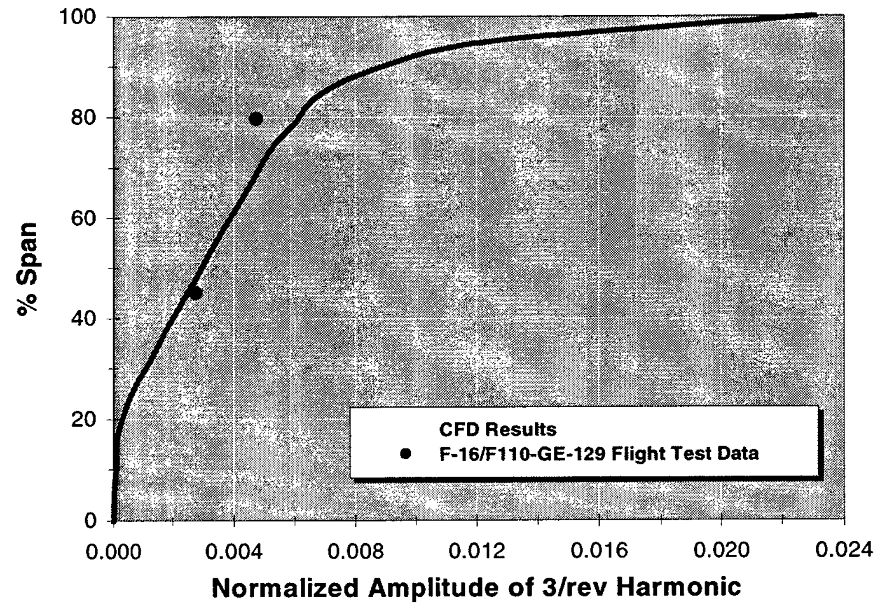


FIGURE 61. CFD Prediction and Measurements of 3/rev of Supersonic, Decel

To determine if this is the possible cause of the two correlation trends seen in Figure 60, the radial distribution from the CFD results was matched to the data and the MEI calculation was performed. The resulting MEI was increased roughly by a factor 2 to 3. As seen in the modified correlation of Figure 62, this causes the supersonic, cruise data point (1a) of the upper curve to be a better match (Point 1b) the trend of the lower curve. Thus, this implies that the two correlation trends are due to some flight conditions having important distortion content in regions at higher radius than the measurements.

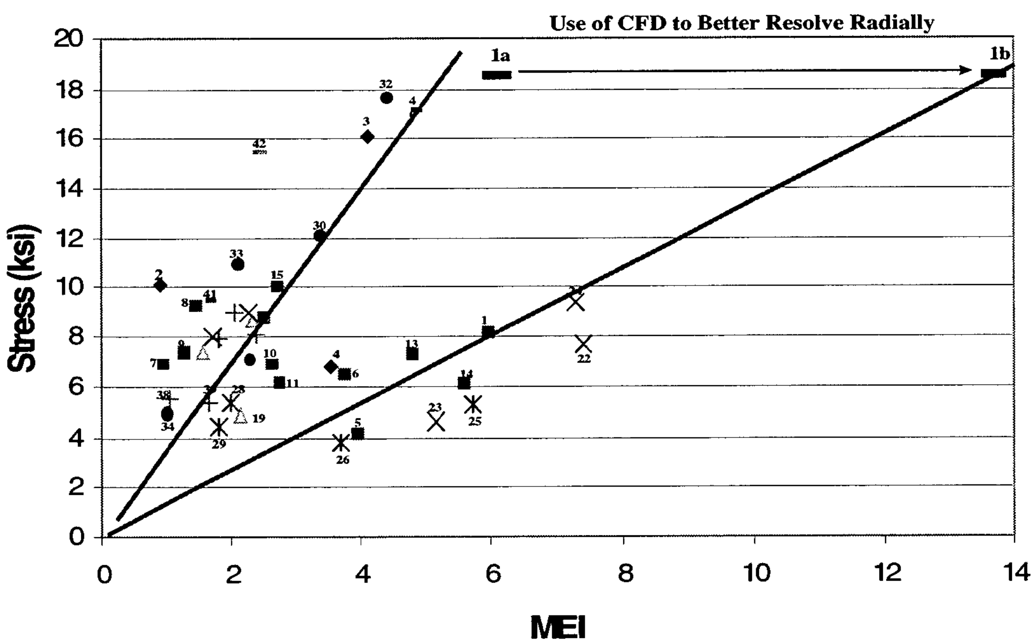


FIGURE 62. Modified Correlation between Vibratory Stresses and MEI

Participating Organizations: Aeromechanics Technology

Points of Contact:

Government
Dr. Douglas C. Rabe
U.S. Air Force, AFRL/PRTE
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-6802 x231
Fax: (937) 255-0898
Email: douglas.rabe@terc.wpafb.af.mil

Contractor
Dr. Steven Manwaring
Aeromechanics Technology
Address:
GE Aircraft Engines
One Neumann Way MD-A413
Cincinnati, OH 45215
Phone: (513) 243-3428
Fax: (513) 243-8091
Email: steve.manwaring@ae.ge.com

7.8 Engine Structural Integrity Program (ENSIP) / Joint Service Specification Guide (JSSG)

FY 98-01

In 1998, an effort was undertaken at the recommendation of the Executive Independent Review Team (EIRT) to update JSSG-87231 and MIL-HDBK-1783A (the ENSIP Manual) with what we have learned as a result of the HCF initiative. Three teams ("Analysis," "Testing," and "Materials") were formed to look into what changes were needed. The teams worked throughout 1998 and early 1999 formulating their recommendations.

In 1999, it was decided to update the ENSIP Manual first. The three teams began providing recommendations in May 1999. A series of draft revisions have been made to the ENSIP Manual based on these recommendations. Some of the updates include new analyses for mistuning and damping, changes in testing procedures, and updated requirements on material properties. The update to the ENSIP Manual is scheduled to be completed in July 2000, with the update to the JSSG to follow.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Systems Command (NAVAIR), NASA Glenn Research Center

Point of Contact:

Government
Ms. Sharon Vukelich
U.S. Air Force, ASC/ENFP
2530 Loop Road West, B560
Wright-Patterson AFB, OH 45433-7101
Phone: (937) 255-4056 x3456 or (937) 255-8553
Fax: (937) 255-8323
Email: sharon.vukelich@wpafb.af.mil

7.9 Conclusion

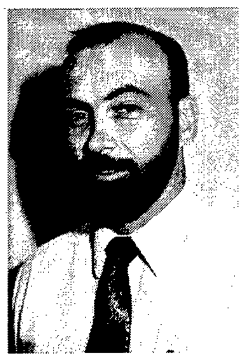
The Aeromechanical Characterization Action Team completed a F119 turbine rig test, which successfully measured the unsteady airflows acting on engine airfoils. In addition, a fan test rig was completed which demonstrated unsteady pressure measurements using pressure-sensitive paint. Key effort is focused on cooperative efforts across the Science & Technology (S&T), Test & Evaluation (T&E), and service engine development organizations to establish a new Joint Service Guide for High Cycle Fatigue. The guide includes materials, analysis methods, and new test protocols. The draft document is now under review.

8.0 ENGINE DEMONSTRATION

BACKGROUND

The Engine Demonstration Action Team (Engine Demo AT) has the responsibility of coordinating all the emerging HCF technologies with planned engine demonstrator targets. The engine demonstrations are responsible for acquiring the necessary data to establish, or update, the design space for the specific emerging HCF technologies so that the technology can then transition to meet user mission-specific requirements. The technology action teams will develop their specific HCF technologies to an acceptable level of risk to run on a demonstrator engine. Initial engine demonstrator planning was based on the original set of HCF technologies that was approved, and is constantly being updated as the budget and technologies change. The Demo AT has been concentrating on the turbojet/turbofan fighter engine class, which includes IHPTET demonstrator engines, JSF F119, JSF F120, and F-22 F119. Planning for the F110-129, F100-229 and other engines in the operational inventory is in process. Detail is only given on the IHPTET demonstrators because of the competitive and proprietary issues associated with the product engines.

ACTION TEAM CHAIRS



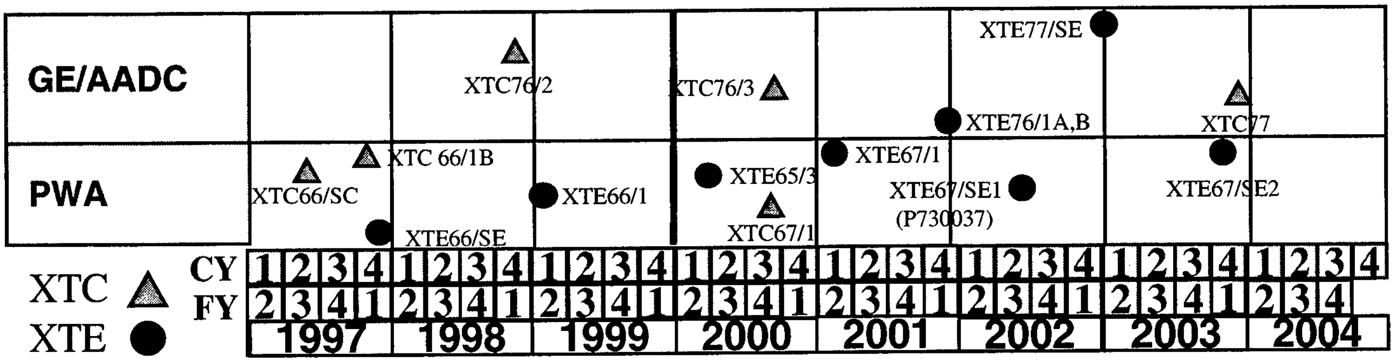
Chair
Mr. Mark Dale
U.S. Air Force,
AFRL/PRTP, Bldg. 18 Room D201
1950 Fifth Street
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 656-4179
Email: mark.dale@wpafb.af.mil

Co-Chair
Mr. Dan Popgoshev
Naval Air Systems Command
AIR 4.4T Bldg. 106
22195 Elmer Road
Patuxent River, MD 20670-1534
Phone: (301) 757-0453
Fax: (301) 757-0534
Email: popgoshevd@navair.navy.mil

INTRODUCTION

The following pages contain tables and schedules; and descriptions of objectives, HCF technologies validated, and results of current and planned HCF engine demonstrations. The tables identify the HCF technologies and engine demonstrator targets that have been planned to date with the General Electric / Allison Advanced Development Company team and with Pratt & Whitney. In general, the engine demonstrations are planned to provide the required data to validate the HCF technology performance and to update the design codes. The action teams develop technologies, then identify them as ready for engine demonstration. These technologies are then planned for incorporation into a core or engine test, which the tables identify. Once successfully demonstrated in a core or engine, a given technology is ready for transition into a fielded engine (F100, F110, etc.) or a development engine program (F119, JSF F119, JSF F120, etc.). Core or engine demonstration of HCF technologies will continue into 2003, but in some cases specific technologies and demonstration opportunities have not been identified.

Demonstrator Engine Schedule



General Electric / Allison Advanced Development Company
Demonstration Targets

Action Team / Program Title	Engine Demonstrator					
	XTC76/2	XTE76/1	XTC76/3	XTE77SE	XTC77/1	XTE77/1
Passive Damping						
Ring Damper Design			X	X		
Mag-Spinel			X		X	
Fan Damper Design						X**
Material Damage Tolerance						
FOD Characterization Non Laser Shock Peen				X*		
Component Analysis						
Probabilistic Data & Correlation				X*	X**	X**
Instrumentation / Health Monitoring						
LIFTP	X*					
COPE Instrumentation		X				
RVM +TOA				X**		X**
Nonintrusive Stress Measurement System				X**	X**	
Environmental Mapping Validation			X			X**
Component Surface Treatment						
Laser Shock Peening Validation				X*		X
Forced Response Prediction System						
VBIA Analysis	X		X		X	X*
HPT/LPT interactions		X			X	X*
TACOMA Analysis & LEFF Studies				X	X	
Aeromechanical Characterization						
Pressure Mapping						X**
X* - Research Agenda Milestones achieved						
X** - Currently Unfunded						

8.1 General Electric / Allison Advanced Development Company

The main focus of the GE/AADC demonstrator programs is to provide the test beds for the evaluation of Integrated High Performance Turbine Engine Technology Program (IHPTET) technologies and new HCF technologies. These critical core and engine demonstrations assess the performance and mechanical characteristics of HCF technologies in a realistic engine environment and provide the data necessary to validate and update advanced HCF prediction tools.

8.1.1 XTC76/2

FY 99 (1st Qtr)

Objectives: Demonstrate technologies to achieve the Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase II T41 objective, variable cycle engine concept, and advanced core technologies required to meet the IHPTET Phase II thrust-weight goals.

HCF Technologies Demonstrated: The need for compressor flutter design and test methods was demonstrated.

Final Results: This test demonstrated the importance of advanced unsteady design methods for use on modern, low aspect ratio compressor airfoils, which have stability properties outside traditional experience.

Participating Organizations: Air Force Research Laboratory (AFRL), GE Aircraft Engines / Allison Advanced Development Company (AADC)

Points of Contact:

Government
Mr. Michael Barga
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 656-4179
Email: michael.barga@afrl.af.mil

Contractor
Dr. Dennis Corbly / Mr. Durell Wildman
GE Aircraft Engines/AADC
Allison Advanced Development Co.
2056 South Tibbs Ave.
Indianapolis, IN 46207
Phone: (317) 230-5670
Fax: (317) 230-6100
Email: durell.wildman@aadc.com

8.1.2 XTC76/3

FY 00 (4th Qtr)

Objectives: Demonstrate The objective of this effort is to demonstrate the core technologies required to meet the IHPTET Phase II thrust-to-weight goal, and the structural durability the advanced technologies. HCF technologies to be validated in this core include unsteady aerodynamics, damping, and the Non-Interference Stress Measurement System (NSMS).

Details/Progress: Flutter analysis will be done with a fully-coupled 3D nonlinear unsteady code. REDUCE has been used to investigate mistuning in Stage 2 compressor blades. Hard damping coatings and ring dampers have been designed for this compressor. The effectiveness of these damping treatments will be evaluated on the bench and in engine testing. NSMS instrumentation will be used to gather blade response data for correlation with predictions.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Warfare Center (NAWC), GE Aircraft Engines / Allison Advanced Development Company (AADC)

Points of Contact:

Government
Mr. Michael Barga
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 656-4179
Email: michael.barga@afrl.af.mil

Contractor
Dr. Dennis Corbly / Mr. Durell Wildman
GE Aircraft Engines/AADC
Allison Advanced Development Co.
2056 South Tibbs Ave.
Indianapolis, IN 46207
Phone: (317) 230-5670
Fax: (317) 230-6100
Email: durell.wildman@aadc.com

8.1.3 XTC77/SE

FY 03 (2nd Qtr)

Objectives: Demonstrate the integration of advanced fan and turbine technologies into an engine system and to provide an early risk reduction evaluation of Phase III technologies.

HCF Technologies to be Demonstrated: Application of laser shock peening (LSP) to forward-swept fans, unsteady aero predictions with a variety of codes, and correlation with the Non-Interference Stress Measurement System (NSMS) and other monitoring sensors, the impact of low-excitation features in front frames, application of probabilistic assessment methods.

Details/Progress: This demo was placed on contract in late 1999.

Participating Organizations: Air Force Research Laboratory (AFRL), GE Aircraft Engines / Allison Advanced Development Company (AADC)

Points of Contact:

Government
Mr. Dan Popgoshev
Naval Air Systems Command
AIR 4.4T Bldg. 106
22195 Elmer Road
Patuxent River, MD 20670-1534
Phone: (301) 757-0453
Fax: (301) 757-0534
Email: popgoshevd@navair.navy.mil

Contractor
Dr. Dennis Corbly / Mr. Durell Wildman
GE Aircraft Engines/AADC
1 Neumann Way
A413
Cincinnati, OH 45215-1988
Phone: (513) 243-5832
Fax: (513) 243-8091
Email: dennis.corbly@ae.ge.com

8.1.4 XTE76/1

FY 2002 (2nd Qtr)

Objectives: Demonstrate the integration of advanced fan and low-pressure turbine technologies into an engine system. This engine demonstration will achieve the Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase II thrust-to-weight goal.

HCF Technologies to be Demonstrated: Application of advanced unsteady design methods on vaneless, counterrotating high-pressure (HP) and low-pressure (LP) turbine systems will be demonstrated. Advanced instrumentation will be used to gather unsteady data on the HP/LP turbine system.

Details/Progress: Hardware is currently being fabricated in preparation for the engine demonstration.

Participating Organizations: Air Force Research Laboratory (AFRL), GE Aircraft Engines / Allison Advanced Development Company (AADC)

Point of Contact:

Government
Mr. Mark Dale
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 656-4531
Email: mark.dale@wpafb.af.mil

Contractor
Dr. Dennis Corbly / Mr. Durell Wildman
GE Aircraft Engines/AADC
1 Neumann Way
A413
Cincinnati, OH 45215-1988
Phone: (513) 243-5832
Fax: (513) 243-8091
Email: dennis.corbly@ae.ge.com

8.1.5 XTC77

FY 2004 (1st Qtr)

Objectives: Demonstrate the technologies required to achieve the Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase III thrust-to-weight goal.

HCF Technologies to be Demonstrated: advanced technologies in the areas of damping, instrumentation, and design methods, including probabilistic and unsteady aerodynamics.

Details/Progress: This effort is in the preliminary design phase.

Participating Organizations: Air Force Research Laboratory (AFRL), GE Aircraft Engines / Allison Advanced Development Company (AADC)

Points of Contact:

Government
Mr. Michael J. Kinsella
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 656-4179
Email: michael.kinsella@wpafb.af.mil

Contractor
Dr. Dennis Corbly / Mr. Durell Wildman
GE Aircraft Engines/AADC
1 Neumann Way
A413
Cincinnati, OH 45215-1988
Phone: (513) 243-5832
Fax: (513) 243-8091
Email: dennis.corbly@ae.ge.com

Pratt & Whitney
Demonstration Targets

Passive Damping								
High Effectiveness Turbine Damping				X			X	X
IBR Dampers					X			X
Material Damage Tolerance								
Titanium Demonstration						X		
Single Crystal Demonstration							X	X
Gamma-Ti Demonstration		X			X		X	
Component Analysis								
Probabilistic HCF Assessment							X	X
FEM Modeling Enhancements	X	X	X	X	X	X	X	X
Instrumentation / Health Monitoring								
Generation IV NSMS					X		X	
Non-Optical NSMS	X						X	
Advanced Pyrometry					X			
Component Surface Treatment								
LSP Demonstration						X		
Forced Response Prediction System								
Robust Airfoil Design / FLARES	X		X	X	X		X	
Aeromechanical Characterization								
HCF Design Tool Eval/Tech Transition								X
X - Research Agenda Milestones achieved								

8.2 *Pratt & Whitney*

The main benefit of the P&W demonstrator programs to the HCF Initiative is to provide the test beds for the initial evaluation of new HCF technologies. These critical core and engine demonstrations, in addition to demonstrating improved thrust-to-weight and providing a validation for technology transition candidates, assess the performance and mechanical characteristics of HCF technologies in a realistic engine environment and provide the data necessary to validate and update advanced HCF prediction tools.

8.2.1 XTE66/A1

FY 95 (4th Qtr)

Objectives: Validate the F119 Hollow Fan Blade integrally bladed rotor (IBR) in an engine environment.

HCF Technologies Demonstrated: unsteady aerodynamic and forced response (FLARES) codes, first-generation eddy current sensor

Final Results: HCF tools correctly identified root cause and fix for unacceptable rotor response. Demonstration of the eddy current sensor to measure blade tip response was successfully completed.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney Independent Research & Development (P&W IR&D)

Points of Contact:

Government
Capt Anthony Cerminaro
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: anthony.cerminaro@wpafb.af.mil

Contractor
Mr. Bill Doehnert
Pratt & Whitney M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-6639
Fax: (561) 796-4901
Email: dohnrtw@pwfl.com

8.2.2 XTC66/SC

FY 97 (3^{rd} Qtr)

Objectives: Demonstrate and evaluate F119 technology transition, Joint Strike Fighter (JSF) technology maturation risk reduction, and Integrated High Performance Turbine Engine Technology Program (IHPTET) technologies.

HCF Technologies Demonstrated: robustness of gamma-TiAl high-pressure compressor (HPC) blades, supercooled high-pressure turbine (HPT) blades

Final Results: Testing demonstrated the HCF robustness of gamma-TiAl blades and supercooling technologies.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Warfare Center (NAWC), Pratt & Whitney

Points of Contact:

Government
Mr. Marty Huffman
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: martin.huffman@wpafb.af.mil

Contractor
Mr. Bill Campbell
Pratt & Whitney
M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561)796-5179
Email:campbell@pwfl.com

8.2.3 XTC66/1B

FY 98 (1st Qtr)

Objectives: Demonstrate temperature, speed, and structural capability of the core to run Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase II conditions and evaluate the aerodynamic and thermodynamic performance of the high-pressure compressor (HPC), Diffuser/ Combustor, and high-pressure turbine (HPT).

HCF Technologies Demonstrated: unsteady aerodynamic (NASTAR V3.0) and forced response (FLARES V1.0) codes

Final Results: Testing provided benchmark data for analytical tool calibration and validation. Data have been used to establish code performance against Action Team metrics.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney

Points of Contact:

Government
Mr. David Jay
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: david.jay@wpafb.af.mil

Contractor
Mr. Bill Campbell
Pratt & Whitney
M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561)796-5179
Email:campbell@pwfl.com

8.2.4 XTE66/1

FY 99 (2nd Qtr)

Objectives: (1) Demonstrate the Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase II thrust-to-weight goal. (2) Provide initial engine demonstration of a vaneless counter-rotating turbine and microwave augmentor.

HCF Technologies Demonstrated: internal low-pressure turbine (LPT) dampers for control of high-frequency excitation

Final Results: A counter-rotating vaneless turbine was successfully demonstrated. Low turbine (LPT2) blade stresses were low in higher-order modes. The configuration was evaluated with FLARES for comparison to Action Team metrics.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney

Points of Contact:

Government
Capt Tony Cerminaro
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: anthony.cerminaro@wpafb.af.mil

Contractor
Mr. Bill Doehnert
Pratt & Whitney M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-6639
Fax: (561) 796-4901
Email: dohnrtw@pwfl.com

8.2.5 XTC67/1

FY 00 (4th Qtr)

Objectives: Demonstrate the temperature, speed, and structural capability of the core to run Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase II and some early Phase III conditions and to evaluate the high-pressure compressor (HPC), Diffuser/Combustor, and high-pressure turbine (HPT) aerodynamic and thermodynamic performance.

HCF Technologies to be Demonstrated: Generation 4 Non-Interference Stress Measurement System (NSMS,) Advanced Pyrometry, Finite Element Modeling (FEM) Enhancements, the FLARES (V2.0) Code, Asymmetric high-pressure compressor (HPC) Stators, Comprehensive Engine Condition Management (CECM), improved platform dampers in the high-pressure turbine (HPT)

Progress to Date: The final design was completed and reviewed by the government in the fourth quarter of 1998 and hardware fabrication is in progress.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney

Points of Contact:

Government
Mr. David Jay
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: david.jay@wpafb.af.mil

Contractor
Mr. Don Adams
Pratt & Whitney M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-2746
Fax: (561) 796-4901
Email: admsdon@pwfl.com

8.2.6 XTE66/SE

FY 98 (1st Qtr)

Objectives: Demonstrate the structural durability of Integrated High Performance Turbine Engine Technology Program (IHPTET) technologies in an F119 engine and to transition some of those technologies to the F119 for the F-22 or Joint Strike Fighter (JSF) aircraft. The demonstration was an accelerated mission test (AMT) using an F-22 IFR mission.

HCF Technologies Demonstrated: robustness of gamma-Ti Compressor Blades, Supervanes and Superblades

Final Results: The engine completed 1505 AMT TACs and most of the technology component hardware met durability predictions.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Warfare Center (NAWC), Pratt & Whitney

Points of Contact:

Government
Mr. Marty Huffman
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: martin.huffman@wpafb.af.mil

Contractor
Mr. John S. Anderson
Pratt & Whitney M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-4621
Fax: (561) 796-4901
Email: anderjs@pwfl.com

8.2.7 XTE67/1

FY 01 (2nd Qtr)

Objectives: Demonstrate the temperature, speed, and structural capability of the engine to run early Integrated High Performance Turbine Engine Technology Program (IHPTET) Phase III conditions and evaluate the low spool and integrated aerodynamic and thermodynamic performance.

HCF Technologies to be Demonstrated: Integrally bladed rotors (IBRs) designed for low resonant stress and flutter response, IBR damping, lightweight turbine dampers, and high-temperature eddy current sensors will be validated. Analytical tools to be applied during the XTE67/1 design include unsteady aerodynamics, FLARES (V2.0), MDA, BDAMPER (V7.0), and CDAMP (V2.0).

Progress to Date: The final design review for XTE67/1 was held in November 1999.

Participating Organizations: Air Force Research Laboratory (AFRL), Naval Air Warfare Center (NAWC), Pratt & Whitney

Points of Contact:

Government
Capt Anthony Cerminaro
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: anthony.cerminaro@wpafb.af.mil

Contractor
Mr. Bill Doehnert
Pratt & Whitney M/S 715-01
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-6639
Fax: (561) 796-4901
Email: dohnrtw@pwfl.com

8.2.8 XTE65/3

FY 00 (2nd Qtr)

Objectives / HCF Technologies to be Demonstrated: (1) Demonstrate the utility and accuracy of new fan blade damage tolerance HCF tools during engine testing of damaged blades. (2) Evaluate benefits of laser shock peening of titanium integrally bladed rotors (IBRs) to mitigate damage-induced fatigue debits.

Progress to Date: The rotor 1 IBR has been laser peened (3 blades). The fan rotor is currently at the vendor for installation of strain and crack detection gages.

Participating Organizations: Air Force Research Laboratory (AFRL), Pratt & Whitney Independent Research & Development (P&W IR&D)

Points of Contact:

Government
Capt Anthony Cerminaro
U.S. Air Force, AFRL/PRTP
1950 Fifth St., Bldg. 18D
Wright-Patterson AFB, OH 45433-7251
Phone: (937) 255-2767
Fax: (937) 255-2278
Email: anthony.cerminaro@wpafb.af.mil

Contractor
Mr. Chuck Annis
Pratt & Whitney M/S 713-58
P. O. Box 109600
West Palm Beach, FL 33410-9600
Phone: (561) 796-6565
Fax: (561) 796-3637
Email: annis@pwfl.com

8.3 Conclusion

Several advanced development technology demonstrator programs provided the test beds for evaluation of new HCF technologies. Both core and full engine tests were conducted at Pratt & Whitney facilities to characterize hollow fan blade integrally bladed rotor (IBR) designs and to evaluate forced response codes (such as FLARES), new eddy current sensors, and advanced internal low-pressure turbine dampers for control of high-frequency excitation. Advanced technology core engine testing at General Electric facilities over the last year has also highlighted the importance of advanced unsteady design methods for use in modern low-aspect-ratio compressor airfoils, which have stability properties outside traditional experience. In all cases, testing provided key benchmark data for analytical tool calibration along with initial HCF robustness characterization of multiple new technologies.