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Measuring Rotor and Blade Dynamics Using an Optical Blade Tip Sensor

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ABSTRACT

This paper describes an optical measurement system for monitoring combustion turbine blade tips. The sensor measures distance to a blade tip using triangulation of reflected laser light. The system accomplishes triangulation using an optical position sensing device and high speed data acquisition. In this way, it is able to monitor not only average and minimum blade tip clearances, but to monitor the variations of individual blade tip clearances. By appropriate signal processing, it is possible to determine rotor vibration at the probe axial location, variations in shaft DC position, transient losses in blade tip clearance, the potential for tip and seal rubs, vibrations of individual blades in the tangential direction, and rotor torsional vibration at the probe location. Some aspects of blade and torsional vibrations would require more than one probe. The paper presents static calibration data for the measurement system, showing its degree of linearity and range. The paper also presents data obtained on a dynamic blade test rig with tip passing speeds and blade widths comparable to those encountered in high performance industrial combustion turbines. Data from this rig have been processed to show rotor vibration, shift in shaft average position, blade-to-blade tip clearance variation, and variation with speed of minimum blade tip clearance. The measurement system is designed to produce data suitable for use in the monitoring of advanced combustion turbine durability and the diagnosis of turbine functional problems, static and dynamic.

INTRODUCTION

There is a need to monitor the radial position of the tip of the individual blades in combustion turbines. Such turbines, both in the compressor section and the hot expander section, seek operational efficiency by minimizing the design clearance of blade tips and interstage seals. At the same time, the harsh operating environment and dynamic characteristics of the turbine mean that the actual minimum and maximum tip clearances can vary substantially. There are excursions of the rotor during start-up and shutdown as it negotiates its critical speeds and changes position in its bearings. There are thermal distortions of rotor and case which vary with ambient conditions and with the time since the turbine was last operated. Further, as properties and dimensions of materials and coatings change due to creep, there can be long-term degradation in operating clearances. The consequences of blade tip rubs can range from loss in operating efficiency, to loss in blade attachment integrity and eventual failure, to severe and immediate blade damage, and even to a catastrophic and expensive wreck.

When we can successively record the clearance of each and every individual blade, there are significant new opportunities for determining rotor steady-state dynamic response, transient changes, and long-term trends. The synchronous and nonsynchronous lateral vibrations of the rotor at the axial location of the monitored blade stage can be accurately inferred. A probe near mid-span between bearings offers more complete measurement of first critical rotor vibration than shaft displacement probes located at the bearings. Vibration at the journals of high performance turbomachinery may be less than shaft center vibration by a factor of four at the first critical speed. To estimate shaft center amplitudes from bearing vibration incurs significant uncertainty, which blade tip measurement can reduce.

The probe can, of course, measure minimum tip clearance. This in itself is possible with commercially available systems, particularly the touch probe[1]. Added information offered by the optical measurement system includes the blade for which the minimum clearance occurs, how much of the loss in clearance is attributable to vibration, and how much of the loss in clearance is attributable to the uniform growth of blades or thermal distortion of casing.

More detailed analysis of individual blades and minimum to maximum clearance variation helps reveal if changes in condition of one or more individual blades are contributing to a loss in clearance.

If the blades exhibit longitudinal bending vibration at a nonorder related frequency, a single probe can provide information on this vibration by virtue of time-of-arrival information and its variation (Roth, 1980). If the blade vibrations are occurring at a multiple of running speed, then a single probe will not detect them. However, the variation in time-of-arrival between two probes at different circumferential locations offers potentially the additional capability to monitor order related tangential blade vibration.

Rotor system torsional vibration can also be detected by a pair of blade sensors and interpretation of time arrival. It would be desirable to view the torsional vibration information obtained in this way as a supplement to that already available through torsiograph, encoder, and strain gage telemetry methods. The unique supplement that the optical measurement system provides is the ability to measure the torsional vibrations at axial locations previously inaccessible to

1 RotaData Limited, Derby, England.

*Presented at the Gas Turbine and Aeroengine Congress and Exposition—June 11-14, 1990—Brussels, Belgium

such monitoring. Thus, the need for such a sensor exists and the benefits from its effective development are significant.

The desirable attributes of a measurement system for blade tip monitoring are: wide linear range, a manageable penetration diameter, ability to survive the environment to which it is exposed, high frequency response, ruggedness of sensor assembly and attachments, low frequency response down to DC, and low sensitivity of signal output to changes in environmental conditions, particularly temperature. These are obviously challenging requirements difficult to combine in a single measurement system and normally subjected to trade-offs. As will be seen, the optical measurement system described in this paper has encouraging capabilities on all counts; making it a serious alternative to the use of eddy current (Biggs, 1976) or capacitance (Foster, 1989) sensors for this application and to other optical devices (Kurkov, 1989). The measurement system builds upon established optical clearance sensor technology (Drinkuth, et al, 1974) (Barranger, et al, 1980), but provides real time measurement capability for each successive blade. The primary contribution of this work is the development of a beam management, transmission, detection, and signal processing system which gives a digital readout of blade position.

This paper describes the physical probe, light transmission, electronics, and initial performance evaluation of the measurement system.

OPTICAL PROBE

The physical arrangement and principle of the probe are shown in Figure 1 and follows the design by Pratt & Whitney Aircraft (U.S. Patent 5574650). Laser light is transported through the probe and focused into a spot on the turbine blade tip. The spot on the blade is then imaged by the probe upon the face of a fiber optic bundle. Because the light strikes the blade tip at an angle, any change in distance between blade tip and probe causes the imaged spot on the fiber optic to move across the face of the bundle. The distance the spot moves on the bundle is directly related to the change in blade-to-probe separation.

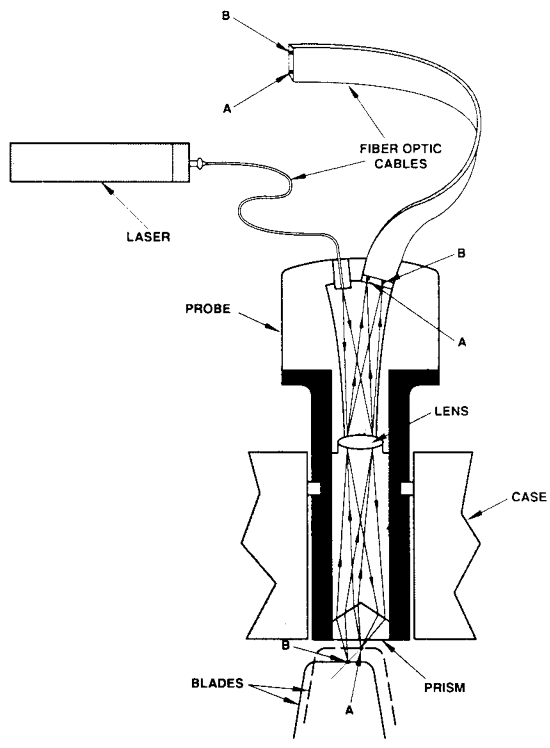

FIG. 1 OPTICAL SENSOR SYSTEM SCHEMATIC

The probe can be considered in three sections: the emitting and receiving sections, the focusing section, and the redirection section. The emitting and receiving sections consist of a 100 micron core fiber optic cable which emits light into the probe, and a coherent fiber optic bundle which receives the returned image from the probe. The fiber optic cable has a gradient index rod lens attached which collimates the light entering the probe into a 5 degree divergence angle. The focusing section of the probe consists of a planoconvex lens which performs two functions: it focuses light from the fiber optic cable into a spot, and focuses the image of that same spot into the coherent fiber optic bundle. The redirection section consists of a prism which causes the incoming rays to be incident upon the turbine blade at a 45 degree angle. As the blade depth decreases by some small distance, the spot will move across the blade by the same distance. The prism also captures the spot allowing the focusing section to image the spot on the coherent fiber bundle. The probe phototype, shown in Figure 2, requires a 25 mm (1 inch) access hole through an engine case which could be reduced to about 19 mm (3/4 inch) or less in a production model.

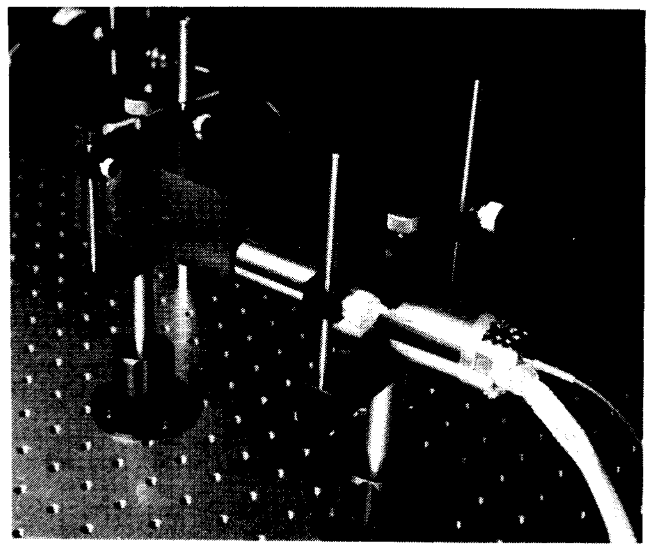

FIG. 2 OPTICAL PROBE IN BENCH TEST FIXTURE

Signal Detection, Processing, and Acquisition

The output of the optical probe is a concentrated spot of light carried by a flexible coherent optical fiber bundle. The coherent bundle transmits an image from one end to the other, maintaining the orientation of the many fiber elements forming the input image. The fiber bundle faces are shaped in a rectangular form, and the image input end is mounted to the triangulation optics of the optical probe. The light spot derived from the optical probe will be transmitted through the bundle and appears at the output image end. The spot traverses the length of the output image face of the fiber bundle proportionate to the spacing between the optical probe and the subject turbine blade tip. The output image end of the fiber bundle is attached to a semiconductor element know as a position sensing device (PSD) (Edwards, 1988). The PSD allows conversion of the position information inherent in the optical probe light spot into an electronic signal that can be processed using analog and digital circuitry.

The PSD is an optoelectronic device that yields photocurrents from which the geometric centroid of all light striking its surface can be computed. The PSD used in this application is a one-dimensional device which indicates the position of a light spot along its axis by way of two photocurrents, i_1 and i_2, depicted in Figure 3. For a position x_a from the center of the PSD active surface which has length 2L, the position of the centroid of a light spot striking the surface is given by:

$$x_a = L * [(i_2 - i_1) \ / \ (i_2 + i_1)] \qquad (1)$$

The subtraction, addition, and division operations needed to compute the position x_a are all done by means of analog electronics in the data acquisition system (DAS). The block diagram of the DAS circuitry in Figure 3 shows amplification, subtraction, and summing components that are realized from operational amplifier building blocks. The division operation is done by an analog divider chip. The sum term "Σ" in the block diagram is an "intensity" measure used by the timing control to indicate presence of a turbine blade tip crossing the optical probe face. The gain adjustment maintains electronic signals within the linear operation limits of the analog computing elements. A lower range limit of intensity is used as a threshold above, which a turbine blade is accepted as being in view of the optical probe. With these design constraints, the DAS circuitry has an electronic band width of 1 MHz, with higher band widths possible. A settling time of about 2 microseconds is allowed

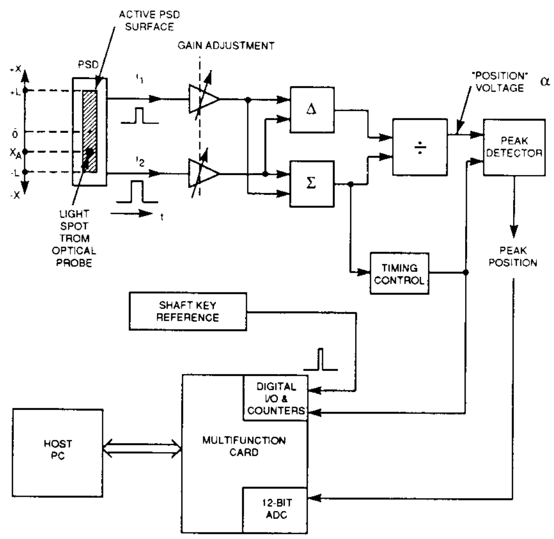

FIG. 3 DATA ACQUISITION ELECTRONIC BLOCK DIAGRAM

following the leading edge of a turbine blade tip across the optical probe, after which a peak detector is activated to record the peak position reading during a blade passage. As the intensity drops below the set threshold indicating that the turbine blade has passed, the peak detector holds the maximum voltage reading that occurred during the blade passage. The peak voltage is proportional to the "minimum" blade tip clearance to the probe by the design of the optics and orientation of the fiber bundle to the PSD.

To extract data from the DAS, a personal computer (PC) has been used. The PC is instrumented with a multifunction card that has digital inputs and outputs, programmable counters, and a 12 bit analog-to-digital converter. Sampling is trigger controlled from the negative-going pulse as the blade passes out of view. The selected number of samples are collected with direct memory access for processing by Fourier transform, data averaging, etc.

<u>Static Calibration Results</u>

The probe has been calibrated in a static fixture to provide output voltage as a function of the gap between the probe tip and the blade tip. The result is presented in Figure 4 which shows voltage output plotted as a function of mils displacement between blade tip and probe. It is apparent from this curve that a near linear range is obtainable over approximately 0.25 inches, with a slope of 18.3 mV per mil. Nonlinear deviation over this range is approximately 50 mV or 3 mils, which can be corrected by subsequent processing. Such performance from a first build probe is encouraging.

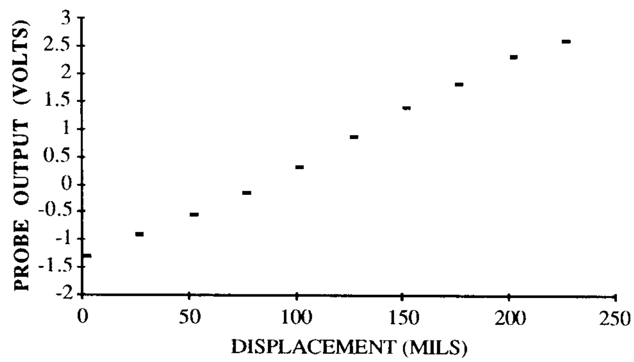

FIG. 4 OPTICAL BLADE TIP CLEARANCE PROBE CALIBRATION

<u>Dynamic Test Rig</u>

A test rig for evaluating the dynamic performance of the optical blade tip measurement system was built by replacing the compressor of a turbocharger with a symmetrical three bladed wheel shown in Figure 5. The wheel is 4 inches in diameter and at 63,000 rpm, achieves a tip speed of 1,100 feet per second. The individual blades at their tips are 0.3 inches wide. Such dimensions and speeds are typical of those to be encountered in an industrial gas turbine of 100 megawatt capacity. The rig is driven by providing shop air to the turbocharger turbine. Available shop air supply has proved capable of driving the rig up to 63,000 rpm, at which point frictional and windage torque equal the drive torque.

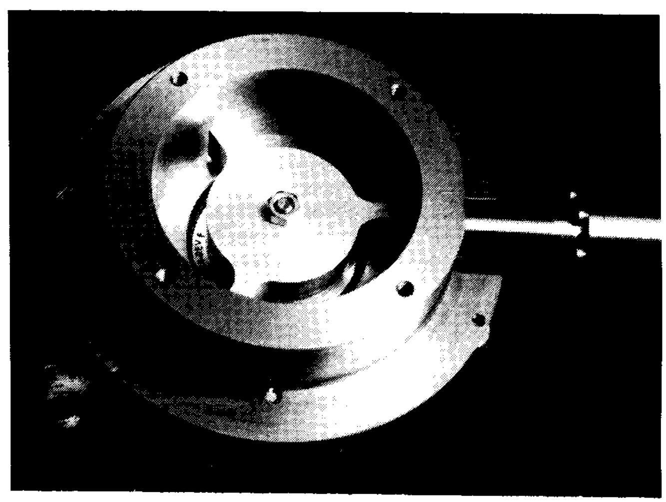

FIG. 5 HIGH SPEED TEST RIG WITH THREE BLADED WHEEL EXPOSED

The casing of the turbocharger outside of the test wheel is modified to accept the optical probe, so that the probe is centered over the passing blades and can be used to measure their gap as they pass the sensor. The present laser supply and PSD are mounted on an optical bench adjacent to the test rig. Data from the signal processing module are acquired by a portable computer. Voltage signals can also be displayed on a scope. Figure 6 presents a photograph of the test rig with probe installed and with turbine air supply visible. Also visible are the fiber optic bundles.

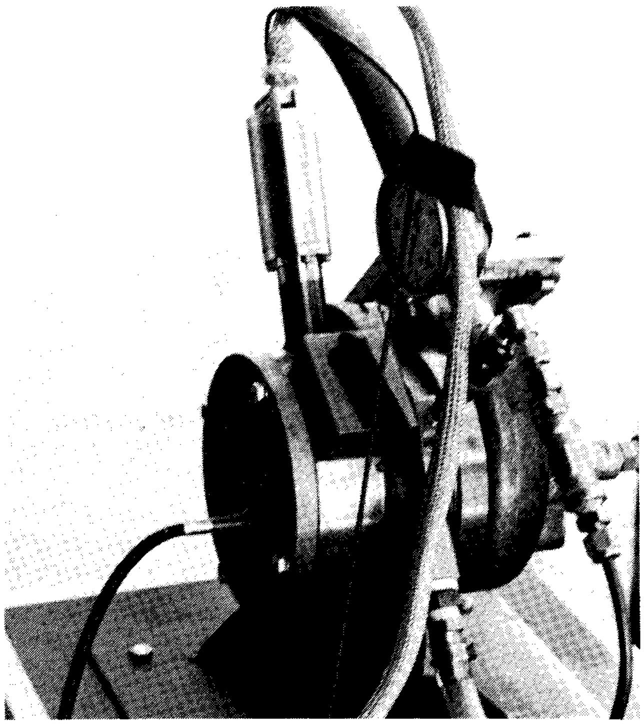

FIG. 6 DYNAMIC TEST RIG WITH
OPTICAL MEASUREMENT SYSTEM INSTALLED

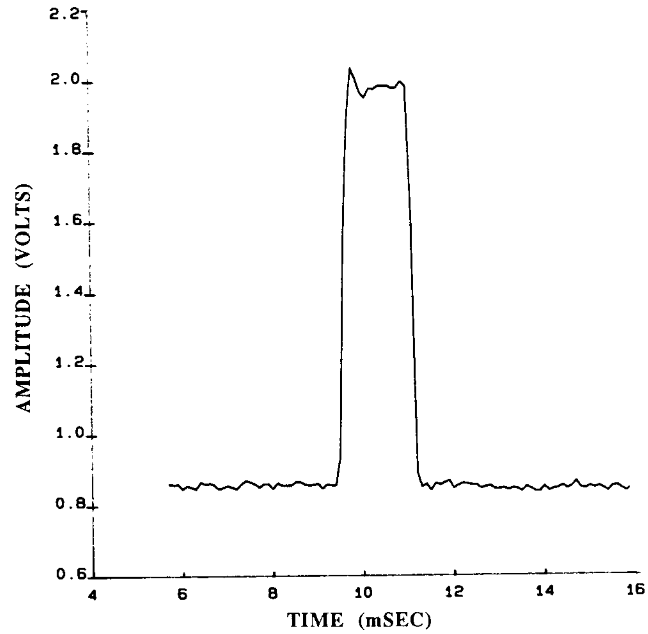

FIG. 7 TYPICAL PROBE VOLTAGE OUTPUT VS. TIME
DURING BLADE PASSAGE

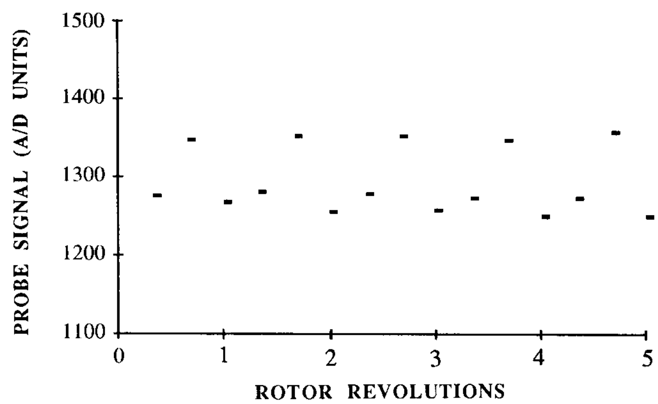

FIG. 8 PROBE ANALOG/DIGITAL OUTPUT FOR THREE
BLADED WHEEL (52,000 rpm)

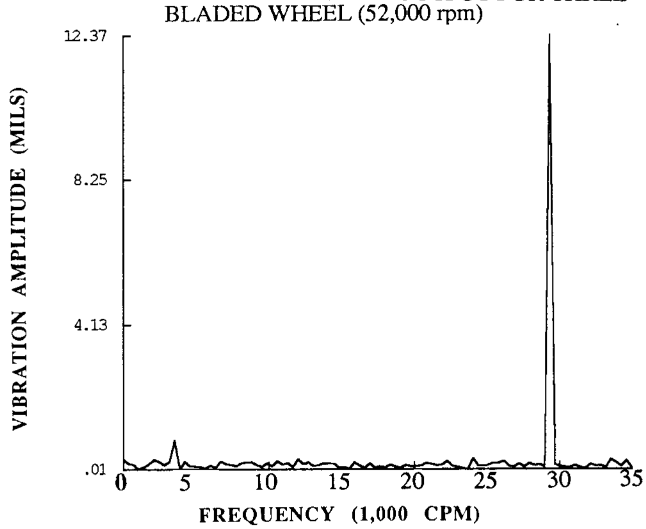

FIG. 9 ROTOR VIBRATION AMPLITUDE SPECTRUM
AT 30,000 RPM

Initial Test Data

Figure 7 presents a typical individual voltage analog of tip clearance traced as a single blade passes the sensor. The signal clearly rises very sharply as the blade comes into view. This feature is to be expected of the optical probe since the probe has no "awareness" of an approaching blade until the blade is in its field of view. Probes based on capacitance or eddy current principles will have some "awareness" of an approaching blade, as the fields for these sensors are not restricted to a directed line of sight. A signal transient appears just after the blade has come into view, due to a partial spot forming on the leading edge of the blade. The minor signal variations in the central portion of the blade passage would appear to reflect small repeatable features of each blade. The electronics must be set to gate the signal and avoid picking up the initial edge transient. Figure 8 shows digital output as a function of datapoint number. Each successive datapoint represents a successive blade. Since the rig has three blades, the pattern is repeated every three points. This is the nature of the blade tip clearance raw information – discrete values of blade tip position relative to the probe. These must be processed further to provide engineering information.

Figure 9 shows a spectrum plot of rotor vibration. The raw data are actually acquired in 252 sample records, a multiple of three. In the spectrum calculation, the first bin represents a frequency of 1/84th rotational of speed and the 84th bin corresponds to running speed. As shown in Figure 9, there is a very pronounced peak at the 84th bin. In the example for 30,000 cpm, no other frequency shows any significant amplitude except a small peak of about 1 mil amplitude corresponding to about 3,000 cpm. This 3,000 cpm peak appears at all speeds from 10,000 to 50,000 rpm.

Figure 10 plots uncompensated or raw running speed vibration amplitudes as a function of speed from 1,000 to 52,000 rpm. Amplitudes are quite substantial, attributable in part to eccentric mounting of the wheel on the rotor. This eccentricity signal, usually referred to as runout, can be compensated for by vectorally subtracting values obtained at a stable low speed condition from all other data.

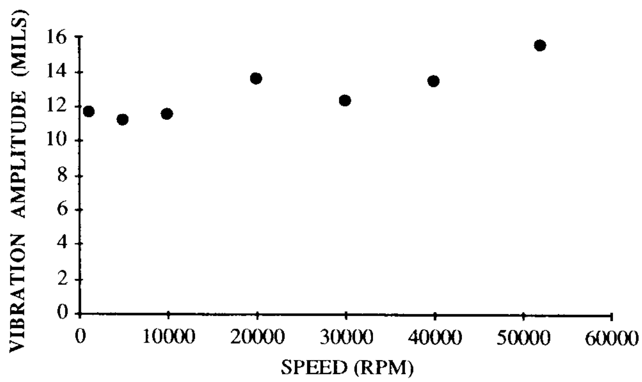

FIG. 10 ROTOR VIBRATION AMPLITUDE VS. SPEED

Figure 11 plots the corresponding rotor vibration phase as a function of speed. Substantial variation occurs, suggesting a well-damped resonance in the region of 40,000 rpm. The main purpose of this data is to show that lateral vibration amplitude can be readily extracted from blade tip data and displayed as a function of speed.

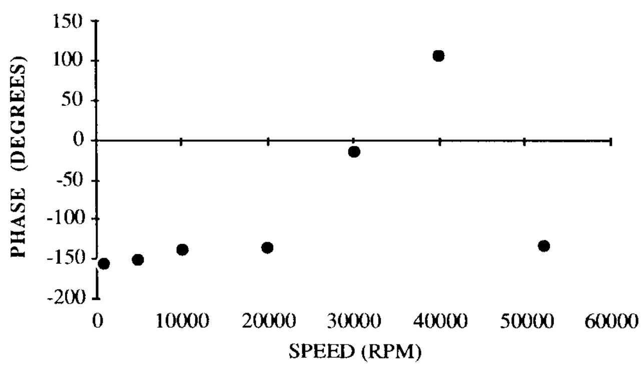

FIG. 11 ROTOR VIBRATION PHASE LAG VS. SPEED

Figure 12 presents the average DC position of the shaft as a function of speed. This is obtained by averaging the signals from the three blades. There is some initial shift at low speed which probably represents the rotor riding up in its bearings as a full fluid film develops. At higher speeds, there is little change; this is an encouraging indicator of the high frequency response of this probe. A drop in signal at high speeds would indicate a frequency response limitation in the electronics.

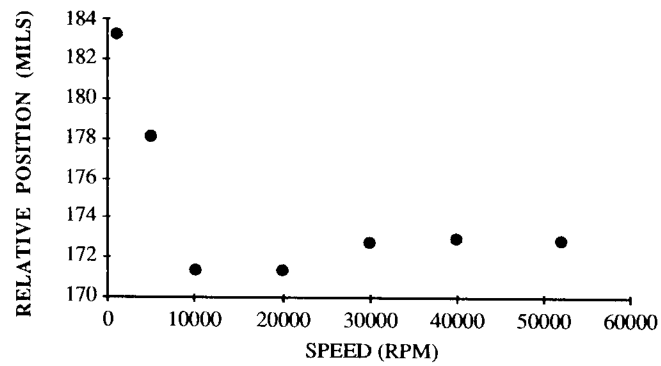

FIG. 12 SHAFT AVERAGE POSITION VS. SPEED

Figure 13 shows how minimum clearance varies with speed. This information is obtained by processing data to obtain the gap between the housing and the blade which most closely approaches the case. This data are similar to the DC shaft position but shows small differences attributable to shaft dynamics, blade-to-blade variations, and wheel eccentricity.

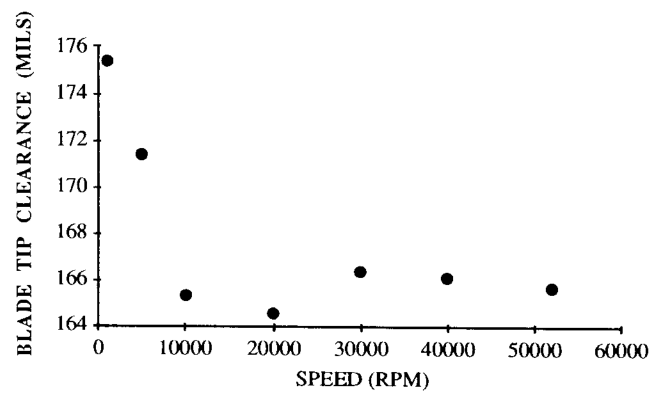

FIG. 13 MINIMUM BLADE TIP CLEARANCE VS. SPEED

DISCUSSION

The optical measurement system described in this paper opens up new options and opportunities for measurement, condition monitoring, and diagnosis of machinery – particularly hot gas and combustion turbines with free-standing blades. Results for the first build of this probe show that its linearity and repeatability are encouraging, with an absolute deviation from linearity over its 225 mil range of about 3 mils or 1.5 percent of full scale. The range for this size of probe at 0.225 inches is very satisfactory and should meet the needs of many applications. Higher ranges can be designed by changes in optics or an increase in diameter of the probe itself; further optimization of the probe for range and linearity can be expected.

The frequency response is high and fully capable of tracking blade passing signals typical of large combustion turbines or expansion turbines. Some gating of the signal is necessary to avoid momentary blade edge effects, but there is no loss in gain at the frequency of blade passing which has been tested. Low frequency response is also good and static calibration has been demonstrated. The size of penetration required for the range demonstrated is satisfactory and could be minimized.

Some capabilities have not yet been tested. The ruggedness of the mechanical structure needs evaluating in various aggressive environments. There is definitely a need to engineer more rugged optical connectors between fibers and light source. The ability of the sensor to survive more severe environments has not been tested; in fact, the probe has only been engineered for room temperature testing so far. We plan some near-term tests to evaluate sensitivity to temperature, materials, light intensity, reflectivity, etc.

CONCLUSIONS

- A new blade tip measurement system has been demonstrated based on already established optical triangulation principles.

- The system frequency response provides the capability for real-time tip clearance and time-of-arrival measurements for each blade in a blade row.

- The measurement system has adequate linearity and range for industrial turbine application.

- These capabilities are achieved in a probe package whose size should be acceptable for its intended application.

- The ability of the probe to monitor shaft vibration, shaft displacement, and minimum clearance from blade tip measurements have been demonstrated.

- Further tests to evaluate torsional vibration measurement and sensitivity to materials, reflectivity, and some change in temperature are planned with the present rig.

- The measurement system appears essentially ready for applications engineering.

ACKNOWLEDGEMENTS

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The measurement system builds on the optical probe principles developed by Pratt & Whitney Aircraft. The authors appreciate the advice and encouragement of Ron Burr of Pratt & Whitney Aircraft.

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