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Procedia Engineering 15 (2011) 984 – 988

Procedia Engineering

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Advanced in Control Engineering and Information Science

An optical fiber Blade Tip Clearance Sensor for Active Clearance Control Applications

Jia Binghui, Zhang Xiaodong *

School of Engine& Energy, Northwestern Polytechnical University, Xi'an, Shaanxi Province, 710072, China

Abstract

Active clearance control has been used to improve efficiency and performance in commercial aircraft engines. This paper describes a optical fiber sensor for active control, which is simple and thin in structure. The sensor system data sampling rate is about 100 kHz, and its resolution ratio is better than 0.01mm. Sensor's ability to monitor tip clearance was tested using a rotor test rig and individual blade tip clearances at different speed and a blade failure measurement example was given. The results show: the sensor was able to detect the blade flaws, and have a large bandwidth, high data sampling rate. It will be presented to show the viability of the sensor for use in active clearance control.

Selection and/or peer-review under responsibility of [CEIS 2011]

Keywords: Fiber optical sensor; Blade tip clearance; measurement

1. Introduction

Active clearance control of the high pressure turbine is one of the techniques designers use to increase performance of their engines. In most of the new large commercial engines, the size of the turbine case is controlled through cooling using compressor bleed air in an open loop control system. Pinch points of minimum clearance normally occur at takeoff and at re-acceleration due to emergency maneuvers during a landing approach. Although open loop clearance techniques are able to improve performance, many of the engine's actual characteristics responsible for the minimum clearance are unknown. These characteristics include rotor dynamics as well as changes in rotor geometry due to wear or operating condition. Therefore, open-loop techniques must be conservative in closing the gap which results in suboptimal performance.

In addition, the use of compressor bleed air results in a system that is unable to rapidly control clearances under more dynamic conditions, such as asymmetric clearance changes during aircraft maneuvering. Current systems are able to control clearances on the order tens of mils. However, closing clearances to within 5-10 mils can improve engine efficiency by several percentage points. It has been

* Corresponding author: Zhang Xiaodong. Tel.:13359206818.
E-mail address: xdzhang@nwpu.edu.cn

doi:10.1016/j.proeng.2011.08.182

reported by Lattime and Wiseman et al that for every 0.001” increase in gap in the HPT, SFC increases 0.1% and EGT increases 1°C[1-4], and the noise will reduce along with the reduction of aircraft emission, which benefits environment and economy a lot[5].

Increased efficiencies can be achieved by using an active actuation technique that can precisely control clearances at rates sufficient to handle the dynamic conditions encountered during takeoff and landing as well as providing for optimal clearances during cruise. So to measure the tip clearance exactly and in real-time is crucial for active control. With the development of fiber-optic sensing technology, we have developed a tip clearance sensor using fiber-optic technology that for achieving blade tips clearance information [6-13]. This paper describes the tip clearance sensor and provides results form a rotor test rig.

2. Sensor Overview

The reflective intensity modulated optical fiber sensor consists of the light source, input fiber, receiving fiber and photo-detector. The light sent out from the light source is transmitted to the target surface and received by the receiving fiber, as is shown in figure1. At last, it is sent to the photoelectric converter. The size of the receiving light intensity reflects the distance between the reflector and the fiber probe. When the displacement is changed, the receiving light intensity is changed at the same time, so the displacement can be obtained through measuring the receiving light intensity.

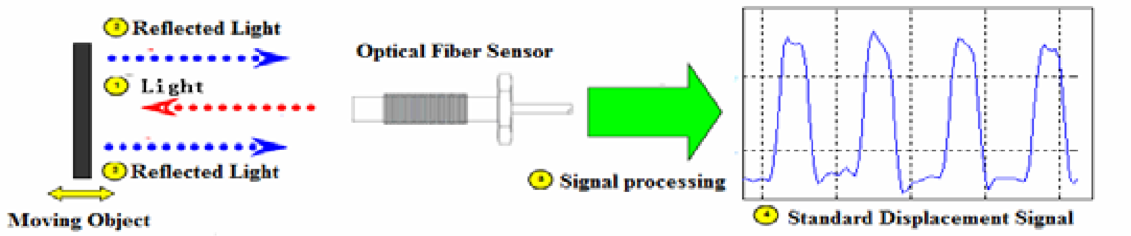

Fig.1. Sensor overview

Because of the maximal receiving light intensity of the multimode fiber is greater than the single mode fiber about one order of magnitude. In order to increase the signal to noise ratio of the measurement, we use multimode fiber as the fiber of the optical fiber sensor. The arrangement of the input fiber and receiving fiber is shown in Fig 2. The middle fiber is the input fiber, and circle coaxial tightly arranged fibers are the receiving fiber. The receiving fibers bundle is composed of six multimode fibers. Since the measurement object is rotor blade, and blade top generally have some curvature, for a fiber with the launch angle θ_c, effected by the convex reflector, the arrival angle becomes $\theta_c + 2\alpha$, if the input and receiving optical fiber numerical aperture is equal, because $\theta_c + 2\alpha > \theta_c$, then the reflected light can not enter the receiving optical fiber, as shown in Figure 3. In our design the numerical aperture of inputting fiber used are 0.22 and 0.37 respectively.

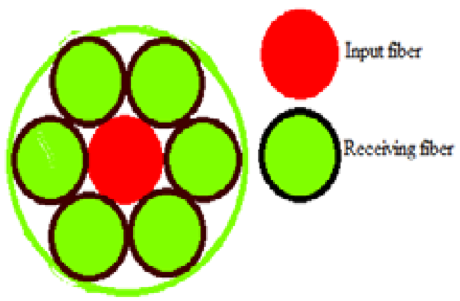

Fig2. The arrangement of the fiber bundle

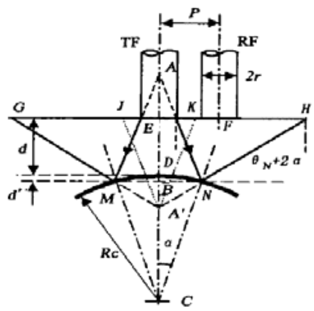

Fig 3. Convex reflector

3. Advantages of Optical Fiber Sensor

The fiber displacement sensor has the advantages than the traditional displacement sensor, such as anti-electromagnetic interference, small size, light weight, fast response, high sensitivity, non-contact measurement in the severe working environment and so on. In kinds of fiber displacement sensors, the reflective intensity modulated optical fiber sensor is one of the most basic and mature sensors, it is simple in structure, convenient in design and manufacturing, stable and reliable in performance [3].

The probe can be made very tiny and can be embedded in the shroud easily. One probe is typically can provide a full characterization of blade tip clearance, as shown in figure 4. Additional probes may be desirable to account for conditions such as asymmetric clearance or for health monitoring and prognostics of blades and disks. In addition, Calibration and electromagnetic interference which often give microwaves and capacitance systems trouble, has little effect to the optical system.

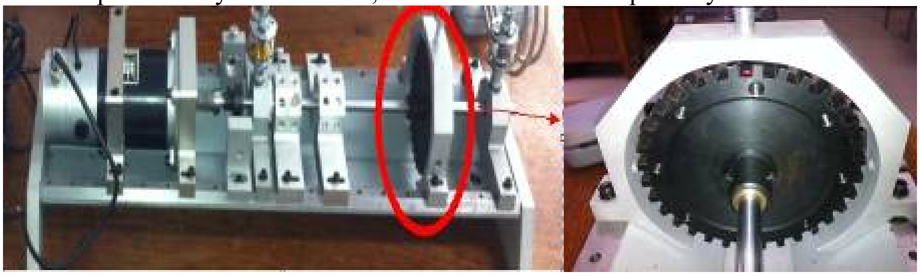

Fig. 4 Rotor test rig (right) and sensor configuration

4. Blade Tip Measurement

The key measurement for active clearance control is accurate and repeatable measurements of tip clearance. For active clearance control, it is critical that the longest blade be measured so that tip rubbing can be avoided. This requires high resolution measurements and a fast data rate so that the individual blades can be accurately profiled. Since there are a variety of blade tip geometries as well as rotor dynamics that can be present in a typical system, it is critical to accurately extract the correct waveform features.

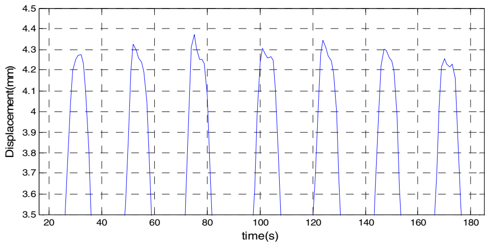

Fig. 5 Profile of blade slugs at 3674 RPM

An example profile of seven blades from a disk with 32 blades moving at 3674 RPM is shown in Figure 5. The scale in the Y direction has been significantly stretched to accentuate the clearance measurement. On a one-to-one scale the blades look nearly flat. An interesting feature to note is that the blade slugs show slight humps at the leading and trailing edges. This is due to the fact that the blades are ground flat and traveling on a circular arc, which means that the corners actually come closer to the sensor. And the surface irregularity of blade means that there are lumber manufacturing defects of my rig. This data was sampled at 25 kHz, yielding a distance measurement every 0.01mm.

5. Using the Sensor For Active Clearance Control

Technologies implemented to date rely on compressor bleed air to control clearances based on open loop control and the flight regime (takeoff, cruise, etc.). Open loop systems necessitate a wide safety margin to accommodate the uncertainty in system models that are used to drive such systems. Implementing a feedback control system to optimize clearance has been difficult due to the lack of survivability of clearance measurement technology. Current technologies such as eddy current, capacitive, and laser sensors have been effectively used in laboratory environments but lack the robustness and reliability necessary for long-term use.

Lattime and Steinetz described the desired properties of a clearance sensor for active clearance control. They state that the sensor should have accuracy on the order of 0.025mm and that the sensor response (bandwidth) should be on the order of 50 kHz. What is more, the sensor should be as thin and light as possible which affect the airflow less, that optical fiber fit very well.

Since turbines are extremely complex mechanical systems, simply looking for the peak clearance during a given revolution will not be sufficient to give an accurate clearance measurement for active clearance control. Sub-synchronous rotor dynamics, such as bearing whirl, means that clearance must be monitored for more that one revolution to ensure that smallest clearance of the entire system is measured. In addition, any asymmetries due to case warping or the rotor not being centered must be accounted for as well. Multiple sensors at different circumferential locations should be able to accurately characterize these phenomena. The actual number and placement of the sensors to handle the various asymmetric clearance states is not yet clear.

As the tip clearance change is fast and complicated, control although suit for active blade tip clearance should be research in detail as well.

6. Example Data

Blade tip clearance measurement can be applied to disk and blade health management. However, the data collected under these tests are useful in demonstrating the sensor's ability to monitor tip clearance within a somewhat realistic environment. All of the data presented were performed on actual rotor test rig with 32 blades. The tests were run at continuously cycled from approximately 500 to 7,000 RPM. All of the graphs shown are plotted as a function of cycle number.

In Figure 6, the plot shows a blade failure at 2506 RPM, compared with a typical normal blade plot in figure 7. As the blade 3 falls off at cycle 5060, clearance between blade 3 and the shroud become large obviously.

An additional means of viewing the data is shown in the radar chart of Fig.8. The plot shows the individual blade clearances measured by the probe for several fan speeds. As noted previously, the plot shows that the individual blade tip clearances decrease as the fan speed is increased. A noticeable change in the individual clearances can be observed in the radar chart in Fig. 8. This clearly shows the decrease in the individual blade tip clearances as the fan is operated at higher speeds. The clearance decrease is biggest at 5500 RPM because the speed close to critical speed of the rotor test rig.

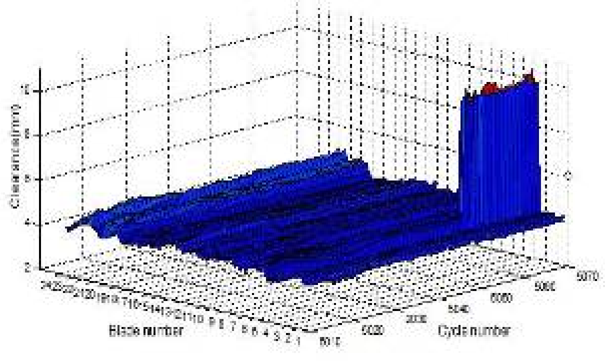

Fig. 6 Example blade failure shown in clearance

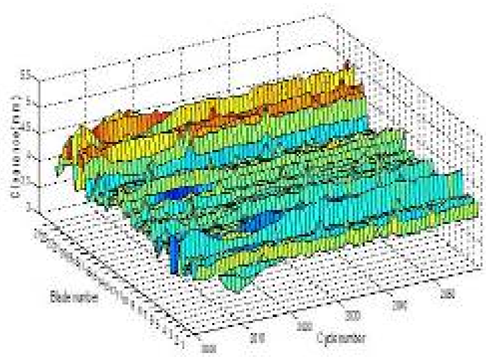

Fig. 7 Typical normal blade tip clearance

7. Conclusion

An optical fibre blade tip clearance sensor for active clearance control has been introduced. Rotor test rig experiment data has been shown demonstrating sensor performance. The sensor system data sampling rate is about 100 kHz, and the resolution ratio is better than 0.01mm. The sensor was able to detect the blade flaws within the system, and individual blade tip clearances can be measured fast.

Acknowledgments:

The authors are grateful for the supports provided by the Shenzhen Key Laboratory of Sensors Technology Open Project(SST201008).

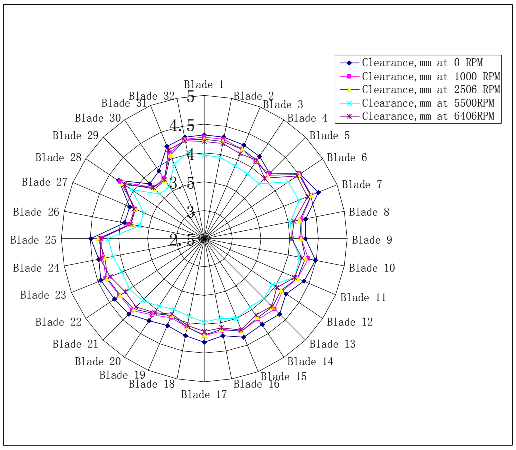

Fig. 8 Individual Blade Tip Clearances at different speed

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