HIGH PERFORMANCE ROTOR HEALTH MONITORING

New Multi-Element Capacitive Sensor & High Bandwidth Preamp Form Basis Of Data Fusion System For Real Time Measurement Of Individual Blade Tip Clearance, Blade Vibration, Crack Detection And System Vibration In Aircraft Engines And Industrial Machinery

Mike Drumm & Dr. Wayne C. Haase, ExSell Instruments, Acton, MA   June 2000

Abstract

This paper describes the development of a high bandwidth, capacitive sensing system to monitor blade tip clearance, system vibration, blade time-of-arrival, blade vibration and detection of low cycle fatigue cracking on aircraft engines and industrial machinery. All measurements are fused into a single sensor and single channel of electronics. The paper describes the development of the multi-element capacitive sensor and high bandwidth preamplifier, presents results from tests conducted in a spin pit, and compares their time-of-arrival performance to the current Non-Intrusive Strain Measurement System being developed by the Propulsion Instrumentation Working Group.

The system measures the clearance between the tip of each blade on a rotating disk and a thin multi-element capacitive sensor mounted close to the rotating part. The sensor is coupled to a very high bandwidth and high signal-to-noise preamplifier that allows detection of individual blades in real-time and the use of narrow striped capacitive sensors for increased resolution. The device can be used as the heart of a rotor health monitoring system for detection of High Cycle Fatigue blade vibration, Low Cycle Fatigue disk cracking, active tip clearance control input, blade damage from foreign objects, and monitoring of system vibration and speed.

Existing Sensors

Most tip clearance systems using capacitive sensors have been unable to accurately measure both clearance of individual blades in real-time, and circumferential motion of blades due to the limited lateral spatial resolution of the typical spark plug type sensor. Many capacitive sensors intended for blade tip measurement have a primary electrode that is circular, with a diameter considerably larger than the blade tip thickness. Furthermore, most of these sensors do not have a ground close to the primary electrode. As a result, the electrostatic field lines, which originate on the primary electrode and terminate on ground, extend away from the primary electrode toward the rotor center (see Fig.

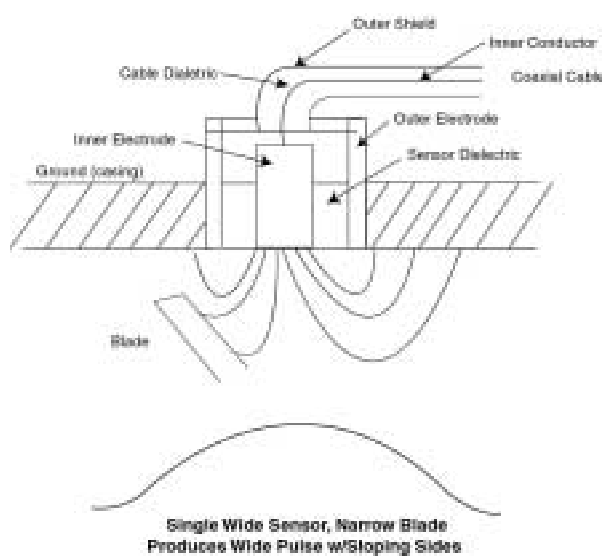

Fig 1 - Example of Low Resolution Output from a Capacitive Measurement Using a Typical Wide, Single Element Sensor

1). The electrostatic field also extends in a circumferential fashion in both directions from the center of the sensor. As a blade passes the face of the sensor, the system generates an output pulse due to the change in capacitance of the primary electrode. Since the electrostatic field extends a significant distance in the circumferential direction compared to the blade thickness, the output signal has a wide pulse width. In terms of spatial resolution, such a system would have a pulse width many times the diameter of the primary element of the sensor, and would only be able to resolve circumferential distances on the order of half the sensor diameter. If the diameter of the sensor were considerably larger than the blade thickness, the system would not be able to resolve even one blade thickness.

Sensor Improvements

Two methods used to increase the resolution of a capacitive sensor are to make the primary electrode thinner and to add a ground electrode close to the primary electrode. The resulting sensor will have much higher lateral spatial resolution but at the expense of a significant reduction in signal level. A sensor designed with a stripe-shaped primary electrode, with the stripe width equal to the blade tip thickness, will have an output pulse that has a much narrower width and corresponding higher bandwidth. If additional ground electrodes are positioned adjacent to the primary electrode, the pulse width will be reduced even further (see Figs. 2 & 3). To process the signal, the channel bandwidth must now be significantly higher. The net effect in system performance is that while the spatial resolution has been improved, the signal amplitude has been greatly reduced and the noise has been greatly increased (due to the increase in bandwidth), resulting in the signal-to-noise ratio taking a severe beating. Most capacitive systems that use modulated signals to indirectly measure gap do not enjoy such a large signal-to-noise ratio that they can operate with high spatial resolution due to fundamental limitations of their gap measurement technique. These typical tip clearance systems also have problems with large gaps when using a thin-striped sensor because the electrostatic field does not extend far from the primary electrode.

The multi-element capacitive sensing *HiBand* system from ExSell Instruments is unique in that it uses multiple thin striped electrodes for sensors, and has both a very high signal-to-noise ratio and wide signal bandwidth. This result is due to the unique design of the sensor (patent pending), and a patented DC biasing technique used in the probe preamplifier. High voltage (100 to 200 volts) provides a high signal level, and the DC nature of the preamplifier provides high bandwidth (20 MHz).

For most capacitive systems, a sinusoidal drive signal is used and the system bandwidth is forced to be a fraction of the drive frequency. The peak amplitude of the typical signal must also be limited to drive the sensor cables. *HiBand* is a DC system that uses blade motion as the modulating action, and incorporates a self-calibrating technique that provides long-term stability in excess of 10,000 hr. In head-to-head tests with conventional capacitive systems, *HiBand* has demonstrated signal-to-noise ratios that are as much as 60 dB higher. By designing the sensor electrode to maximize spatial resolution, the ExSell system is capable of highly

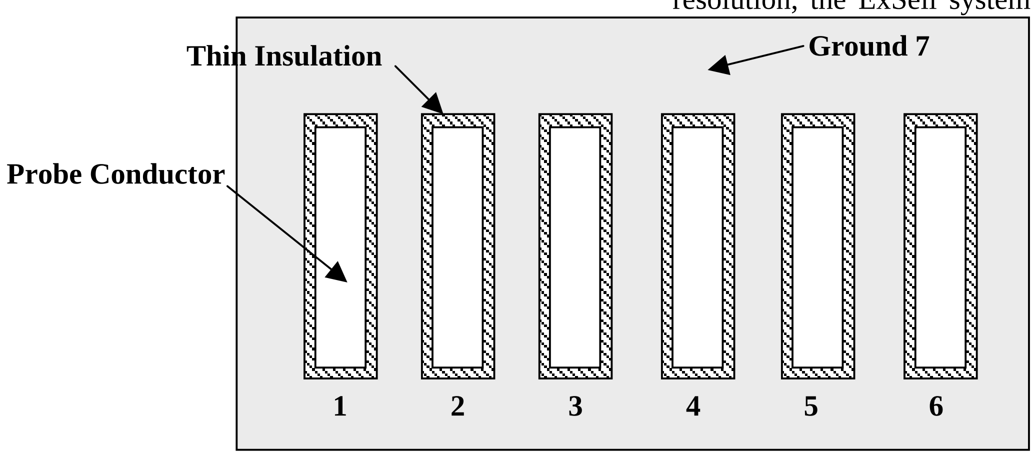

Fig. 2
MasterPlex Probe Generic Design. Multiple Elements Fit Within Blade-to-Blade Spacing
(Patent Pending)

accurate, real-time measurements of blade vibration, radial vibration and individual blade tip clearance.

MasterPlex Probe (multi-element capacitive sensor)

The new MasterPlex probe concept (patent pending) that incorporates these elements into the design is shown as a generic example in Figure 2.

This probe is constructed with multiple electrodes (shown as 1-6 in the figure), separated by a grounded electrode (7). Each of the electrodes 1-6 could be connected to individual signal processing circuits much like conventional systems; however, connecting all of the electrodes together electrically and applying the composite signal to a single preamp channel simplifies the system significantly.

If the spacing of the electrodes is small compared to the spacing between adjacent turbine blades, then a single blade will completely pass each of the electrodes 1-6 before the next blade arrives at electrode 1. As a result, the output voltage of the preamp connected to the sensor will be a burst of pulses (six in this example) for each blade. Signal processing of the output signal is required to measure the time of arrival for each of the pulses in the burst. The height of each pulse is a direct measure of the blade's distance from the sensor, and the distance between minor peaks is a direct measure of the high frequency vibration of each blade (see Fig. 3). The minor peaks are stair-stepped in this example because the sensor used was flat.

The net result is that a specially designed capacitive probe and a <u>single</u> channel of electronics are able to measure the time of arrival of individual blades at multiple positions within the same sensor. Variations in blade time of arrival indicate vibration of the blade tip. Note that several sensors of the type shown above could be located around the circumference of a rotor stage, increasing the resolution and providing significantly more information on a wide variety of blade vibration modes.

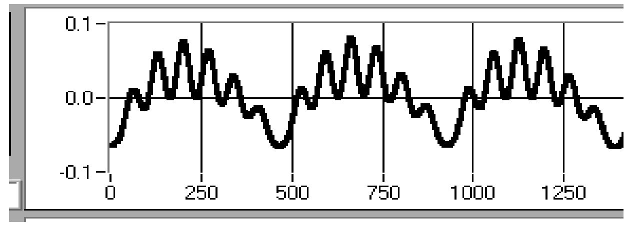

Fig. 3
MasterPlex Six Element Probe Output Displays The Passing of Three Blades

Examples of MasterPlex Sensors

Shown below is a range of designs for MasterPlex sensors for different applications. The fundamental thinness and flexibility of the sensor allows it to be used in places normal sensors cannot go. Sensors can be made for both low and very high temperature applications (2000+°F), and can be integrated into rub strips as permanent installations for tip clearance and vibration measurement. Shown in Figure 4 is a 4-element MasterPlex sensor for a small bladed disk.

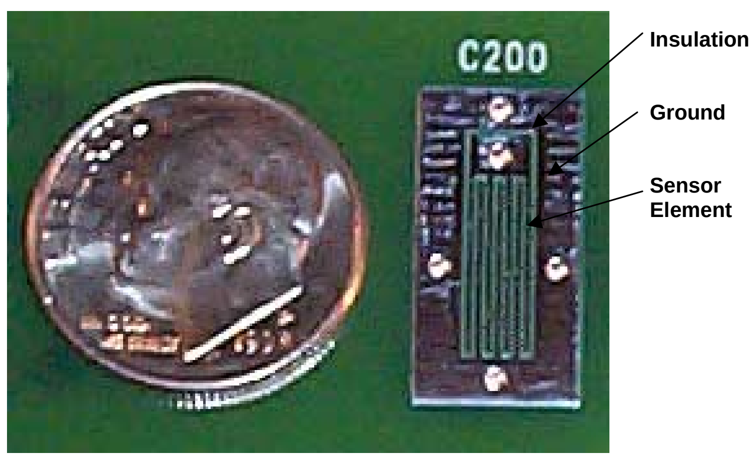

Fig.4 - Small MasterPlex probe for bladed wheel. Measurements on this sensor with a line width of 15 mils produced a circumferential resolution of 0.12 mils at a standoff distance of 5 mils.

HiBand Preamp

The *HiBand* preamp used with MasterPlex sensors has a measurement bandwidth of 20 MHz, a wideband signal-to-noise ratio (SNR) of 53 dB, and a narrowband SNR of over 100 dB (see output waveform of actual test in Fig. 5). The preamp has a volume of approximately 20 cu. inches and dissipates a total of 1 Watt. Resolution in the radial direction (for blade tip clearance) is 0.01 mil. Circumferential resolution (for blade vibration) is 0.12 mils for small disks and close standoffs, and 1.7 mils for very large disks and standoffs.

Current optical Generation 3+ Non-Intrusive Strain Measurement Systems (NSMS) have a circumferential resolution of 2 – 10 mils, and Generation 4 systems being prototyped now have a goal of 0.1 mil as a circumferential resolution.

There are no electronics in the probe and the *HiBand* preamp can be located up to 30 feet away from the sensor.

Typical blade tip clearance systems suffer from the influence of substantial error sources: cable vibration can change the cable capacitance; cable bending can produce a piezoelectric effect generating a charge or voltage difference between the cable's center conductor and the shield; pyroelectric effects can cause changes in output voltage with variations in temperature; and triboelectric effects can cause a charge or voltage difference between the center conductor and the outer shield. Unfortunately, in many measurement situations, the change in the preamp output due to a change in the tip clearance of a blade is often of the same order of magnitude as the noise effects listed above.

The inherent design of the *HiBand* preamplifier plus the addition of signal processing at the output virtually eliminates the effects of these noise sources up to the blade passing frequency (e.g. 40 blades, up to 40E).

Application Example

Shown below are the results from a spin test of a large fan in an evacuated chamber using a multi-element capacitive sensor inside a spin pit. A 3-element MasterPlex probe was mounted 250 mils from the tips of the blades of a large fan, and a *HiBand* preamp was located on top of the spin pit about 20 feet away from the sensor. The output of the preamp was connected to an ExSell Vibration Monitoring System located in a control room, about 300 feet across the hall. Fig. 6 is a picture of the 3-element MasterPlex sensor mounted in the spin pit that was used in this low cycle fatigue test.

Fig. 5

Output of HiBand Preamp. Input was 3-element MasterPlex sensor shown in Application Example below. Standoff distance from sensor to blades was 250 mils.

Note small noise in lower left of graph.

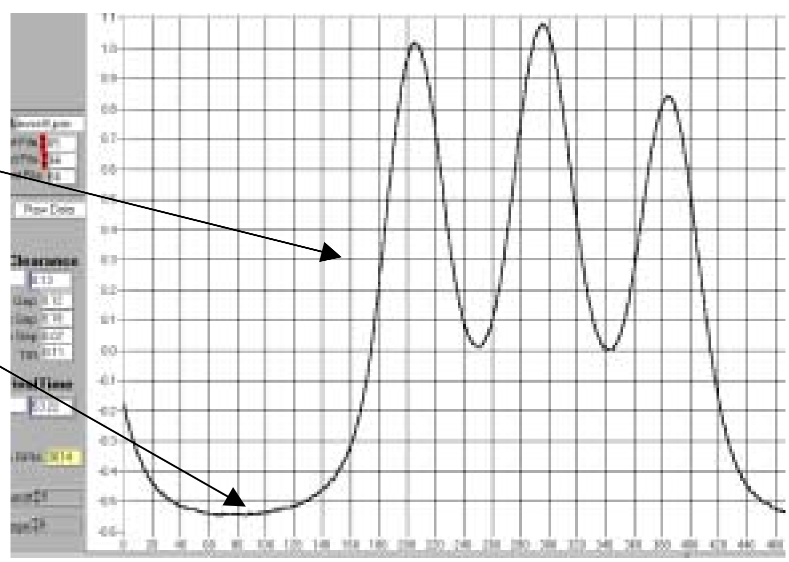

Fig. 6

3-Element MasterPlex sensor mounted in spin pit for low cycle fatigue test. Measurements on this sensor with a line width of 280 mils produced a circumferential resolution of 1.7 mils at a standoff distance of 250 mils.

The test was designed to induce cracks in an aircraft fan by cycling the part from top speed to a substantially lower speed, then continuously repeating the cycle. The *HiBand* system was measuring and displaying the raw signal, blade tip clearance, time-of-arrival of blades, and processing the vibration signal to produce plots that track small changes in the balance of the system, typically due to the formation of low cycle fatigue cracks. In addition, the *HiBand* system was generating several plots that compared the current tip clearance with a baseline tip clearance after the 1E (first engine order) vibration was removed, and the difference in time-of-arrival of blades from an established baseline.

Data was taken on one revolution near the top speed of the fan on each cycle. Data was displayed in real-time and also stored for later playback and analysis. Storing the data taken during each acquisition revolution allows the test to be run again and again with different filters, different windows, different graphs, different baselines, etc. Fig. 7 is a screen shot from the ExSell acquisition system.

Raw data is shown in the upper left (the sensor was contoured to the shape of the fan, but was slightly skewed during installation causing unevenness of the three pulses). Raw data from seven blades are shown, and the height of each set of pulses represents the tip clearance of each blade. This clearance is shown in the black graph for each blade immediately below the raw data (scale is in inches). Note the variation in the length of the blades. The bars are direct measures of gap, so the longer the bar, the shorter the blade. The blue graph below the tip clearance plot was constructed to display the change in length of each blade compared to an initial baseline, with the effects of the synchronous vibration removed. Negative values are blades whose gaps have grown shorter, positive values are blades whose gaps have grown longer (scale is also in inches).

The two time-of-arrival (TOA) graphs at the bottom left compare each blade's TOA with a baseline. In the first graph the baseline is a theoretical model of a perfectly symmetric fan, and in the lower graph the baseline is the position of each blade at the start of the test. The units are microseconds.

The three graphs on the right hand side are tracking the change in balance of the part, typically due to a crack that initiates in the disk. The unbalance of the disk is measured in real time as a vector quantity and signal processing allows a display of the difference between the initial balance

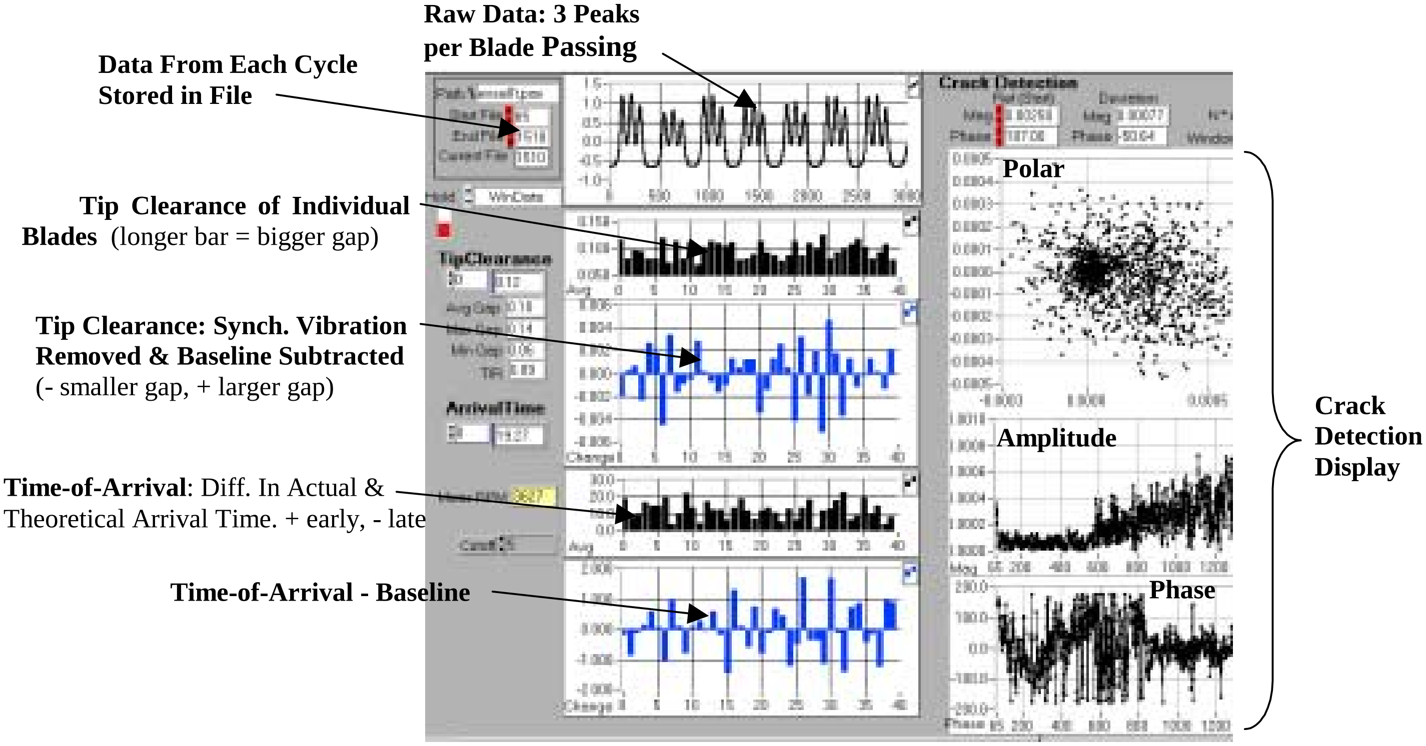

Fig. 7 – Screen From ExSell Acquisition System Showing Raw Signal, Tip Clearance, Blade TOA and Crack Detection From Spin Test of Large Aircraft Fan.

of the rotating system and the current location of the center of mass. When cracks form they distort the strain field in the disk and cause minute changes in the unbalance of the system. These changes are then displayed in the graphs on the right side. The top graph is a polar plot of the change in balance of the system, and the bottom two plots are the amplitude and phase of the difference in unbalance. A rise in amplitude and a constant phase is typically an indication of the growth of a crack, assuming some internal movement of the rotating structure does not cause the unbalance. In this case the system is tracking a crack growing in the disk.

Fig. 8 is a plot of the movement of a single blade during the test. The vertical axis is time-of-arrival in microseconds compared to a baseline, plotted against the distance of the blade tip from the sensor (horizontal axis). The sensor and initial blade positions are shown in the plot, along with the blade rotation direction. The graph clearly shows that during the test this blade continued to grow slightly and always arrived early. Similar plots of every blade's movements during the test are available.

Capacitance vs. Light When Measuring Blade Vibration

Capacitance weighs in very heavily vs. light when measuring parameters associated with a rotating blade. Light's defining characteristic is that it is a traveling wave, as opposed to an electrostatic field (capacitance sensor), or a magneto-static field (eddy current probe). Traveling waves can make measurements across a room, whereas a field effect device needs to be in reasonably close proximity to the measured parameter because of rapid field divergence.

Light cannot be easily used to measure blade tip clearance or radial vibration because of the short travel times and special equipment (e.g. interferometers) required. Capacitance can make a direct measurement of gap between a sensor and rotating blade, and measure radial vibration at the same time. Because of this, light is normally

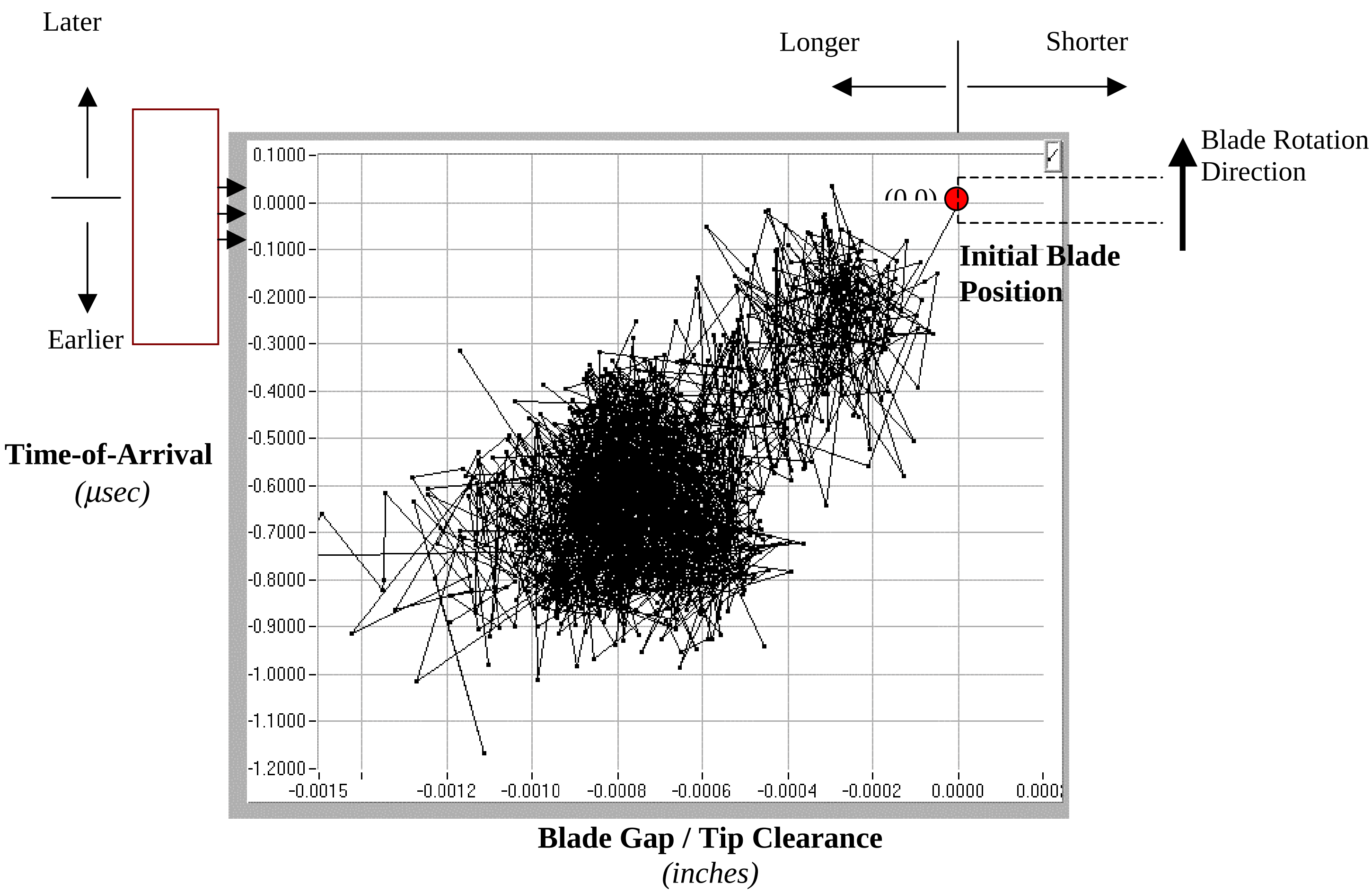

Fig. 8 – Blade Movement Plot During Spin Test of Large Fan Showing Time-of-Arrival on Vertical Axis and Blade Gap on Horizontal Axis

relegated to measuring time-of-arrival of blades in rotating systems.

To take a measurement of a rotating blade with light the measured surface needs to be polished, or at least reflective. Light can also measure non-conductive materials that have sufficient reflective properties. Capacitance measurement requires that the rotating object be grounded and be able to conduct some current, but even a highly resistive material works well with capacitance systems.

The return signal in a light probe depends heavily on the angle of incidence, and the individual LED's or collimated source with a lens required for line probes tend to be bulky, making it very difficult to have multiple sensors in close proximity. Multiple capacitive sensors can be closely spaced to measure high frequency vibrations directly and can be connected together to feed into a single channel of electronics, reducing electronics cost and saving premium space.

Contamination from debris is a substantial problem with light. Opaque debris can block the light completely, or oil/water droplets can cause dispersion or refraction effects. The dielectric material between the blade and a capacitive sensor needs to be altered dramatically for contamination effects to occur. These effects are typically a reduction or change in the peak of the signal (giving a false reading of gap), but have no effect on the time-of-arrival measurement.

The potential bandwidth of both optical and ExSell's capacitive system far exceeds requirements for blade vibration measurement. High temperature, however, can cause light probes a problem. Lenses and light probes can be damaged severely when in close proximity to the rotating device and the heat generated by an engine. Because of this optical systems are usually relegated to low temperature applications on fans or compressors. Capacitive sensors, on the other hand, can be made for very high temperature applications for use on high-pressure compressors or turbines.

Summary

Typical capacitive sensors have been unable to accurately measure individual blade tip clearance and circumferential motion of blades due to the limited lateral spatial resolution of the common spark plug type sensor and a lack of bandwidth in the typical preamp.

Improvements in design for spatial resolution brought by the MasterPlex sensor include making the primary electrode thinner and adding a ground electrode close to the primary electrode. To make full use of these improvements the preamp attached to the sensor must have both a wide bandwidth and a high signal-to-noise ratio.

By designing the sensor electrode to maximize spatial resolution, adding signal processing at the output to remove unwanted effects of cable generated noise, and providing a single, high bandwidth channel for multiple sensor elements, the *HiBand* system is capable of high resolution, real-time, individual blade measurements of blade vibration, radial vibration, blade tip clearance and detection of fatigue cracking.