Health Monitoring and Prognostics of Blades and Disks with Blade Tip Sensors[1]

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Abstract--Blade tip sensors embedded in the engine case have been used for decades to measure blade tip clearance and blade vibration. Many sensing technologies have been used: capacitive, inductive, optical, microwave, infrared, eddy-current, pressure and acoustic.

This paper outlines the technology of blade and disk health monitoring with such sensors. The basic measurement techniques are reviewed, along with damage signatures which might be recognized with such sensors. The compromise between system complexity (in terms of sensor count) and data quality is discussed.

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1. INTRODUCTION

Attempts to monitor the performance and health of jet engines began almost simultaneously with widespread introduction of jet aircraft in the late 1940's. For example, in 1949 a patent was filed for a system to determine blade vibration using magnets attached to the blade tips (see Table 1 below). That patent in turn refers to earlier methods employing optical and electrical devices.

The typical blade passage sensor provides the potential to detect blade clearance and time of arrival (Figure 1).

The signal pattern can be analyzed to infer rotor and blade health. Blade lengthening occurs due to elastic stretch, thermal expansion, spool imbalance, crack growth leading to blade failure, or blade creep. Interpretation of a signal pattern can readily discriminate between factors that affect all blades equally (e.g. thermal and centrifugal expansion), signals that vary synchronously with rotation of the hub (spool imbalance), and signals with other time dependence (crack growth damage, and blade vibration). Differentiation among time-varying phenomena requires further interpretation of the signals.

2. SURVEY OF EXISTING SYSTEMS

Various sensing technologies have been proposed to monitor blade position, relying on capacitance, induction, optics, eddy currents, and/or magnetism. For example, a search of patents shows more than five dozen dealing with turbine blade health and prognostics. Over half of those address clearance measurement, and approximately one-third more are concerned with vibration monitoring using blade time-of-arrival. (Several patents are listed in Table 1.) Many techniques have been used in engine development, but none has yet been widely installed in a fleet.

Several companies offer for sale commercial blade tip sensing systems. The worldwide market for such systems, at less than $5 million per year, does not support a great deal of product development.

Table 2 summarizes the systems currently commercially available.

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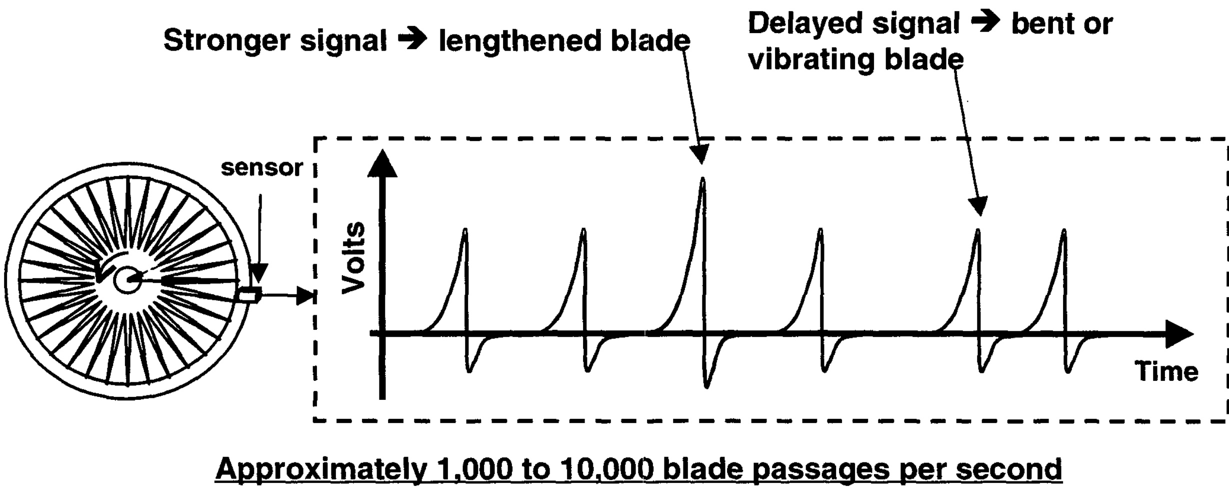

Figure 1. A typical blade tip sensor allows measurement of clearance and time of arrival of each blade.

Table 1: Patents for non-contacting blade tip sensing systems

Patent Number	Filing Date	Title	Description
US 2,575,710	1949	Apparatus for Measuring Rotor Blade Vibration	Tip timing with magnet on blade, pick up coil.
US 2,842,738	1956	Capacitance Probe	Capacitance probe for blade clearance and tip timing
US 3,058,339	1958	Vibration Detector and Measuring Instrument	Inductive/eddy current sensor with bias magnet. Additional 1/rev pulse.
US 3,504,279	1967	Noncontact Interrupted Surface Inspection …	Clever electronics for displaying tip clearance of many blades
US 3,467,358	1968	Vibrator Indicator for Turboengine Rotor Blading	Two-sensor tip timing. Clever analysis electronics.
US 3,932,813	1974	Eddy Current Sensor	Tip timing and tip clearance sensor with coils and bias magnet
US 4,063,167	1976	Blade Tip Clearance Measurement Apparatus	Capacitive probe and pre-amp
US 4,122,708	1976	Capacitive Proximity Sensors	Tip timing and tip clearance with AC capacitive sensor
US 4,153,388	1977	Method for Monitoring the State of Oscillation of….	Tip timing with hub sensor and blade sensor, simple logic
US 4,326,804	1980	Apparatus for Optical Clearance Determination	Optical triangulation sensor for tip clearance
US 4,384,819	1980	Proximity Sensing	Microwave Tip Clearance Sensor
US 4,518,917	1982	Plural Sensor Apparatus for Monitoring Turbine …..	Tip clearance with multiple sensors. Corrected for axial rotor movement.
US 4,593,566	1984	Vibration Monitoring in Rotary Machines	Two DC-biased capacitive tip-timing probes. Clever analysis circuit.
US 4,823,071	1985	Capacitive Measuring System for ….	DC-biased capacitive sensor and pre-amp
US 4,804,905	1986	Capacitive Measuring System for….	DC-biased capacitive sensor and pre-amp

US 4,847,556	1986	Eddy-Current Clearance Transducing System	Magnet-biased sensor, pre-amp, electronics, software
US 4,806,848	1987	Compressor Blade Clearance Measurement…	10 MHz capacitive sensor and pre-amp
US 4,813,273	1988	Turbomachine Tip Clearance Sensor	Capacitive sensor accommodating axial motion of the rotor
US 4,922,757	1988	Apparatus for Precision Detection of Blade….	Magnet-biased sensor with simple tip timing electronics
US 4,967,153	1989	Eddy Current Turbomachinery Blade…	Magnet-biased sensor, pre-amp, electronics, software
US 5,065,105	1989	Capacitive Dimensional Measurement Chain….	AC-biased capacitive sensor and pre-amp
US 5,140,494	1990	Gas Turbine Engine Tip Clearance Sensors	Technique to improve DC-biased capacitive sensor measurements
US 5,101,165	1990	Electrical Capacitance Clearanceometer	AC-biased capacitive sensor and demodulation technique
US 5,119,036	1990	Electrical Capacitance Clearanceometer	Details of AC-biased capacitive sensor
US 5,097,711	1990	Shrouded Turbine Blade Vibration Monitor…	Conductive targets in shrouds. Eddy current blade sensor. 1/rev sensor
US 5,723,980	1995	Clearance Measurement System	DC-biased capacitive sensor and pre-amp

Table 2. Sensor Technologies

Technology	Company	Comments
Capacitive: DC Modulation	Many groups	Very simple sensor and pre-amp.
Capacitive: AC Modulation	Rotadata BICC Capacitec GE/AMETEK	Two main approaches: 20kHz AM modulation or several MHz FM modulations with resonant probe. Much gas turbine experience.
Variable-reluctance/eddy current, DC bias	Westinghouse VATEL	Magnet-bias. Very simple pre-amp.
Eddy Current, AC bias	GDATS Westinghouse	MHz bias signal. Synchronous demodulation in pre-amp.
Infrared	Westinghouse	Observe variation in emissivity of hot surface.
Optical	Pratt & Whitney General Electric Allison IHI NASA AEDC/USAF	Illuminate with structured laser light; observe reflection.
Micro/Millimeter Wave	Westinghouse	Illuminate with continuous wave; observe change in reflection coefficient.

3. Prognostics Signatures

Blade data, both time-of-arrival and tip clearance, can be used to indicate the health of turbine rotors. Figure 2 outlines a representative list of signatures that can be detected.

Example 1.

Foreign object damage causes blade deflection, both vibratory and permanent. Tip time-of-arrival measurements can be used to detect both instantaneous blade displacement and displacement accumulated over time. Figure 3 illustrates the deformation of two adjacent blades resulting from intentional foreign object damage to a shrouded fan. Figure 4 shows blade displacement for the full blade set and for a series of FOD events. Figure 5 shows the individual events that are accumulated in Figure 4.

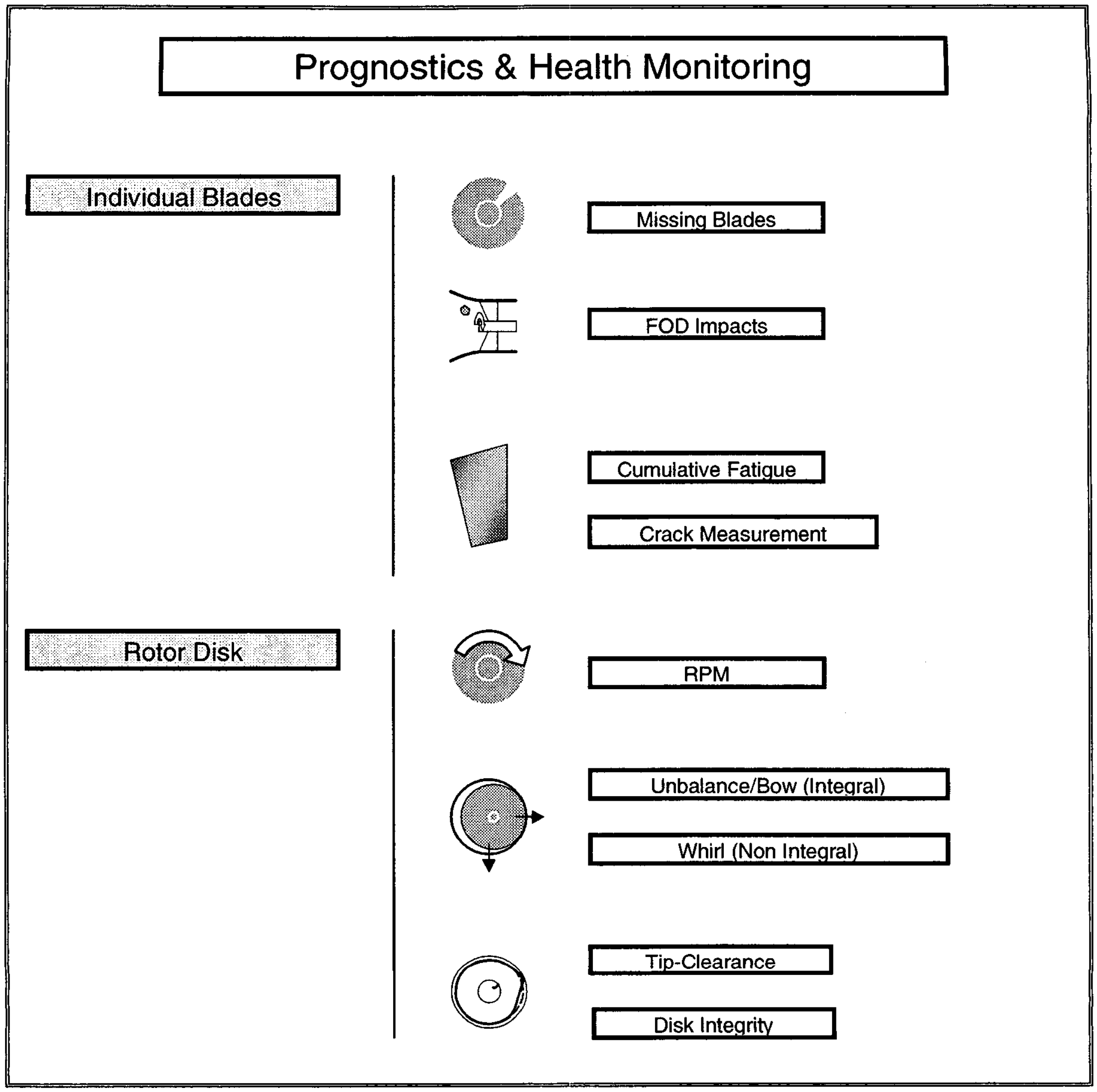

Figure 2. Blade time-of-arrival and tip-clearance measurements can provide a variety of data indicating current and future health of blades and rotor.

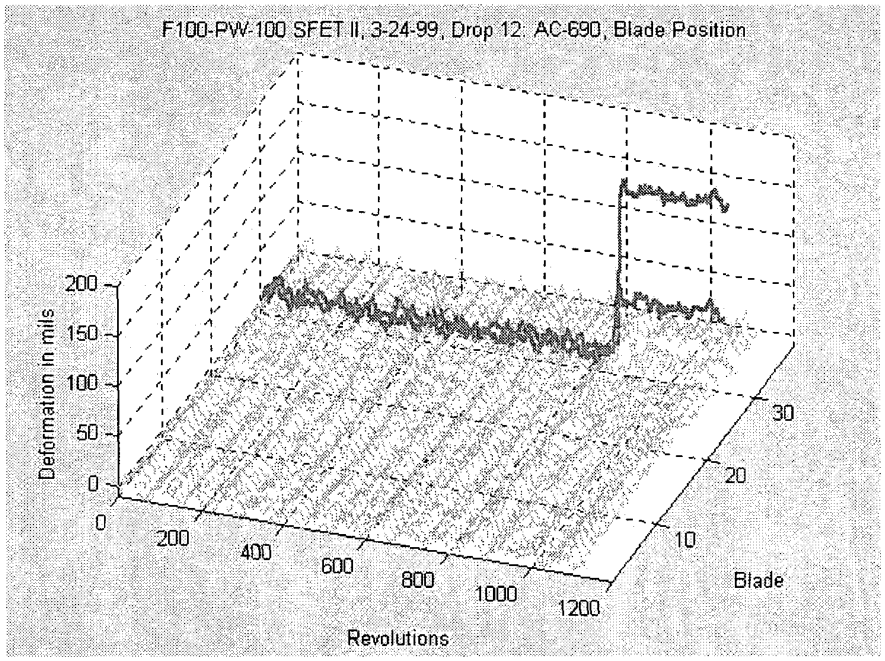

Figure 3. Foreign object damage signatures (in a seeded fault engine test--SFET) for two adjacent blades.

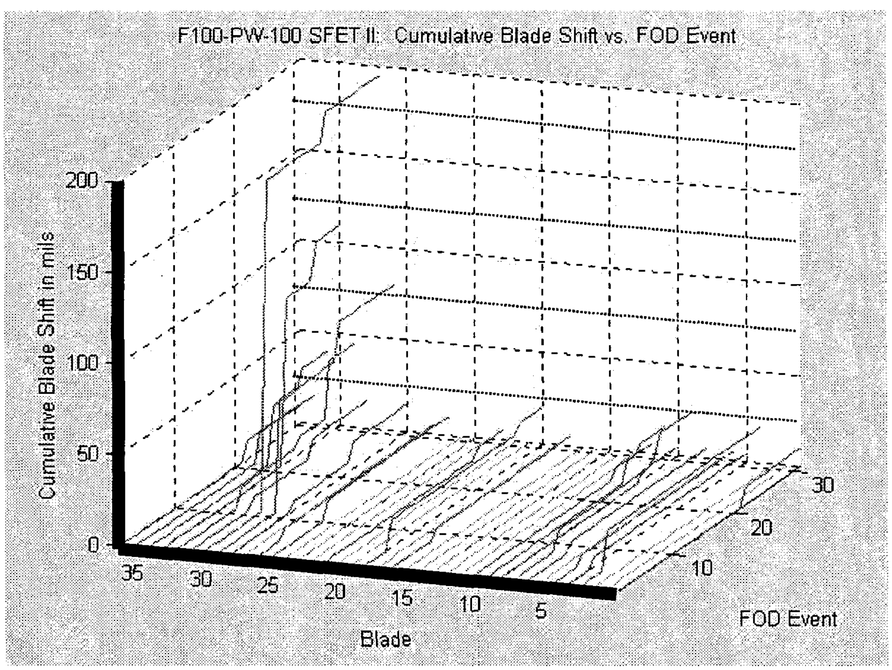

Figure 4. Blade displacements from a series of events of foreign object damage in a seeded fault engine test.

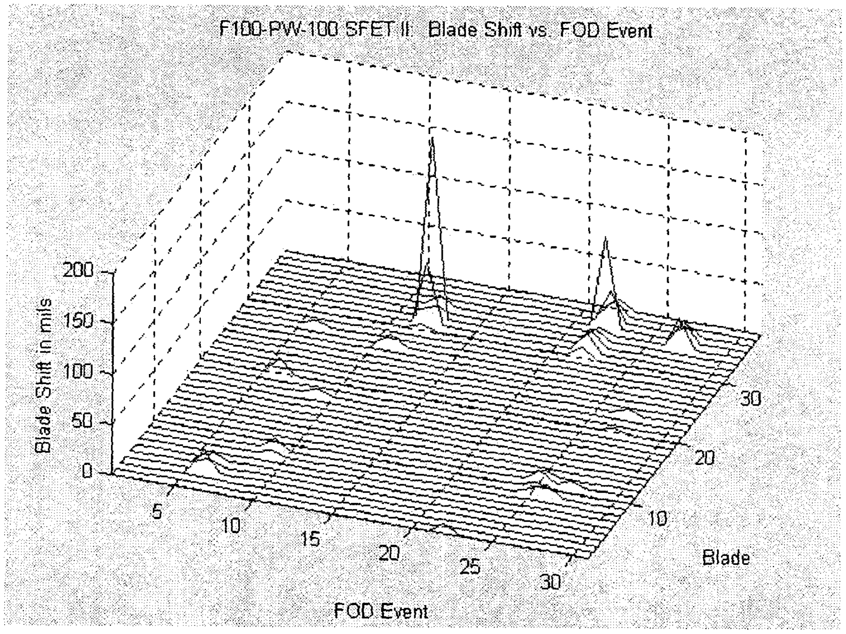

Figure 5. Blade shift caused by a series of events of foreign object damage.

Example 2.

Blade growth may result from fatigue cracks in the rotor hub. Blade tip measurements therefore may provide a means of early detection of such cracks, and thereby predict impending rotor burst. Figure 6 illustrates the concept.

According to this concept, crack growth will be reflected in blade lengthening over time. Unlike uniform blade growth due to thermal expansion or centrifugal force, and unlike the expected sinusoidal pattern from spool imbalance, this phenomenon will most directly affect the blades directly above the crack. RPM, temperature, and sinusoidal variations can be eliminated using clever data reduction, so that the failure signal can differentiated. Figure 7 illustrates how hub cracks may be detected in a spin pit.

Current work on this phenomenon continues. Spin-pit tests are being conducted to test the concept and to refine data measurement and interpretation.

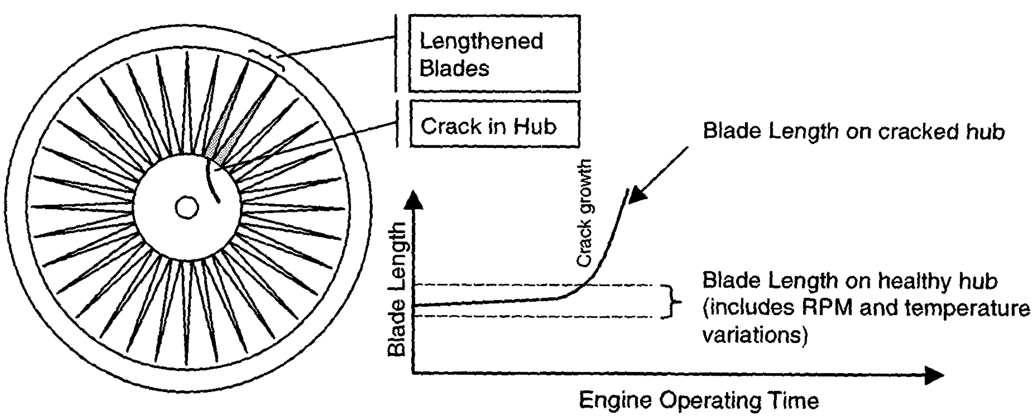

Figure 6. Hub cracks are detected as lengthened blades above the crack.

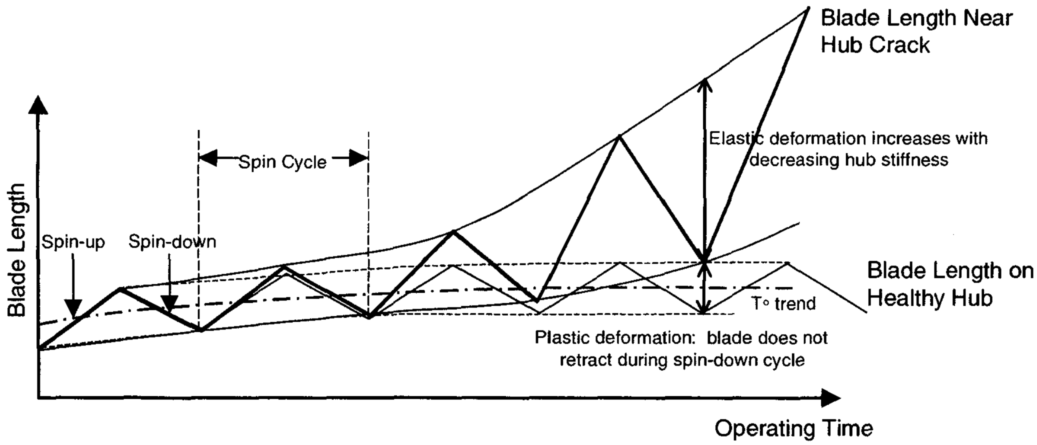

Figure 7. Both elastic and plastic deformation may grow as a result of hub cracks.

4. CONCLUSIONS

Table 3 summarizes the current capability. The challenge is to imbed these capabilities within a compact and autonomous signal analysis system and to convince fleet operators and engine developers that this system adds value to their engines. This is a challenge no one yet has overcome.

Table 3: Summary Health Monitoring and Prognostics Capability

	Long Range Goals	**Current**
Foreign Object Damage (FOD)	Count and classify FOD events, for each blade	***Can be done:*** All FOD events can be detected, by impact transients of each blade. FOD classification is more difficult.
High Cycle Fatigue (HCF)	Monitor HCF damage accumulation.	***Can be done.*** HCF damage accumulation can be estimated by monitoring FOD events and by counting vibratory stress cycles.
	Anticipate HCF failure.	***Maybe.*** Shifts in resonance, amplitude and damping are under investigation as reliable failure precursors.
Turbine Blade Creep	Monitor creep through long-term trend of turbine blade length.	***Can be done.*** Long-term trend in tip clearance can be measured.
Bent blades	Detect bent blades	***Can be done.*** Bent blades are easy to detect, from time of arrival.
Rotor Burst	Anticipate rotor burst	***Maybe.*** Ideas for this exist. Feasibility not known.
Fully Autonomous	A fully autonomous system.	***Development required.*** All current laboratory systems require much human intervention for data interpretation.

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