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Future Issues and Approaches to Health Monitoring and Failure Prevention for Oil-Free Gas Turbines

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April 2004

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Abstract

Recent technology advances in foil air bearings, high temperature solid lubricants and computer based modeling has enabled the development of small Oil-Free gas turbines. These turbomachines are currently commercialized as small (<100 kW) microturbine generators and larger machines are being developed. Based upon these successes and the high potential payoffs offered by Oil-Free systems, NASA, industry and other government entities are anticipating Oil-Free gas turbine propulsion systems to proliferate future markets. Since an Oil-Free engine has no oil system, traditional approaches to health monitoring and diagnostics, such as chip detection, oil analysis, and possibly vibration signature analyses (e.g., ball pass frequency) will be unavailable. As such, new approaches will need to be considered. These could include shaft orbit analyses, foil bearing temperature measurements, embedded wear sensors and start-up/coast down speed analysis. In addition, novel, as yet undeveloped techniques may emerge based upon concurrent developments in MEMS technology.

This paper introduces Oil-Free technology, reviews the current state of the art and potential for future turbomachinery applications and discusses possible approaches to health monitoring, diagnostics and failure prevention.

Introduction

Recent breakthroughs in foil air bearings, high temperature solid lubricants and computer based modeling have enabled the successful commercialization of small Oil-Free turbines for terrestrial applications [1]. As this technology further matures, larger and more complex turbomachinery systems will become “Oil-Free” [2–4]. The benefits of replacing oil-lubricated rotor support systems are many and include reduced weight and initial costs, reduced maintenance costs, higher reliability, higher potential shaft speeds and more [5]. However, removal of the oil system also eliminates major health monitoring tools used to ensure long, safe operational life. For instance, many traditional approaches to turbomachinery health monitoring are based upon oil analyses [6,7]. This method can be done on-line or through the use of periodic oil sampling. An Oil-free system necessarily precludes this approach. Without a recirculating lubricating fluid it can be difficult if not impossible to collect “wear debris” as an indicator of impending failure. New approaches must be considered. On the other hand, current methods for vibration signature analysis, for example detection of ball pass frequency anomalies, could be modified to specifically detect orbit size and shape changes. In place of oil supply and discharge temperature monitoring, one could examine bearing temperature gradients utilizing miniaturized thermocouples placed at strategic locations within the bearing (e.g., near the minimum film thickness).

Prior to further developing new approaches and concepts for health monitoring of future Oil-Free Turbomachinery systems, a basic understanding of this new rotor support technology is needed. Based upon current practice in commercialized Oil-Free Air Cycle Machines and small (micro) turbines, health monitoring and failure prevention is a surmountable technical challenge providing significant opportunities for development.

Background

When considered in its most basic form, a turbomachine's rotor support system functions to precisely locate and hold a shaft with respect to a stationary housing or structure and simultaneously allow free rotation. This rotor support system must operate over a wide range of demanding conditions which often include high speeds, high loads and high temperatures. In modern turbomachines, this is accomplished through the use of oil lubricated rolling element or hydrodynamic bearings along with a complex lubricating system comprised of pumps, filters, coolers, etc.

Over the last century, or more, oil-lubricated rotor support technology has matured to the point that new machines are routinely reliably designed and built and provide predictable and excellent long life performance. In fact, rotor support technologists have done such a good job providing robust, reliable systems that this technology is often taken for granted [8].

Recent studies, however, have found that as other turbomachine systems (e.g., bladed components, combustors, nozzles, etc.) have matured, the ongoing maintenance costs of the rotor support and bearing lubrication system has become among the major system operating expenses [9]. For aircraft gas turbines, fully half of on-wing maintenance costs are attributed to the oil system. Because of this, there has been a renewed interest in replacing traditional oil lubricated bearings with alternate approaches.

A promising technological candidate is compliant surface foil air bearings. A recent workshop held to explore this and other technologies identified the advantages and disadvantages of an Oil-Free rotor support system [8]. One challenge identified in the report is that new approaches will be needed for health monitoring such systems.

Foil Bearings

Foil air bearings are self acting hydrodynamic bearings which use air as their lubricant and working fluid. These fluid film bearings do not require external pressurization but rather are self-pressurized through the viscous pumping effect between the moving (rotating) shaft surface and the ambient fluid (air). The fluid film is formed between the moving shaft surface and a flexible, sheet metal foil which is, in turn, supported by a series of spring foils which provide "compliance." The compliant characteristics accommodate misalignment and distortion and allow for micro-sliding between foil layers providing coulomb damping [10]. Figure 1 schematically shows typical foil journal bearings. Various designs exist which utilize both single or multiple pieces of inner or top foils as well as different features to provide compliant spring support.

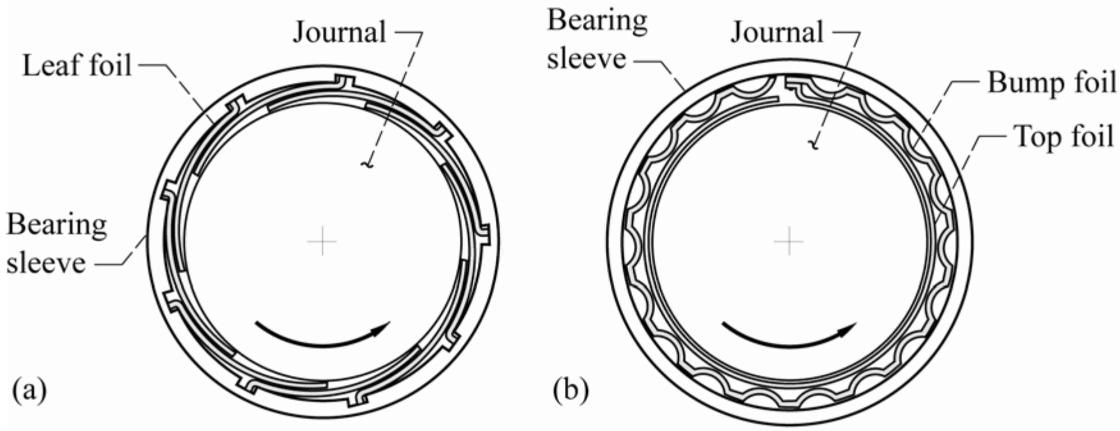

Figure 1.—Schematic example of first generation foil bearings with axially and circumferentially uniform elastic support elements. (a) Leaf-type foil bearing. (b) Bump-type foil bearing.

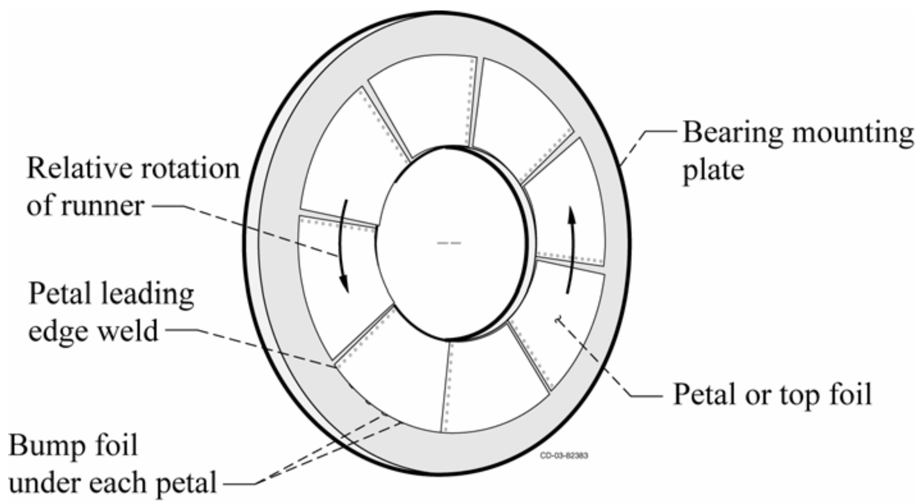

Figure 2.—Thrust foil bearing configuration.

Foil journal bearings support radial loads. For the support of axial loads thrust foil bearings are used. Figure 2 schematically shows a typical thrust foil bearing. In this type of bearing, the foils are generally preformed (shaped) to provide a hydrodynamic wedge shaped profile which encourages the formation of a lubrication fluid film much in the same way a tilting pad bearing functions. Figure 3 shows a cross section sketch of a single thrust bearing section. Both thrust and journal foil bearings operate passively and the operating film thickness is a direct function of the bearing design and geometry, lubricant properties (namely cavity air pressure and temperature) and velocity of the runner surface.

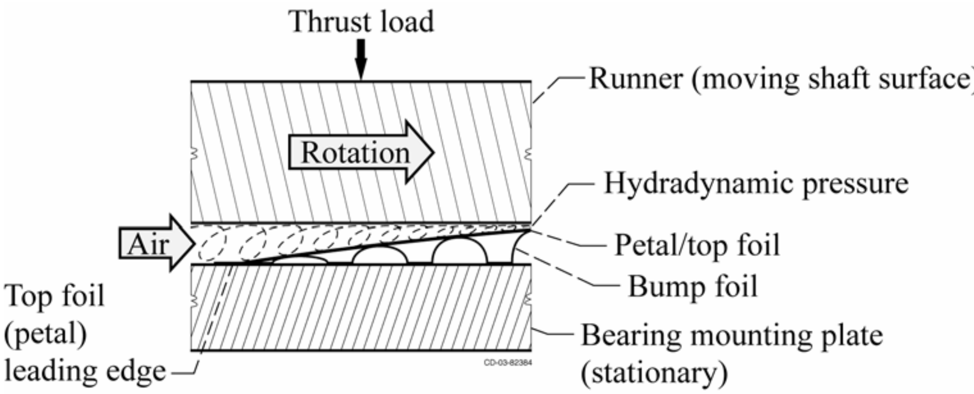

Figure 3.—Thrust foil bearing cross section detail.

Foil bearings ride on a self generated, hydrodynamic air film at high speeds but experience sliding contact during initial start-up and during final coast-down when the surface velocity is insufficient to generate a fluid film. Under these conditions, sliding contact occurs between the delicate metal foils and the moving shaft surfaces. Without the provision of a suitable solid lubricant wear occurs which can limit the bearing life and result in unacceptably high starting torque [11]. While airborne, the fluid film separates the surfaces and no wear occurs. However, recent experiments have shown that at moderate loads (greater than about one-half the rated load capacity) occasional, localized contact can occur [12]. Therefore, a solid lubricant is a critical part of the bearing system and cannot be excluded even if alternate approaches are used to minimize or prevent contact during start-up and shut down, such as hydrostatic shaft lifting.

PS300 is a solid lubricant shaft coating developed for foil air bearings which can operate from below room temperature to over 650 °C [11]. PS300 is a plasma sprayed coating comprised of a nickel based matrix strengthened by chrome oxide particles with silver and barium/calcium fluoride solid lubricant additions. This coating has been used in foil bearings operating from room temperature to over 650 °C and demonstrated bearing lives in excess of 100,000 start-stop cycles [11]. During operation, the solid lubricants in PS300 combine with metals and oxides from the counter-face foil materials and form a smooth, lubricious glaze. This glaze fills in surface pits and irregularities in the PS300 and transfers to the foil surface offering reduced friction and wear. Research tests of foil bearings lubricated with PS300 have shown that both foil wear and shaft coating wear are approximately linear functions of the load and sliding distance (number of cycles) and can be predicted [11].

Further research in the use of PS300 for foil bearings has indicated that the wear resistance and bearing load capacity are diminished during initial installation. After a break-in period of several hundred cycles the advantageous surface glaze develops and performance is restored. To counter this deficit, temporary, sacrificial solid lubricant coatings, such as graphite or molybdenum disulphide, are applied to the as-ground PS300 surface or the foil surface. In practice, by the time these temporary layers have worn through the beneficial glaze from the PS300 has developed [13].

These tribological characteristics of PS300 offer opportunities for diagnostics and health monitoring of Oil-Free engines. By examining the wear debris formed, which is often ejected from the bearing, one can assess the extent of the wear-in process. Further, the predictable and gradual wear process observed in laboratory testing make other techniques of health monitoring possible.

Approach to Health Monitoring

Given that the rotor support system for an Oil-Free engine eliminates the lubricating oil, rolling element bearings and the oil-system and replaces them with foil air bearings and advanced solid lubricants new approaches for health monitoring must be considered.

Dynamic Shaft Motion

One approach is to monitor the dynamic behavior of the rotor during transient and steady state operation in an effort to infer the health of the bearings. Shaft displacement sensors located at various axial and radial positions can give both orbit and displacement (acceleration) information. The theory employed in this approach is that the primary role of the bearings is to prescribe the location of the shaft center. Deviations occur as the result of applied forces, like imbalance or shock and maneuver loads, or due to some anomaly in the bearings. By mapping out an envelope of "normal and expected" orbit and shaft location data, deviations outside the norm can be readily detected [14]. Position sensors located at each bearing location as well as at other pertinent points, such as at large mass concentrations like compressor stages, can indicate much about the health of the bearing/shaft system.

For this type of displacement measurement, technology is well developed in the form of low cost, low temperature sensors such as eddy current probes. Figure 4 shows a typical arrangement for measuring shaft orbit using typical data processing methods (e.g., orbit plot from an x-y oscilloscope). To properly utilize this type of information to its fullest, phase angle data is also required. This is typically acquired through the use of a once per revolution detector which can also serve as a convenient and accurate shaft speed monitor.

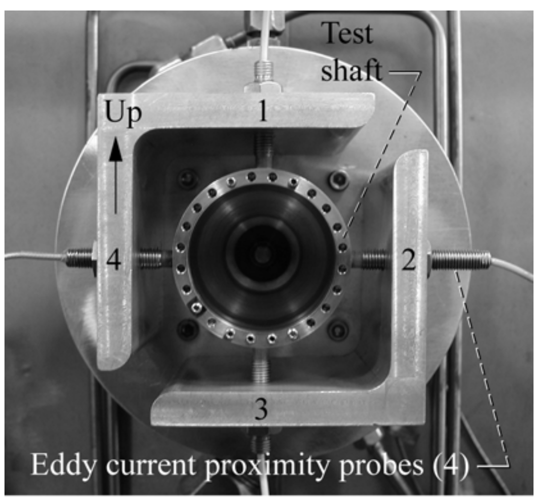

Figure 4.—Eddy current type probe arrangement to measure shaft diameter and orbit changes on high speed foil bearing journal test rig.

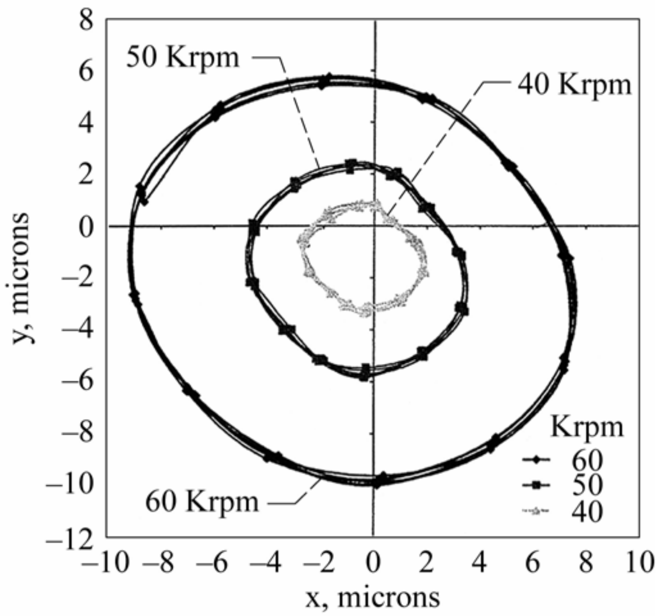

Figure 5.—Foil bearing journal (shaft) orbit showing growth as a function of increasing shaft speed from 40 to 60 000 rpm.

These types of probes can also be used to measure shaft shape and diameter changes if more probes and data analysis are employed. Dykas et al. studied the diametric growth, orbit and possible shape distortions of thin walled hollow shafts used for a foil bearing as part of a shaft failure analysis. In this instance, four probes positioned 90 degrees apart from one another, orthogonal to the shaft were used to differentiate between centrifugal stretch of the shaft and dynamic orbit changes [14]. In his work, assumptions regarding shaft shape were made to simplify the data but these measurements would not be impossible. Figure 5 shows the measured diametral growth of the journal and orbit growth for a range of shaft speeds and axial distance from the shaft bearings on this test rig.

Existing, fully matured eddy current displacement sensor technology is somewhat limited in that temperatures above 400 °C can damage the electrical integrity of the probe [15]. Further, electrical resistance variations in the shaft material (the target surface) can degrade the accuracy. For most applications this is not a limiting factor and new technology is continuously being developed to overcome these drawbacks. Capacitance type probes have been developed for more severe temperature conditions,. These probes are capable of temperatures well in excess of 600 °C utilizing ceramic insulting elements but require generally more complex drive electronics [16]. Also, capacitance probes are subject to electrical charging problems especially when used with an ungrounded shaft as would typically be the case for an air film lubricated engine. Optical displacement probes have been successfully used at high temperatures for measuring shaft and bearing motion in foil bearing systems [17].

These probes use optically transmitting glass and sapphire fibers to transmit a light to a reflecting surface mounted on a rotating shaft (the target). A second fiber receives the reflected light and the attenuation of the signal is then calibrated as the distance of the probe. Figure 6 shows such a set-up. While the operating principle is simple, the practice is not without its complications. For instance, the target surface must be reflective with a reflectivity which doesn't vary unpredictably with temperature or time. Also, the target is typically the rotating shaft which carries with it all the rigors associated with centrifugal stresses. In Howard's work utilizing this approach, sapphire and platinum probes projected a beam onto a polished silver target which had been deposited as a thin layer onto a ceramic coated metal shaft [17]. At high speed and temperature the reflective layer of silver could soften and fly off the surface if made too thick. Numerous other target surfaces were tried included many polished ceramic layers but these were found to be too transparent or translucent to reflect an adequate signal. Structural metal surfaces like superalloys were reflective but became dull and oxidized in high temperature air. The novel use of platinum tipped sapphire probes and complex multi-layered ceramic/silver target surfaces worked well enough for research purposes but were not robust and reliable enough for engine use. Consider, for example, the effect of wear debris or dust on an optical sensor.

These and other issues appear to affect every approach to displacement measurement which will need to be overcome.

Regardless of the technique used to acquire the shaft displacement data, once taken it can yield important health monitoring clues. For instance, rotor orbit measured while an engine passes through critical speeds during acceleration or deceleration can indicate the integrity of the bearing. If excessive foil or shaft wear has occurred, observed orbits are likely to be larger at critical speeds than at the time of bearing installation. In contrast, orbits which are smaller than their initial values could indicate abnormal shaft growth. This could be due to local misalignment, coating delamination, wear debris accumulation behind the foils or increased local shaft temperature. Regardless of the reason for change, displacement data can yield important information for health monitoring to help offset that information which is lost through the elimination of the oil system.

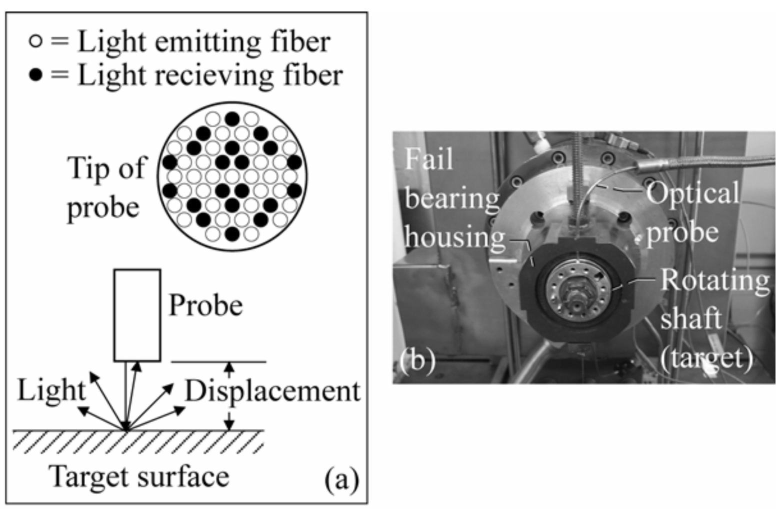

Figure (6a).—Schematic of optical probe operation.
(b) Fiber optic probe mounted on foil journal bearing.
Reflective target is on shaft adjacent to bearing.

Temperature Measurements

Another approach to bearing health monitoring is to measure fluid temperatures in the immediate vicinity of the bearing foils. Since some heat is generated in the bearing via shearing of the lubricating gas film, fluid temperature is a good indicator of the friction level. In fact, an abrupt rise in temperature at one location, or an increase in the temperature gradient across a bearing can indicate impending failure.

In most foil bearing applications, a small amount of air is bled through the bearing to stabilize the temperature. This bleed air also serves to purge the bearing of wear debris and to prevent the possibility of particulate contaminants, for instance from the combustion gas stream, from entering the bearing. Proximity thermocouples can be positioned to measure this air temperature or they can be physically attached to the foil backsides at specific locations. Since the foils rest in a stationary housing, routing the thermocouples out of the engine usually poses no significant problem.

In his work, Radil et al. used thermocouples to monitor bearing temperatures under varying loading and speed conditions with and without bleed air [18]. In his test set-up, he was also able to measure bearing power loss (torque) as a corroborating measurement to the temperature since bearing power consumption shows up as fluid film heating. Radil’s results indicate that the onset of bearing failure, due to intentional overload or overheating, is preceded by sharp, local rises in bearing temperatures. Thus judiciously located bearing thermocouples can serve to augment displacement measurements for rotor support system health monitoring. In the event that the data indicates impending bearing seizure, the engine could be shutdown without serious damage occurring.

Related System Data

In addition to these fairly conventional approaches to monitoring, several as yet undeveloped techniques may be applicable to Oil-Free Turbomachinery systems. For instance, wear sensors could be embedded into the foil surface to electronically monitor foil thickness much in the same way automotive brake pad wear sensors work. When the wear depth reaches the sensor a circuit is disrupted triggering a response. The typical foil wear measured in lab testing over 10,000 cycles is about 3 microns so these sensors would have to be small and located in the foil surface region at a circumferential location expected to wear, for instance at the bottom of the bearing where the shaft lays at rest.

This type of sensor would be more difficult to install on the rotating shaft unless a slip ring for carrying out the signal were available. In this case, one could embed trace impurities into the coating at a selected wear depth and inspect the bearing wear debris via an access port to detect this additive. The additive would need to be non-contaminating to prevent environmental degradation of the solid lubricant. A good choice might be gold. Like the silver used in PS300, gold is thermochemically stable and a good solid lubricant. The presence of gold in the wear debris could signal that shaft wear had reached a certain depth. This approach would be simple but lack on-line capability.

If a slip ring were available, the electrical continuity between the shaft and the engine structure could be used as an indication of the extent of the lubricating fluid film. In preliminary tests in the author’s laboratory, it has been observed that a fully airborne, lightly loaded foil bearing is completely electrically isolated from the non-rotating bearing. At loads exceeding about one-half the rated load capacity, sporadic electrical conductivity is measured. At high loads the frequency of these contacts increases and continuous conductivity is observed as the ultimate load capacity is reached and the fluid film thickness thins to the point that it is approximately equal to the average surface roughness of the foil and shaft. Under these heavily loaded conditions, both fluid film and solid lubrication play a role in load support. For an engine operating under normal steady-state conditions one could expect full fluid film lubrication everywhere thus no electrical conductivity between the engine structure and the shaft. This measurement could thus be used for health monitoring. Also, during engine coast-down, the electrical conductivity could be used to ascertain the speed at which the fluid film is lost which can be an indicator of bearing health. Bearing lift-off and touch down speed is often a good indicator of bearing performance and health since it also represents the bearing load capacity at that speed (under the static load of the shaft).

Lastly, conventional accelerometer data, properly processed, can offer valuable information regarding the rotor support system. With ball bearing supported rotors, acceleration data can indicate damage bearing balls and raceways. For foil bearing supported rotors, imbalance level can be detected. Changes to the vibration signature not otherwise interpreted as due to known, benign causes would be reason for investigation.

Concluding Remarks

Oil-Free Turbomachinery has been commercialized in various forms for over three decades. For most of these systems, namely small air cycle machines and turboexpanders, failures are a nuisance to be avoided but typically not life threatening. The advent of Oil-Free gas turbines for power generation and eventually aircraft propulsion, however, dramatically heightens the need for appropriate failure prevention and health monitoring of these systems. Because Oil-Free Turbomachinery systems lack traditional rolling element bearings and their lubricating systems, other approaches for health monitoring are required. Table I shows a comparative summary of approaches to health monitoring for conventional and Oil-Free turbine rotor support systems.

Turbine engines supported by foil air bearings offer both opportunities and challenges for health monitoring and failure prevention. Rather than concentrating on vibration (acceleration) signatures, carefully located displacement probes will be needed. New and improved technology for shaft location measurement in hostile environments will be needed. A new body of interpretive data must be developed to understand this displacement data, how it changes over time or trending,

Table I.—Comparative approaches to health monitoring of conventional and oil-free rotor support system.

Measurement	Conventional approach	Oil-free approach
Wear-online	Oil chip detectors	In-situ wear depth sensor
Wear-offline	Oil sample metal analysis	Tracer wear debris inspection
Bearing temperature	Thermocouples/Oil	Proximity/Contact thermocouples
Bearing integrity	Accelerometers	Shaft displacement/Orbit sensors
Oil system health	Oil pressure/Temperature sensors	N/A
Foil bearing health	N/A	Shaft orbit/Coastdown monitoring Contact resistance sensor

and how it relates to bearing health, imbalance levels and surface wear. Rather than measuring oil temperatures and flow rates, Oil-Free systems will need to employ proximity thermocouples and purge air temperatures to determine the proper functioning of the rotor support system. New, innovative wear sensors may be needed in certain locations although evidence suggests that state of the art solid lubrication can provide “lifetime” lubrication. When these systems penetrate the market and mature, subtle performance clues, such as start up and coast down behavior, may be combined with computer based predictive analyses to assess system health.

Oil-Free turbines for power generation have moved from 30 kW systems fielded in 1999 to 200 kW systems being fielded today just four years later. Laboratory demonstrations of small, unmanned propulsion gas turbines are occurring as well. Future turbine systems will undoubtedly require larger and more complex Oil-Free rotor support technology. Health monitoring and failure prevention technologies will be developed to address these new systems as we move into an Oil-Free turbomachinery future.

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13. ABSTRACT ***(Maximum 200 words)***

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