Real-Time Tip-Clearance Active Control System

Overview

The goal of this program will be to develop and validate a real-time clearance measurement and control system using through-the-case sensors capable of operating in the harsh environment of gas turbine engines.

Significance of the Problem

Control of blade-tip clearance in the compressor and turbine sections of gas turbine engines can improve efficiency, minimize leakage flow, and shorten engine development time. Tip clearance varies throughout different operating conditions (e.g., start-up, idle, full power, shut-down) because of different radial forces and different thermal expansion coefficients and heat transfer. A real-time clearance control system can lead to turbine designs that eliminate rubbing of the housing and minimize leakage flow for maximum engine efficiency. Data collected from engine operation can provide information on the condition of the stage for improved maintenance.

Summary

The development team of Aerogage Corp. and Barbour Stockwell Inc. propose a two-phase program to develop an active tip-clearance control system capable of operating in the compressor and turbine sections of a gas turbine engine. The control system will utilize through-the-case eddy-current sensors for primary measurement of tip clearance for individual blades. During Phase 1, the sensors and measurement electronics will be optimized for the specific requirements of an active control system. Phase I will also involve the initial design of a control methodology capable of adjusting the tip clearance of the specific engine sections. Phase II will involve the integration of tip-clearance measurement with algorithms for active control. Phase II will also address prognostic health management issues.

History

The proposed program will build on an Aerogage Phase II SBIR sensor development program [1] currently funded by the US Navy F-35 Joint Strike Fighter program. The JSF program is entitled "High-Resolution Non-Intrusive-Stress-Measurement-System (NSMS) Sensor," and is focused on two specific applications of NSMS systems: elimination of blade vibrations characteristic of high-cycle fatigue (HCF) and detection of flutter and stall precursors. High resolution NSMS systems concentrate on measuring the blade time-of-arrival using eddy current and optical probes that require through-holes and bosses in the engine case. To date, NSMS systems have been used only to a limited extent on operational engines. As NSMS technology matures and becomes more affordable, it is transitioning to additional engine operational and test applications, including detection of blade vibration and detection of flutter and stall precursors through the engine case and at the first stage fan via the inlet aperture using time-of-arrival sensors.

A major restriction on use of existing NSMS sensors is the requirement for pre-drilled holes in the engine case. Standoff capability greatly enhances the value of NSMS to military aircraft turbine engine applications by removing the significant barriers to incorporating NSMS onto engine tests, as well as providing flexibility in locating sensors on fielded engines. Such capability facilitates incorporation of NSMS at various stages on fielded operational engines based on service-related issues rather than to just pre-planned locations identified during engine design. Such capability also facilitates retrofit to existing and research engines for such purposes as durability, depot level pass-off, and research-related tests. A reliable NSMS sensor with standoff capability and high resolution would be of significant benefit to both the military and the civilian turbine engine market, as well as to the stationary power generation market.

The proposed development program will focus on the use of through-the-case eddy-current sensors to measure blade-tip clearance in real time.

The program will also build on two other successful Aerogage R&D programs. The first involves a capacitance-based blade-tip clearance measurement system [2] developed under Phase I and II SBIR programs with NASA Glenn Research Center. The system has been used in numerous spin pit tests in Massachusetts, Ohio, and at Pax River, MD, primarily for measuring changes in tip clearance and time-of-arrival for individual blades in order to detect disk cracks during low-cycle-fatigue (LCF) studies. The second program involves a capacitance-based wireless link [3] for transmitting high-bandwidth (0-850 KHz) acoustic emissions data from rotors during operation.

Background

Although the potential benefits are high, control of blade tip clearance in turbine engines has been an elusive goal for the aircraft engine industry for several reasons. The first is that sensors are generally not capable of accurate, long-term operation in the engine environment. For example, optical sensors can be used in the low-temperature sections (e.g., fan and compressor), but their performance is severely compromised by contaminants such as water and oil. Capacitance sensors can also be used in the low-temperature sections, but they too are affected by contaminants. Eddy-current sensors are not affected by the contaminants, but they too are restricted to use in the low-temperature engine sections. Microwave sensors are also affected by contaminants and have been used only in the low-temperature engine sections.

Very few technologies are capable of operation in the gas generator and power turbine over the full range of operation. Potential sensors must operate in extreme environments up to 2000° F. For example, capacitance sensors have met with limited success in the turbine section due to the effects of ions in the gas stream.

Solution Areas

This proposal will develop a through-the-case eddy-current sensor capable of operation on all sections of the turbine engine. The use of permanent magnets allows the static magnetic field to penetrate the conductive engine housing without requiring the magnetic source to be inside the engine. Motion of the turbine blades through the magnetic field causes eddy currents to develop inside the turbine blade. The resulting secondary magnetic field from these eddy currents is detected by a coil inside the sensor located outside the engine housing. Thus the sensor is capable of detecting the motion of the turbine blade through the conductive engine housing, and as a result, the sensor can be located in a more benign environment. Additional cooling can be used as necessary to further reduce the temperature of the sensor. Since an eddy current sensor is unaffected by contaminants such as water and oil, long-term operation is possible.

The development work for the JSF program has focused on the use of the through-the-case eddy-current sensor for NSMS applications, particularly involving time-of-arrival measurements for individual blades. The effort for this proposal will concentrate on the use of the sensor in tip-clearance measurement applications.

History

Figure 1 shows a through-the-case eddy-current sensor and preamplifier as developed for the JSF program. The preamplifier is unique in that it is located not at the sensor but rather at the far end of the sensor coaxial cable (not shown).

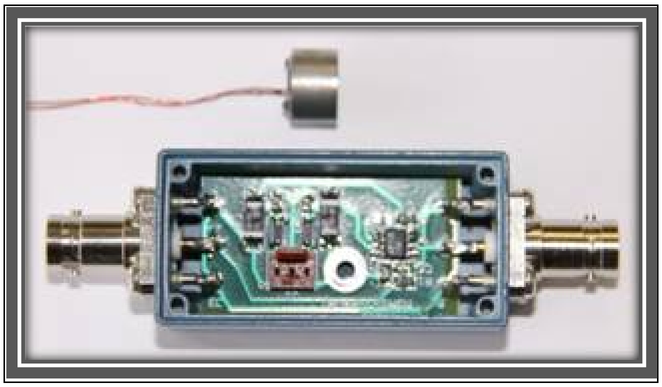

Figure 1. Through the Case Sensor and Preamplifier.

Figure 2 shows performance of the system in a low-rotation-rate test rig; the plot shows the output voltage of the preamp as a function of tip clearance measured at the end of a ten-foot cable with a blade passing frequency of 480 Hz. The eddy-current sensor will be the primary sensing component for the tip-clearance control system.

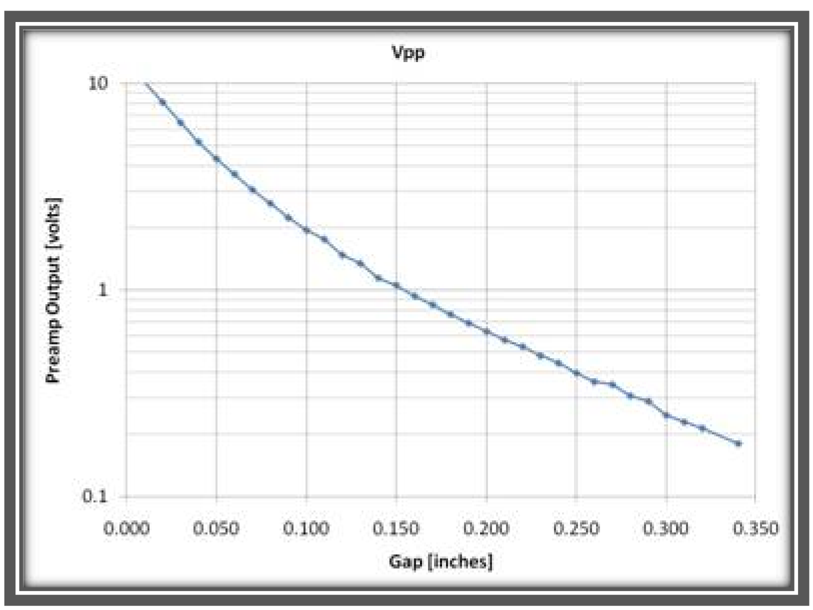

Figure 2. Preamplifier Output Voltage

Capacitance-based sensors have been developed by Aerogage for a number of different engine and spin-pit tests. Sensors of this type will be used to verify the performance of the through-the-case eddy-current sensors. Figure 3 shows one of the larger devices, a multi-electrode sensor for low-cycle-fatigue tests done in a spin pit at Pax River, MD, of the primary fan of the TF-39 engine (for the C-5A airframe). A single preamplifier would measure the tip clearance and time-of-arrival as each blade passed each of the sensor stripes.

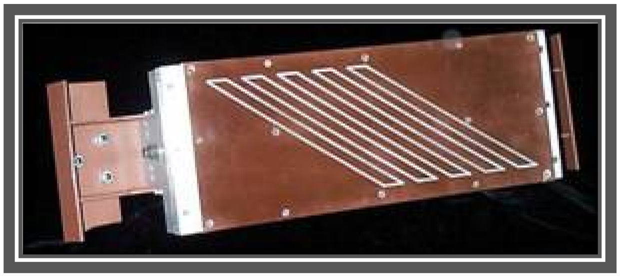

Figure 3. Sensor for TF-39 LCF Test

In contrast, Figure 4 shows one of the smaller capacitance-based, multi-electrode sensors; the four sensing stripes are approximately 0.010” wide.

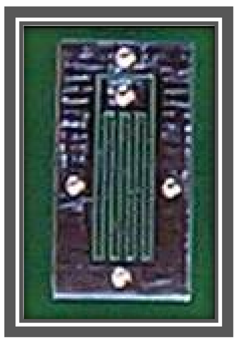

Figure 4. Capacitive Sensor

The Figure 5 shows the capacitance-based wireless link developed by Aerogage for NASA Glenn Research Center to transmit high-bandwidth signals from acoustic sensors located on a rotating turbine section. The system was developed for crack detection studies and provides a non-contact slip ring for bi-directional communication between stationary and rotating engine components. The slip ring will be available for use in validation tests of the eddy-current sensor.

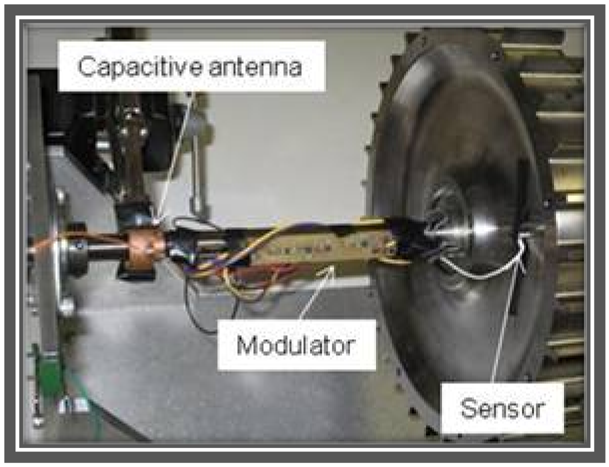

Figure 5. Wireless Slip Ring

Figure 6 shows the fidelity of the wireless slip ring in transmitting the acoustic emission signals from the rotating engine section.

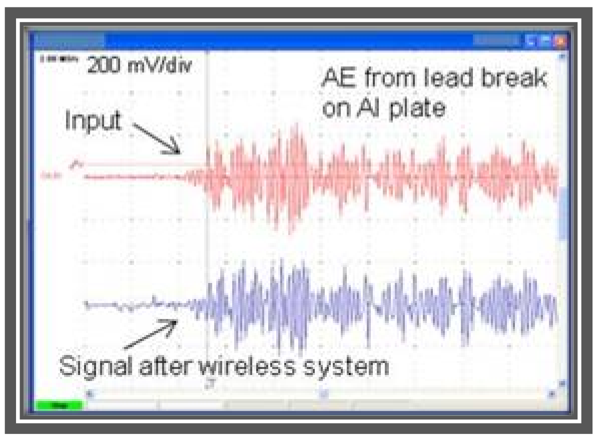

Figure 6. Acoustic Emission Signals

Development Team

Aerogage Corporation was formed in 1994 by Dr. W. C. Haase and MIT Professor Dr. J. K. Roberge to develop instrumentation for turbine engines. The first product developed by Aerogage was a capacitance-based system for measurement of blade tip clearance. This device has been used for spin pit testing at numerous facilities, including NAVAIR, Patuxent River, MD, and for crack detection in turbine engines at NASA Glenn Research Center. The system was also used in a Phase 1 SBIR crack-detection program with the U.S. Navy.

Aerogage also developed a multi-electrode capacitive sensor for detecting higher-order vibrations in blades. This system has been used in spin pit testing at NAVAIR and at NASA Glenn. Aerogage also completed two Phase 1 and one Phase 2 SBIR programs with NASA Glenn using the multi-electrode capacitive sensor for vibration sensing and crack detection.
More recently, Aerogage has developed through-the-case magnetic sensors for use in non-intrusive stress measurement systems (NSMS) under SBIR programs with the US Navy JSF program.

BSi is a world leader in the provision of equipment to generate and precisely control very high speed rotation. The company's products are used by the majority of the world's manufacturers of turbo machinery and other equipment which demand rigorous testing to assure reliability as well as human safety. The US Navy uses the company's equipment to drive the spin tests performed at the Patuxent River Rotor Spin Facility. Most recently, BSi has provided tools for the Navy to study the High Frequency Fatigue of jet engine rotor blading. BSi supplied an HCF excitation system for speed control within 1 rpm and sweeps at less than 1 rpm per second; the precision necessary to identify blade resonances within the operating range.

Design work will be conducted at Aerogage in Devens and at Barbour Stcokwell Inc. (BSi) Woburn, Massachusetts. Demonstration tests will be performed at BSi's lab in Woburn.

References

1. "Non-Intrusive Stress Measurement System (NSMS) Sensors with Standoff Capability," SBIR Phase 1 and 2, Topic N06-022, Contract No. N68335, Naval Air Warfare Center, Patuxent River, MD.
2. "Capacitance-Based Turbine Blade Vibration Monitor," SBIR Phase 1 and 2, Contract No. NAS3-00046, NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH, 44135
3. "Rotor Health Monitoring by Wireless Localized Sensing," A. Gyekenyesi and W. Haase, Proceedings of ASME Turbo Expo 2010 Power for Land, Sea, and Air, June 14-18, 2010, Glasgow, Scotland (to be presented).