EMERGING OIL-FREE TURBOMACHINERY TECHNOLOGY FOR MILITARY PROPULSION AND POWER APPLICATIONS

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ABSTRACT

Oil-Free turbomachinery is defined as high-speed rotating equipment, such as turbine engines, that operate without oil-lubricated rotor supports, i.e. bearings, dampers and air/oil seals. Recent technology breakthroughs in foil air bearings, high temperature solid lubricant coatings, and rotordynamic and mechanical system modeling and analysis enable the application Oil-Free technology to larger, hotter, and more challenging military turbomachinery systems. Relative to state-of-the-art oil lubricated systems, Oil-Free turbomachinery technology offers impressive system level benefits. For gas turbine engine propulsion systems found in Army helicopters and tanks, and military fixed wing aircraft, projected Oil-Free benefits include significant reductions in engine weight, engine maintenance, and life cycle cost while improving fuel efficiency. Emerging opportunities for Oil-Free turbomachinery in military power and propulsion include a broad range of systems from turbochargers in diesel engines, to turbogenerators, and turbine engines for missiles, tanks, and air vehicles. The process of transitioning the breakthroughs in Oil-Free foil air bearing technology from the laboratory to turbomachinery systems is key to realizing the benefits. This paper introduces Oil-Free turbomachinery technology, reviews current research activities, and discusses the transformational impact that the technology can have through incorporation in military propulsion and power systems.

1. INTRODUCTION

Turbochargers found on ground vehicle and genset diesel engines and gas turbine engines that power helicopters and tanks are common examples of turbomachinery devices in extensive use on military systems. All of these turbomachinery systems incorporate oil-lubricated bearings as critical elements providing load support for the high-speed rotating shafts. Oil-lubricated bearings have been used in these types of applications for decades and have evolved and matured to the current state-of-the-art as integral elements of turbomachinery rotor system design.

In engineering design of turbomachinery systems, performance improvements as well as design tradeoff compromises are linked to attributes and limitations of oil-lubricated bearings. As an example, on high-speed shafts, bearing diameter is held to a minimum to keep centrifugal loading of the bearing rolling elements manageable. This bearing sizing in turn leads to a rotordynamic design compromise of long slender supercritical shafting. Safely passing through critical speeds requires damping and adequate clearance between housings and rotating compressor and turbine blades leading to compromises in system efficiency.

Recent advances in Oil-Free foil air bearing technology enable an opportunity to overcome limitations of oil-lubricated bearings and yield improvements in weight, efficiency, performance and life cycle cost for systems. This paper introduces Oil-Free turbomachinery and foil air bearing technology, reviews recent developments and research activities, and discusses the transformational impact that the technology can have through incorporation in military propulsion and power systems.

2. BACKGROUND

Oil-Free turbomachinery is defined as high-speed rotating equipment, such as turbine engines, that operate without oil-lubricated rotor supports, i.e. bearings, dampers and air/oil seals. This paper addresses Oil-Free turbomachines where rotor support is provided by foil air bearings. Foil bearings provide an attractive alternative to common practice oil-lubricated bearing systems particularly in high-speed rotating equipment.

Foil air bearings are hydrodynamic bearings that use air as the lubricant or working fluid [Agrawal, 1990; Heshmat, 1981; Marley, 1969]. Through the combined effect of relative surface velocity and fluid viscosity, hydrodynamic bearings generate a self-pressurized fluid film that separates the bearing and shaft surfaces. Like all hydrodynamic bearings, foil air bearings are self-acting; they do not require an external pressurized air supply. However since relatively low viscosity air is the working fluid, the thickness of the hydrodynamic fluid film is often less than the magnitude of centrifugal, structural and thermal deformation in the bearing or shaft. Unlike higher viscosity oil-lubricated hydrodynamic bearings with relatively generous fluid film thickness, foil air bearings must employ a compliant "foil" surface to maintain a fluid film thickness or clearance over a broad operating range. Foil bearings, as shown in Figure 1 and 2, use a thin metal foil that is supported by a spring structure formed by a corrugated "bump" foil, overlapping foil leaves, cantilevered tangs or other compliant support concepts. The foil structure responds to fluid film pressures generated by loads and deformations during operation. Micro sliding between the bearing top foil and the compliant support foils provides Coulomb friction damping to the bearing and rotor system. Increasing shaft speed or surface velocity tends to increase fluid film thickness, and the load capacity of foil bearings increases linearly with speed [DellaCorte, 1998]. In other words, the faster the shaft rotates, the greater the load capacity.

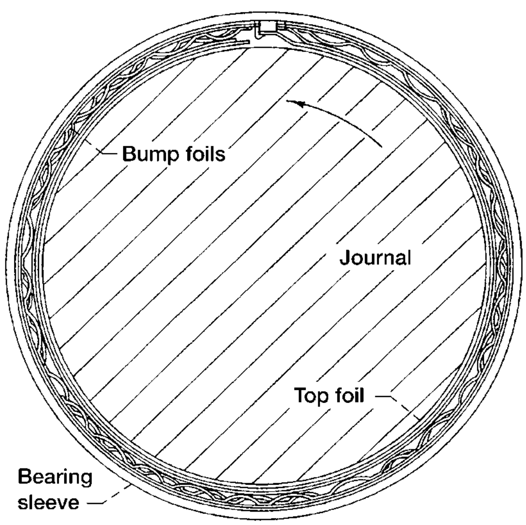


Fig. 1 Foil air bearing

A challenge in foil air bearing development is effective design of the compliant foil support structure to enhance desirable features such as bearing load capacity, stiffness and damping. Early foil air bearing designs were regarded as providing relatively low load capacity, stiffness and damping characteristics.

Foil air bearings can operate at very high speeds, exceeding the capabilities of oil-lubricated rolling element bearings. Bearings such as ball or roller bearings have rolling elements that are centrifugally loaded against the bearing outer race as the shaft rotates. As shaft speed or bearing diameter are increased the rolling element centrifugal loading increases and eventually can diminish the useful load support capability of a bearing. This leads to the well-accepted concept of bearing DN speed limitations [Avallone and Baumeister, 1986]. Foil air bearings do not have rolling elements and are only speed limited by the burst strength of the shafting. Therefore foil air bearings have very high rotational speed capability.

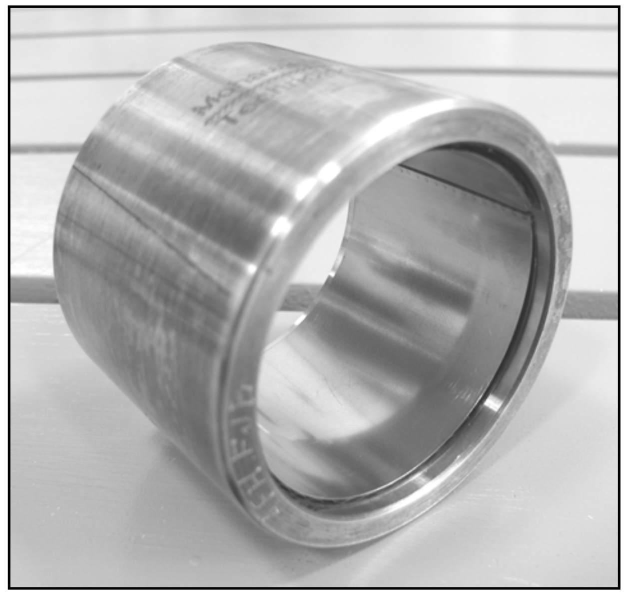


Fig. 2 Foil air bearing

In addition to load, speed and rotordynamic performance characteristics, foil bearings must also provide long-term durability. In operation, the hydrodynamic air film prevents surface-to-surface contact between the shaft and bearing foils; however, during startup and shutdown the foil and shaft surfaces are in sliding contact. In order to provide long service life, a solid lubricant tribological coating system is needed. Polymer based foil coatings and chrome-plated shafts have evolved as common industry practice in foil air bearing applications providing excellent wear and service life performance for relatively low temperature (<500°F) applications.

As a technology, foil air bearings have been used since the 1960's [Gray et al., 1981]. They are commercialized and commonly found in air cycle machines of environmental control systems providing clean Oil-Free pressurized cabin air for passenger comfort in civil and military aircraft [Agrawal, 1990; Emerson, 1978]. In addition to the significant Oil-Free air quality aspects, foil bearings achieved success in air cycle machines because of their performance, durability and reliability characteristics that outperform other bearing technologies in these turbomachinery devices. Relative to gas turbine engines used in propulsion and power applications, air cycle machines are typically smaller, more lightly loaded, and operate at low temperatures. Beyond air cycle machine applications, foil-bearing technology has had market niche success in turbocompressor, turboexpander, and turbopump applications where the process fluid is used as the bearing lubricant [Barnett and Silver, 1970; Gu, 1988]. Through the 1980's and mid-1990's attempts to insert foil bearings into gas turbine systems were hampered by technology barriers associated with foil bearing load capacity limitations, relatively low operating temperature range, and limitations in foil bearing and rotor system modeling and design tools [DellaCorte and Pinkus, 2000].

Technology breakthroughs in foil air bearings, high temperature solid lubricant coatings, and rotordynamic and mechanical system modeling and analysis enable the application Oil-Free technology to larger, hotter, and more challenging military turbomachinery systems.

3. EMERGING TECHNOLOGY

Foil air bearings have enjoyed significant load capacity improvements [DellaCorte and Valco, 2000]. This reference chronologically traces and categorizes experimental foil bearing load capacity data and links load capacity to foil air bearing design features. A convenient "rule of thumb" and load capacity coefficient are used to assess foil air bearing load capacity performance. In general, recent advanced bearings with optimized spring structures outperform early bearing designs with simple elastic supports. Generation I foil bearings typical of 1960's and 1970's possess load capacity coefficients on the order of 0.1 to 0.3. Generation II bearing designs of the 1970's and 1980's doubled load capacity performance with load capacity coefficients of 0.3 to 0.6. More advanced Generation III bearings developed in the 1990's doubled load capacity relative to Generation II bearings and exhibit load capacity coefficients of 0.8 to 1.0. Generation III levels of load support capability are a technology breakthrough that enable Oil-Free foil air bearings to provide real engineering rotor support to a broad range of turbomachinery systems including gas turbine engines. Figure 3 shows the relative load capacity of bearing design generations for one bearing size.

Foil bearing load capacity improvement is essential for gas turbine applications but the thermal environment is also a significant challenge. Oil lubricates current engine bearings and also functions as a coolant to maintain bearing location temperatures below oil damaging conditions beyond 350°F. Without oil cooling at gas turbine engine bearing locations, temperatures could easily exceed 1000°F. Foil bearing polymer based coatings used for bearing startup and shutdown wear protection cannot tolerate high temperatures. To overcome this technology barrier a NASA developed high temperature solid lubricant coating system, PS304, is used [DellaCorte et al., 1999; DellaCorte and Edmonds, 1999]. PS304 is a mixture of NiCr, Cr_2O_3, BaF_2/CaF_2 and Ag particles, and is applied by the plasma spray process to shaft surfaces. Figure 4 shows the PS304 coating application process. During startup and shutdown the PS304 slides against nickel super alloy foil bearing material. The PS304 tribological coating system is a technology breakthrough that has demonstrated long-life durability for foil air bearings up to 1200°F for 100,000 startup and shutdown cycles [DellaCorte et al., 2000]. For gas turbine engine applications this level of durability represents a maintenance free bearing system for the life of the engine.

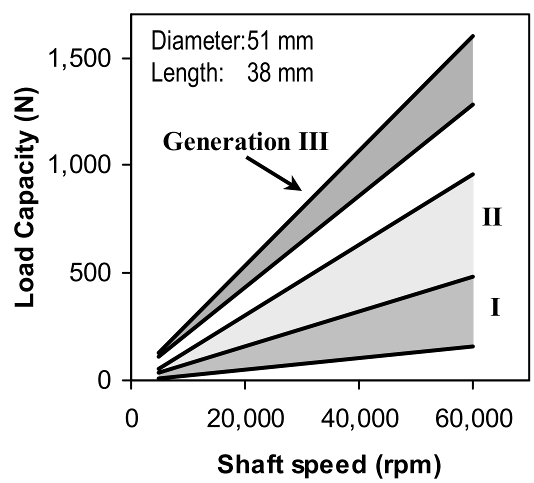
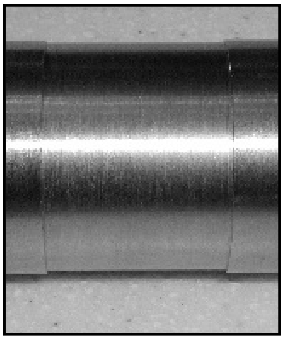


Fig. 3 Foil bearing load capacity by design generation

At the mechanical design level, foil air bearings involve a complex combination of structural, fluid and thermal interactions that offer a challenging analytical task for researchers seeking to improve, optimize and extend bearing performance characteristics [Arakere, and Nelson, 1992; Carpino, 1991; Carpino et al., 1994; Howard, 2000; Ku and Heshmat, 1992; Wu and Wu, 1990]. Advances in finite element analysis, computational fluid dynamics, and rotordynamic modeling provide analytical tools to explore the intricacies of foil air bearings. Understanding and accurately predicting bearing rotordynamic characteristics such as stiffness and damping are critical in the development of stable high speed rotating systems. For foil bearings these characteristics are known to be nonlinear and cross-coupled. Advanced computational tools and foil bearing design flexibility provide bearing designers the ability to tradeoff load capacity for design tailorable enhancements in stiffness and damping. These tools provide a technology breakthrough enabling design integration of bearing technology for an optimized turbomachinery system.



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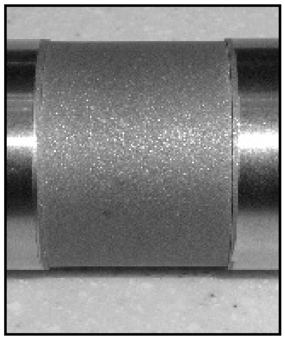

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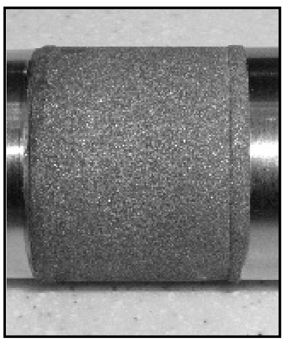

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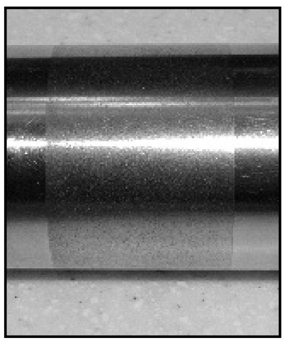

d.

Fig. 4 PS304 solid lubricant coating plasma spray process: a) undercut, b) sandblast surface, c) as deposited PS304, d) PS304 ground finish

4. OIL-FREE BENEFITS

Combination of the foil bearing breakthroughs with the inherent benefits of Oil-Free technology provide an opportunity to achieve dramatic system level benefits over a broad class of military applications that use turbomachinery devices. Relative to state-of-the-art oil lubricated systems; Oil-Free turbomachinery technology offers weight reductions, fuel efficiency improvements, maintenance and logistic support reductions, and decreased life cycle costs.

For gas turbine engine propulsion systems found in Army helicopters and tanks, the oil-lubrication system required for the rolling element bearings consists of pumps, coolers, filters, tubing and fittings, valves, sensors, oil and other ancillary equipment as listed in Figure 5. The net weight of the complete oil-lubrication system is typically about fifteen percent of the total engine weight. Through Oil-Free technology, these oil system items are eliminated and the significant weight saved can be traded for a lighter vehicle, additional fuel to extend range, or greater payload capacity for equipment or munitions.

Foil air bearing technology has high speed and high temperature capability relative to oil-lubricated bearing technology. Taking advantage of these attributes can increase power density of gas turbine engines and produce more power out of a lighter and smaller package. The rotordynamic features of foil bearings enable high-speed rotors with stiffer shafts allowing designers to operate subcritical rotors with tighter clearances and lower losses thereby improving component and cycle thermodynamic efficiencies and reducing fuel consumption.

Oil Pump	Oil Sumps
Oil Debris Sensor	Oil Cooler
Pump/Filter Manifold Assembly	Oil Suction Line
Oil Filter	Oil Scavenge Lines
Filter Bypass Flow Screen	Protective Scavenge Pump Screens
Filter Bypass Valve	Scavenge Pumps
Oil Filter Bypass Indicator	Oil Tank
Oil Temp./Pressure Sensor	Oil Tank Chip Collector
Pressure/Temp. Bypass Valve	Air/Oil Separator
Overpressure Relief Valve	Low Oil Level Sensor
Regulator Valve	Oil Tank Vent
De-Oil Valve	Oil Tank Vent Valve
Check Valve	Oil Tank Filler Port/Cap/Screens
Oil Transfer Tubes/Lines	Oil Level Sight Gage
Oil Fittings	Oil Drain Valves
Carbon Face Seals	Captive Fasteners on Lube LRU's
Ball Bearings	Mounting Brackets & Clamps
Roller Bearings	Emergency Oil System
Squeeze Film Dampers	Oil
Bearing Lubrication Jets	Cockpit Indicators & Software
Air/Oil Buffer Seals	Sensor to Cockpit Wiring Harnesses

Fig. 5 Eliminated engine lubrication system components

Elimination of the oil system from a gas turbine engine has a significant impact on engine maintenance. Well-maintained turbine engine oil systems are essential for readiness and flight safety. Maintaining clean and leak-free engine oil systems is a critical and time-consuming process. Furthermore maintaining other engine components often requires removal and proper reinstallation of oil system elements. Through elimination of the need for the oil system, Oil-Free foil air bearings do away with oil system related maintenance issues and offer a maintenance free bearing system for the life of the engine. In addition to maintenance time and cost savings, the engine maintenance logistics burden is reduced since the numerous oil system parts, spares, and oil can be dropped from the logistics system.

All of these benefits not only impact turbine engines but also enhance the performance, versatility, and availability of military vehicle systems. Oil-Free technology also provides a decrease in life cycle cost for the equipment. Acquisition costs decrease due to design simplification, oil-lubrication system elimination, and parts count reduction. Operational cost savings occur through elimination of oil system maintenance actions, reduced maintenance time, fewer replacement and spare parts, and fuel efficiency gains. However, in order to realize these significant benefits and the transformational effect on military power and propulsion systems, Oil-Free technology must be properly transitioned from research laboratories to fielded systems.

5. TECHNOLOGY TRANSISTION PROCESS

The process for transitioning the breakthroughs in Oil-Free foil air bearing technology from the laboratory to turbomachinery systems is a critical aspect of the technology development process. Foil bearing characteristics differ considerably from ball bearings and therefore a simple bearing substitution into an existing rotor system is rarely viable. Figure 6 shows the diverging load capacity versus speed trends for ball and foil bearings.

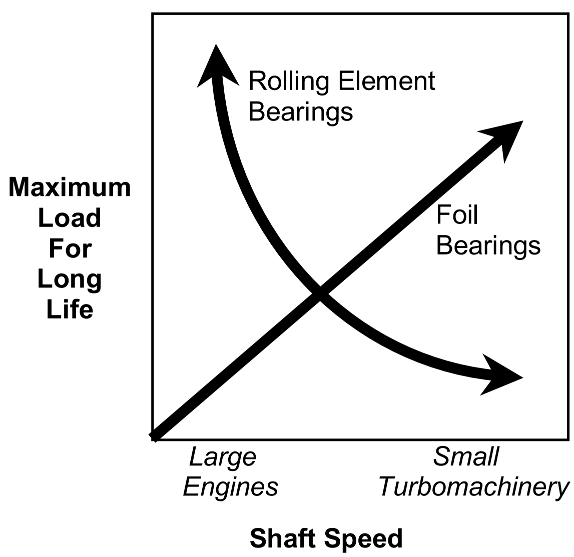

Fig. 6 Bearing load capacity trends

To realize the system level benefits offered by Oil-Free foil air bearing technology requires integration of the bearing features and characteristics with those of the turbomachinery system. The approach for transitioning foil bearing technology into Oil-Free applications consists of four steps: 1) concept feasibility assessment; 2) bearing component development and testing; 3) simulated rotor system testing; and 4) turbomachinery system demonstration. This technology transition process is intended to verify technology readiness and manage technical risk in a logical progressive order from concept to full-scale demonstration.

The first step involves conceptual design of the turbomachinery system and development of layouts of the rotating group including identification of major components, bearing locations, and approximate specifications. The feasibility of the concept is analytically assessed through comparison of the required bearing performance with the available foil bearing technology level. Also, there are opportunities for conceptual design iteration to adjust the design layout for system level improvements. If the concept cannot be shown to be feasible with foil bearings then this step is the end of the process.

Once the feasibility of the system is established a foil bearing development and test verification step is started. Foil bearings are sized and designed to meet the performance requirements established by the conceptual design. The bearings are tested and evaluated as individual bearing components in laboratory test rigs to verify adequate load support at the required speed and temperature conditions. If the bearings cannot meet the performance requirements then either the turbomachinery system must be reconfigured or more development is needed.

Following verification of individual bearing performance, the next step is a simulated rotor system test. A simulated rotor is fabricated to incorporate representative masses and inertias of the actual rotating group aerodynamic components (compressors and turbines). The simulated rotor system is tested using the prototype foil air bearings to verify rotordynamic stability and performance. This step is also an opportunity to explore operational limits such as bearing misalignment or rotor imbalances in a controlled test environment.

Finally, after completing concept feasibility, bearing testing, and rotor simulator testing, the Oil-Free turbomachinery system is ready for a system level technology demonstration of the actual hardware assembly. Using this process Oil-Free technology was successfully demonstrated in an Oil-Free turbocharger, shown in Figure 7, for a heavy-duty truck diesel engine and the process is underway on a small gas turbine engine sized for general aviation and business jet aircraft. [Howard, 1999; Heshmat et al., 2000]

6. MILTARY PROPULSION AND POWER APPLICATIONS

With successful technology demonstrations, opportunities emerge for application of Oil-Free turbomachinery in military propulsion and power systems as well as dual use commercial systems. Oil-Free turbochargers are alternatives to the oil-lubricated turbochargers on diesel engines that power trucks, armored vehicles, boats, and ships. Oil-Free turbochargers eliminate turbocharger oil coking problems while providing benefits in efficiency, particulate emissions, and mounting and installation freedom.

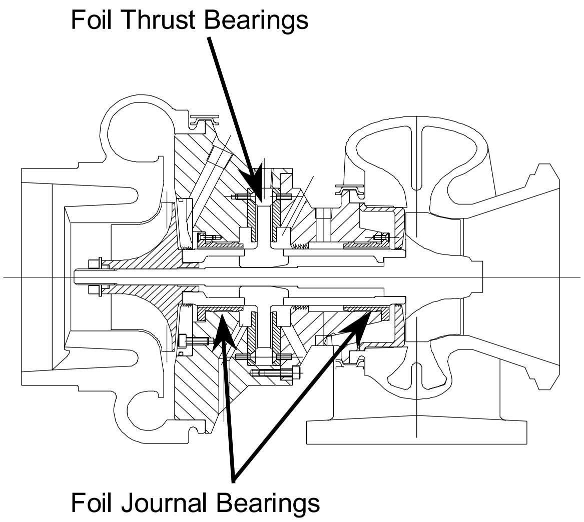

Fig. 7 Oil-Free turbocharger for diesel engine

Fuel cells are being developed for military electrical power systems. However, fuel cells require clean compressors because trace oil will poison a fuel cell stack. Oil-Free foil bearing turbocompressors offer a solution. Also, Oil-Free foil air bearing turbogenerators for electrical power generation are commercialized in the 30-60 kW range. Larger and more efficient systems are being developed for stationary power generation.

Lightweight, high speed, high temperature, and simplified design characteristics make foil air bearings attractive for single use turbojet engines in missiles. Oil-Free features simplify requirements for long-term stable storage. In this same engine size class are opportunities for lightweight Oil-Free turbine engines for reusable target drones and unmanned vehicles.

On tanks, helicopters and fixed wing aircraft, Oil-Free auxiliary power units are envisioned for onboard generation of electrical, hydraulic and compressed air needs of the vehicle. For main propulsion, Oil-Free turboshaft and turbofan engines will be lighter, more efficient, and require less maintenance providing lower operating costs with improved performance.

7. SUMMARY

Technology breakthroughs in Oil-Free foil air bearing load capacity, high temperature solid lubricant coatings, and analysis and modeling tools offer an opportunity to apply Oil-Free technology to a range of military power and propulsion systems. Oil-Free turbomachinery has significant benefits that impact new unmanned air vehicles, the Army Future Combat System and the ongoing transformation to the Army Objective Force.

Oil-Free technology offers weight savings of fifteen percent relative to oil-lubricated turbine engines. Lighter engines make lighter vehicles that enhance military deployability. The weight savings with high speed and high temperature features of Oil-Free technology increase engine power density, which improves vehicle performance characteristics enhancing agility, lethality and survivability.

Oil-Free technology offers system simplification, efficiency, and other rotor system features that introduce new design freedoms, flexibility and versatility to vehicle systems.

Finally and potentially most significantly are the maintenance free characteristics of Oil-Free turbomachinery technology and the elimination of the oil lubrication system and the corresponding maintenance and logistics support. The engine parts count reduction and maintenance burden reduction enhances readiness and improves responsiveness and sustainability of the military systems.

High speed and high temperature Oil-Free foil air bearings are an emerging technology that is ready for transition and technology demonstration in military power and propulsion system applications.

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