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FINITE ELEMENT MODELING AND EXPERIMENTAL STUDY OF A GAS TURBINE ENGINE BLADE UNDER BIAXIAL LOADING

Ming Xie, Mohan Balan and Norman Frey
AdTech Systems Research, Inc.
1342 N. Fairfield Road
Dayton, OH 45432 USA

Jeffrey Brown and Gary Terborg
Aero Propulsion Directorate
Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433 USA

ABSTRACT

Gas turbine engine blades are subjected to both radial centrifugal force and transverse excitation under operating conditions. It is very difficult to perform fatigue test on an engine blade in the laboratory because of this biaxial loading condition. In the present study, a simple approach for high cycle fatigue testing of gas turbine engine blades under biaxial loading is proposed. A radial force is applied to the blade to simulate the centrifugal force due to rotation, while a transverse fatigue loading is applied to simulate the vibration of the blade.

A three-dimensional finite element analysis was used in the design and optimization of this biaxial loading mechanism. Several important experimental parameters were investigated, including the gripping design at the tip of the blade, the flexible connection between the blade and the test frame, and the application of the transverse vibratory loading.

A four-post test frame was constructed to implement the biaxial loading mechanism. A vertical actuator on the frame was used to apply the radial force, while a second actuator was installed horizontally at the side of the frame, to apply the vibratory load to the test specimen. The stress states in the blade specimen, obtained from strain gages, compared well with the finite element results.

INTRODUCTION

Modern gas turbine engines need to maintain a balance between high performance, affordability, and design robustness in order to maximize engine investment. Development for component robustness and a need for longer time between inspections and overhauls require parts with improved fatigue behavior. However, it is very difficult to use either analytical or experimental methods to predict the high cycle fatigue life of the engine components.

Fatigue failures may be the most common failure mode among engineering components and structures. Most of the fatigue test data have been obtained from laboratory experiments involving uniaxial loading conditions, which are seldom present in practical engineering situations. For example, gas turbine engine blades are subjected to both radial centrifugal force and transverse excitation under operational conditions. It will be very difficult and expensive to apply this biaxial loading and perform the dynamic test on a blade in the laboratory. However, the durability of engine blades under operating conditions is one of the most important issues in the design of gas turbine engines, which impact their affordability and robustness. It is very important that a simple and economical test method be developed to test and predict the high cycle fatigue life of the engine blades.

A typical gas turbine engine includes compressor blades and turbine blades, while some turbofan engines also have fan blades. A stator row of blades guides the gas onto a rotor row of blades in the turbine to extract the mechanical power from the machine. In the compressor stage, the operation principle is reversed to compress the gas using the supplied mechanical power. A typical rotor blade sees upstream disturbances from the stator row and as it rotates, receives a corresponding number of increasing and decreasing lift and moment forces alternating periodically, depending on the number of stator blades /nozzles/guide vanes (1).

High cycle fatigue failure due to these periodical excitations is the most common failure mode for engine blades. In order to improve the fatigue life of these critical engine components, a new test methodology has to be developed. A rotating blade is also subjected to a centrifugal force in the radial direction at the same time, in addition to the above-mentioned vibratory loading. This biaxial loading condition is the main reason that a conventional test frame is not able to apply these complex loads. In order to apply high cycle fatigue loading to the engine blades and measure their durability in the laboratory, a test system has to be designed and built which is capable of biaxial loading.

A simple biaxial loading mechanism was proposed in the present study to perform high cycle fatigue testing on engine blades. As mentioned before, the blade is subjected to transverse periodical excitation, which is the main source of fatigue loading. A vibratory loading is applied to the blade to simulate this transverse excitation. At the same time, a radial force is applied to the tip of the blade, through a flexible connection, to simulate the centrifugal force. The flexible connection is used to prevent local bending at the gripping area due to transverse loading. This simple biaxial loading mechanism will avoid spin tests, which require powerful motor and expensive containment facility.

A second stage fan blade in a General Electric F110 turbofan engine was investigated in the present study. Since the junction area of the airfoil and the platform is usually where the fatigue failure occurs, the applied biaxial loading has to simulate the stress distribution at that region. Finite element analysis was performed on the fan blade to confirm that this biaxial loading is a valid simulation for operating condition. A three-dimensional finite element model was constructed to investigate the stress states in the blade and the effects of various loading parameters.

In the present study, a test frame was also designed and constructed to test the fan blade under this biaxial loading mechanism. Two actuators, controlled by a single computerized controller, were installed on a four-post test frame to apply the loading from two perpendicular axes at the same time. One vertical actuator applies the radial static force to the blade, while another horizontal actuator applies a transverse fatigue loading. The experimental data were compared to the present numerical results.

FINITE ELEMENT MODELING OF THE BIAXIAL LOADING MECHANISM

A three-dimensional finite element analysis was performed for a second stage fan blade in a GE F110 turbofan engine. The model included the airfoil, the platform, the dovetail, two attachment plates on top of the blade to represent the grips, and a flexible strap. To limit the complexity in this initial analysis, no details of the gripping system were included in the finite element model. Finite element program I-DEAS (2) was used to construct the model and perform the analysis. Parabolic brick and wedge elements were used to mesh the fan blade and the gripping plates, while thin shell elements were used to mesh the strap.

The fan blade was made of titanium alloy Ti-6Al-4V and its properties were assumed to be E = 110.3 GPa (16 x 10^6 psi), $\nu = 0.33$, $\rho = 4.5$ g/cm^3 (3). The gripping system was made of tool steel and its properties were assumed to be E = 206.9 GPa (30 x 10^6 psi), $\nu = 0.33$. The elastic modulus of the flexible strap was arbitrarily selected to be 2/3 of the blade material. The three-dimensional finite element model, including the fan blade, the attachment plates and the strap, is shown in Figure 1.

Before modeling the biaxial loading mechanism, modal analysis was conducted to evaluate the finite element model of the fan blade. The obtained modal frequencies of the model correlate very well with the experimental bench test data, as shown in Table 1. This good agreement between numerical results and experimental data validates the finite element model.

Normalized stress distribution in the blade, obtained in the modal analysis for the first vibration mode, was scaled to a maximum stress of 206.9 MPa (30 ksi). This stress is an industry standard of the maximum alternating stress in large fan blades. An engine speed of 3500 RPM was used to obtain the centrifugal loading in this analysis. The obtained radial stress distributions at the leading edge of the blade are shown in Figure 2. This stress distribution was then assumed to be the stress state in the blade under operating condition, which was used as the basis for subsequent comparison with numerical and experimental simulations.

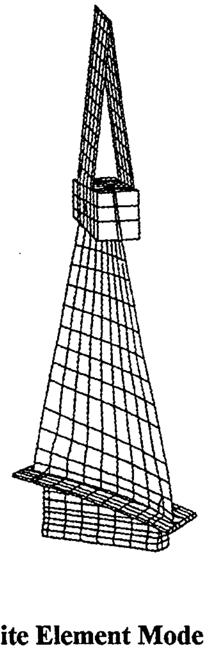

Figure 1. Finite Element Model of a GE F110 Second Stage Fan Blade with Grip Attachment Plates and Flexible Strap

Table 1. Comparison of Bench Test and the Predicted Modal Frequencies

Modes	Bench Test Frequency (Hz)	FE Model Frequency (Hz)
1	239	236
2	648	648
3	1212	1168
4	1458	1504
5	1930	1994
6	2317	2306
7	2407	2460

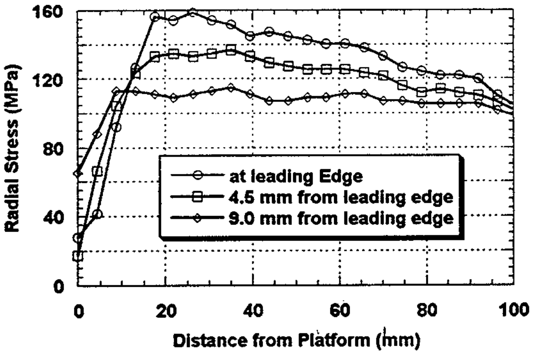

Figure 2. Predicted Radial Stress Distributions in a GE F110 Fan Blade at 3500 RPM

Finite element modeling was then performed to simulate the biaxial loading mechanism. The dovetail of the fan blade was fixed in all directions. A 5334N (1200lb) radial tensile load was applied to the tip of the straps. A 1778N (400lb) transverse load was applied as a point load at the center of the gripping plate, on the concave side of the blade. Analysis was conducted using two different boundary conditions for the ends of the straps, namely, ends of the straps free in the horizontal plane and ends of the straps fixed in the horizontal plane. The present study focused on the radial stress since it was the most critical stress component in the blade under biaxial loading.

Very high tensile stresses are observed in the simulations when the strap ends are unconstrained, as shown in Figure 3, much higher than that under operating condition predicted from previous modal analysis. When the strap ends are free to move in the horizontal plane, the leading edge curves backward as a transverse load is applied due to absence of restraint in this direction, resulting in high tensile radial stresses. Constraining the ends of the straps, however, results in compressive stresses, also shown in Figure 3. When the ends of the straps are restrained from moving in the horizontal plane, the strap exerts a restraining force on the airfoil tip. This force causes the leading edge to curve forward, resulting in compressive radial stresses near the root of the leading edge.

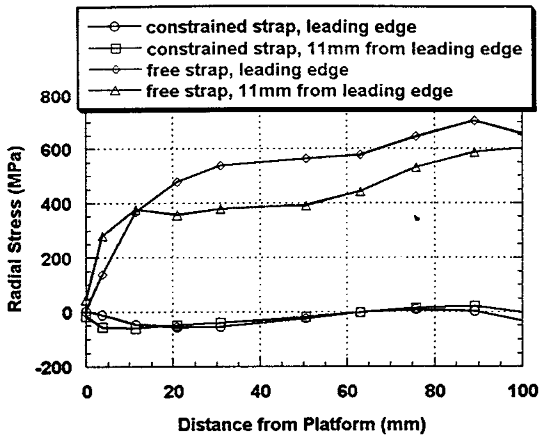

Figure 3. Effects of Strap End Boundary Condition on Radial Stress Distribution

As will be shown later, the actual stress distributions obtained in the biaxial loading tests matched better with the predicted stresses in operating condition. This is due to the present grip modeling is not realistic, since only two simple attachment plates were included in the finite element model. The correlation between the numerical modeling and the experimental study will be discussed in more details later.

The location of transverse fatigue loading was also studied to evaluate its effects. The loading locations and the resulting radial stress distributions at leading edge are shown in Figure 4, for a 889N (200lb) transverse load at four different loading locations. It can be seen that as the loading location is moved down from the top, the location of the peak stress moves towards the platform. It can also be seen that transverse loading near the middle of the airfoil results in a leading edge stress profile that better matches the operating condition predicted in the modal analysis.

BIAXIAL LOADING TEST OF A TURBINE ENGINE FAN BLADE

In the present study, a four-post test frame was designed and constructed to test a GE F110 fan blade specimen under biaxial loading. One vertical actuator applies the radial static force to the blade, while another horizontal actuator applies a fatigue loading. Both actuators are controlled by a single computerized controller with a data acquisition system. A gripping

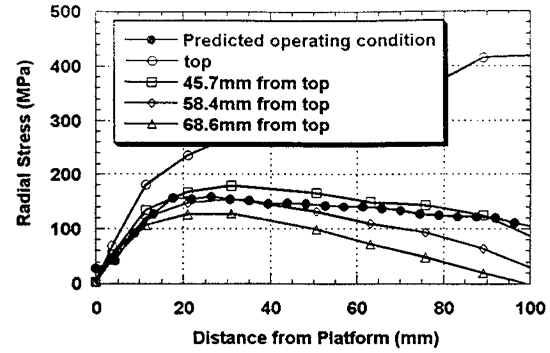

Figure 4. Effects of Transverse Loading Location on Radial Stress Distribution

system was also designed to apply the biaxial loading to the specimen. In the following, the design of the gripping system will be discussed first. Then the general design of the test frame will be presented.

The gripping system for the blade includes a pair of attachment plates, the grip body with a U-shaped notch, a flexible strap wrapped around a roller pin, and a rod-end bearing connection. The attachment plates have internal contours, which conforms to the surface of the blade. The profile of the airfoil was digitized to machine the contour surfaces on the attachment plates. They were bonded to both sides of the airfoil tip using adhesive and the matching contour surfaces of the plates allowed a good bonding between the plates and the blade.

The bonded assembly was then inserted into the U-shaped notch on the grip body. Total of eight screws, four on each side, were used to tighten the assembly in place inside the grip body. A nylon strap was then connected to the grip through a free rotating pin on the grip. Ends of the strap were clamped by the hydraulic grips to apply the radial tensile force.

Transverse fatigue loading was applied to the blade through a rod-end bearing connection on the grip surface. The rod-end bearing was connected to a clevis, which was in turn connected to the piston of the horizontal actuator. This rod-end bearing connection allowed the transverse fatigue loading be applied to the blade specimen and at the same time allows small rotation around the gripping. This extra degree of freedom allowed the blade to bend under transverse loading.

A broach block was used to hold the blade specimen in place. The dovetail of the blade was slid into the block and was tightened against the block by two set-screws underneath. The block was in turn connected to the vertical load train in the test frame through a threaded steel rod. The broach block was used since it resembles a part of the rotor disk and served as part of the gripping system in the present study as well.

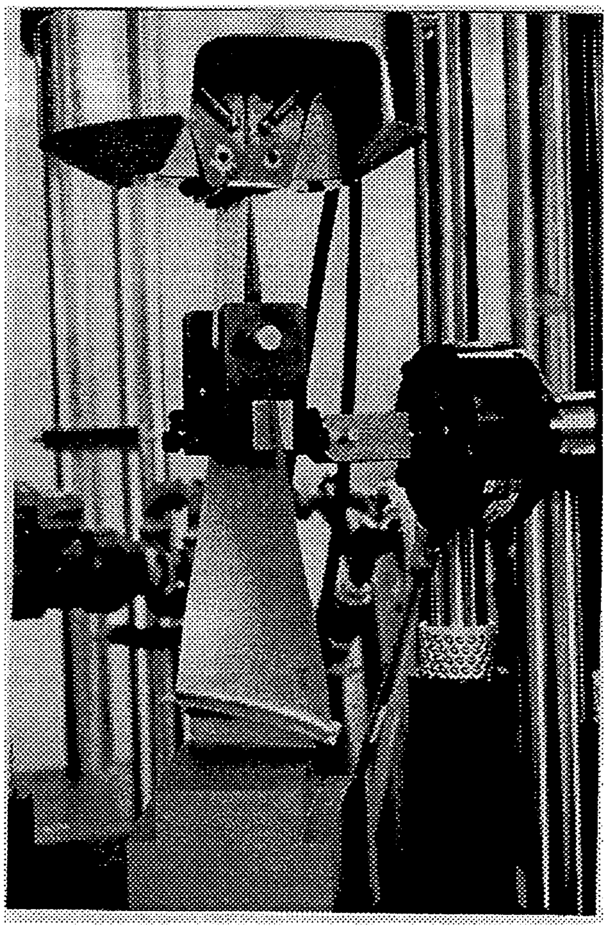

Figure 5. Complete Assembly of Blade Specimen and Gripping System

The complete assembly of the gripping system, the fan blade specimen and the broach block on the load train is shown in the photo in Figure 5. The nylon strap, the hydraulic grip and the load cell on the horizontal actuator can be seen in the photo as well.

A four-post test frame was constructed for the present biaxial loading test. The four-post design was chosen because it provided more structural stability. A four-post die set was fabricated and placed between the top and bottom platforms of the test frame, and was mounted on the vertical load train. A vertical plate was mounted on the side of the die set, on which the horizontal hydraulic actuator was mounted. A photo showing the complete biaxial test frame, with a fan blade specimen mounted on the load train, is presented

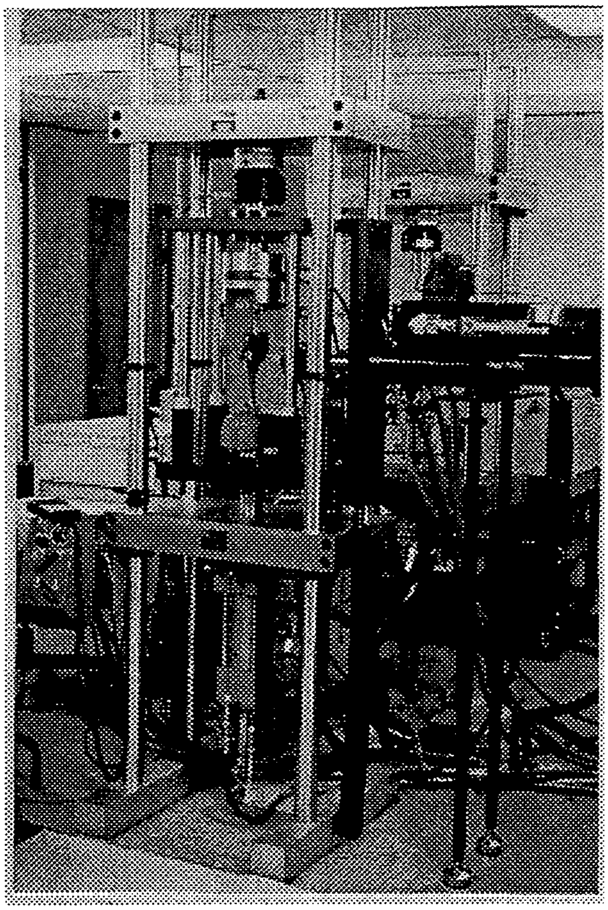

Figure 6. A Four-Post Biaxial Loading Test Frame

in Figure 6. A single control system for the test frame, capable of controlling both hydraulic actuators at the same time, was designed and used in the present study.

The biaxial loading capability of the test frame was first examined. Various combinations of radial tensile load and transverse fatigue load were applied to the fan blade through the gripping system. The numerical modeling results provided a guideline for the range of the loads. Radial load in the range of 4445N (1000lb) to 8890N (2000lb) was applied, while transverse load was varied in the range of 445N (100lb) to 3556N (800lb). In this preliminary experimental study, no high frequency fatigue load was applied to the blade. Figure 7 shows typical load profiles of both actuators recorded on the data acquisition system, in which a 6223N (1400lb) radial load and a 711N (160lb) transverse fatigue load were applied to the blade, at a frequency of 15Hz. It can be seen that both actuators worked well with the controller and the data acquisition system.

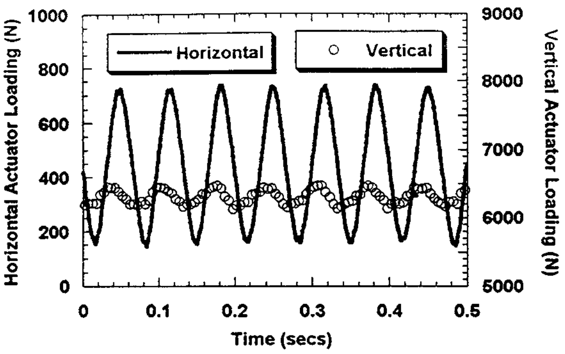

Figure 7. Typical Profiles of Radial Load and Transverse Fatigue Load (15Hz)

The main purpose of this preliminary biaxial testing was to examine the stress distributions in the fan blade specimen. Six (0°,45°,90°) rosette strain gages were placed on both sides of the airfoil to monitor the deformation under biaxial loading. Transverse load was applied to the blade at a frequency of 0.1 Hz to record the strain data. The radial load was 5334N (1200lb) and the transverse load varied from 1778N (400lb) to 3556N (800lb). The strain at locations close to the leading edge was of particular interest. The radial stress at a location 25.4mm (1.0in) away from the platform and 6.4mm (0.25in) away from leading edge was calculated from the recorded strain. The stress levels at this location obtained in the experimental study are presented in Figure 8, together with the previous modal analysis results.

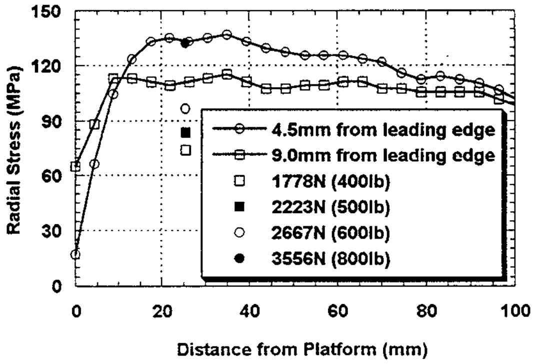

Figure 8. Comparison of Operating Condition and Experimental Simulation Results (6.4mm from Leading Edge) at Various Transverse Loads

It can be seen that the biaxial loading can be effectively used to simulate the stress distribution in the blade under operating condition. The transverse load in the range of 3112N (700lb) to 3556N (800lb), as can be seen in Figure 8, can generate a stress level in the leading edge of the blade similar to that in operating condition.

The experimental results, although correlating well with the predicted operating condition, would fall between the numerical modeling results obtained using the two different boundary conditions for the ends of the straps if they were plotted in Figure 3. This is because that these boundary conditions do not accurately represent the actual radial loading mechanism provided by the gripping system. In the finite element model with the constrained strap ends, the straps had fixed length. In the actual gripping system, however, a single strap folds around a roller. When a transverse load is applied, the strap slides around the roller, permits some amount of airfoil tip movement and results in tensile stresses at the leading edge. The airfoil tip movement permitted by the gripping system, however, is limited and therefore the magnitude of the tensile stress is less than that obtained with an unconstrained strap boundary condition.

SUMMARY

In the present study, a simple biaxial loading mechanism was proposed to simulate both the radial centrifugal force and transverse vibratory excitation that a gas turbine engine blade is subjected to under operating condition. Both finite element modeling and experimental study were performed for a second stage fan blade in a GE F110 turbofan engine. Numerical modeling was used to validate the proposed mechanism and to optimize the experimental parameters. A test frame, with two hydraulic actuators, was designed and constructed to apply the biaxial loading to the fan blade and fixture assembly.

Both the numerical results and the experimental data show that the biaxial loading test can be used to simulate the engine blade under operating condition. The stress state in the blade specimen under operating condition can be reproduced using the proposed biaxial loading mechanism, without using expensive spin tests which require powerful motor and large containment facility.

Both the numerical modeling and the experimental study of high cycle fatigue of gas turbine engine blades are still on going. A combined bending and torsion loading mechanism is being studied to simulate various vibration modes of engine blades under operating conditions. High cycle fatigue testing will be performed on engine blades under multiaxial loading. Life prediction methodology for engine blades will be developed based on the high cycle fatigue test results.

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