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Oil-Free Rotor Support Technologies for an Optimized Helicopter Propulsion System

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June 2007

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Abstract

An optimized rotorcraft propulsion system incorporating a foil air bearing supported Oil-Free engine coupled to a high power density gearbox using high viscosity gear oil is explored. Foil air bearings have adequate load capacity and temperature capability for the high-speed gas generator shaft of a rotorcraft engine. Managing the axial loads of the power turbine shaft (low speed spool) will likely require thrust load support from the gearbox through a suitable coupling or other design. Employing specially formulated, high viscosity gear oil for the transmission can yield significant improvements (~2X) in allowable gear loading. Though a completely new propulsion system design is needed to implement such a system, improved performance is possible.

Introduction

Rotorcraft propulsion systems are comprised of two primary components, the engine and the transmission or drive system. These components are lubricated with highly developed oils delivered by complex lubrication systems. To reduce overall system weight and logistical inventory expenses, many rotorcraft employ a common lubricant, typically an ester based fluid (e.g., Mil-L-7808). Using such a "single fluid" approach necessitates that the oil be capable of lubricating both relatively hot engine components like bearings (~200 °C) and cooler (~100 °C), yet more heavily loaded, components such as transmission gears (ref. 1). As a result, the oil properties are a compromise suitable for engine use yet adequate for lubrication of transmissions (ref. 2).

The U.S. NAVY has highlighted the downside of using single multi-purpose lubricant rather than oils specially formulated for a particular application (ref. 3). For flight vehicles operating in maritime theaters, corrosion of gears and transmission components is a serious problem (ref. 2). In fact, corrosion is the leading damage mechanism for rotorcraft transmission systems in U.S. NAVY applications. To address this problem, the U.S. NAVY has developed a two fluid propulsion system in which specially formulated oil, optimized for corrosion protection, is used in the transmission and a high-grade engine oil (Mil-L-23699) is used in the engine. An extensive body of research has shown that using transmission oil with specialized corrosion inhibiting agents led to vastly improved gear and bearing life in rotorcraft operating at sea. The deployment of dual lubricant propulsion systems has become commonplace in those applications (ref. 3). Unfortunately, this two fluid approach leads to a weight penalty for the separate lubrication system. Other rotorcraft applications, both commercial and military, have retained the use of common fluid and lived with the compromised performance it provides (ref. 4). Nonetheless, there are clear examples that rotorcraft transmissions can be improved through the use of a gearbox specialized oil.

While the U.S. Navy's emphasis has been on the use of transmission oil tailored for corrosion protection, it may also be possible to develop such an oil to be tailored to allow higher loading in the transmission possibly providing significant weight savings in the main gearbox. In this paper, an additional approach to avoid the need for dual fluid lubrication is proposed; the use of an Oil-Free turbine engine coupled with a high power density transmission lubricated with high viscosity gear oil.

Propulsion System Architecture

Recent advances in foil gas bearing technology, high temperature solid lubricants and computer based modeling enable the development of an Oil-Free turbine engine suitable for helicopter propulsion (refs. 5 and 6). Oil-Free gas turbines, with rotors supported on foil air bearings, are in use in terrestrial power generation micro-turbines where environmental loads are small and transients are minimized (ref. 7). Current State-of-Art foil journal bearings possess sufficient load capacity and dynamic characteristics to support both high-pressure (HP) and low-pressure (LP) spools of a ~2000 shaft horsepower (shp) class turboshaft engine (ref. 8). However, limited thrust load capability of air bearings has been a challenge especially for low speed shafting. For rotorcraft propulsion systems, the opportunity exists to overcome the relatively low axial load capacity of foil air thrust bearings by supporting low spool (power shaft) thrust loads in the transmission bearings. This "hybrid" load sharing approach has been used in several other gas turbine engine demonstrations and enables the consideration of an optimized rotorcraft propulsion system in which specially tailored oil can be used for a high power density transmission without the weight penalty of also carrying an engine oil system (refs. 9 and 10). Accommodating the thrust loads in the oil-lubricated gearbox eliminates the challenges associated with high load capacity, low speed thrust foil air bearings.

To allow thrust load sharing between the engine and gearbox, the traditional shaft coupling between engine and transmission is replaced with one that can transmit torque as well as carrying the axial load of the low speed engine power shaft. A coupling such as a properly designed quill shaft or flex plate can be used. Microturbines often utilize such couplings to eliminate the need for multiple thrust foil bearings (ref. 7). Figure 1 shows a cutaway of a microturbine that uses this approach. Alternatively, the low speed shaft can simply be an extension of the transmission input shaft with a transmission oil lubricated bearing at the cooler fan/compressor end and a foil journal bearing in the hotter turbine end (ref. 9). This approach has been used successfully in several engines previously developed for automotive and unmanned flight engines, figures 2 and 3.

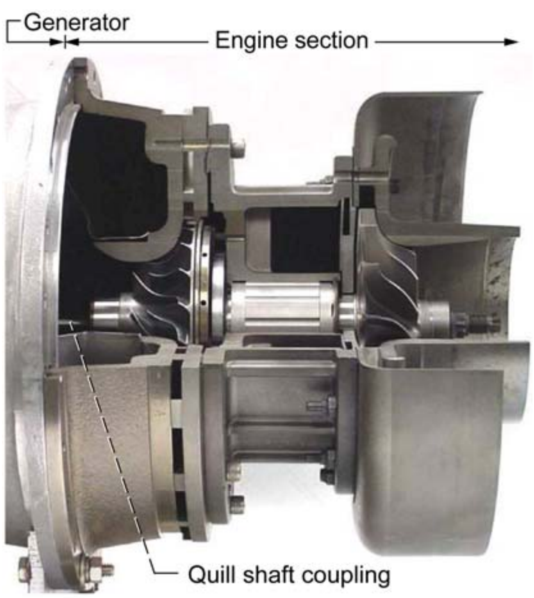

Figure 1.—Cutaway photograph of a Capstone micro-turbine gas generator (engine) section with quill shaft coupling connecting generator (left side) to engine which carries entire thrust load.

In this paper, the state-of-the-art for highly loaded gears is reviewed in the context of a lubricant optimized helicopter gearbox. Recently developed foil gas bearing load capacity and power loss models are presented which greatly aid evaluation efforts for an oil-free helicopter engine. In addition to reviewing the key technologies and systems needed for such an optimized helicopter propulsion system, this paper considers the remaining technical challenges to be addressed before such a system can be implemented in future rotorcraft.

Results and Discussions: (Foil Bearing Integration)

Foil bearings are self-acting hydrodynamic fluid film bearings made from thin flexible layers of sheet metal foil. During operation, a thin lubricating film of air forms between the stationary foil surface and the moving shaft it operates against. The principles of operation mirror those of oil-lubricated sleeve type bearings except that due to the low viscosity of the gas, the film thickness and load capacity are much lower than similarly sized oil lubricated hydrodynamic bearings (ref. 11). To maintain these small lubricating film thicknesses as well as to accommodate the geometric distortions of thin-walled, high-speed engine shafting, an elastic foundation underlays the smooth top foil that comprises the hydrodynamic surface. Figure 4 shows a cross section drawing of a typical foil gas bearing. Unlike conventional ball bearings, foil gas bearing load capacity increases with speed. (see fig. 5). For this reason, foil gas bearings are especially well suited for high-speed lightly loaded shaft systems such as those found in turbine engines. Additionally, the elimination of oil allows bearing operation at higher temperatures. During start-stop and low speed operation, prior to the formation of the lubricating gas film, rubbing occurs in foil bearings and solid lubricant coatings are used to prevent excessive friction and wear (ref. 12).

Newly developed and proven high temperature solid lubricants, like NASA's PS300 shaft coating, have enabled foil gas bearings to be used in small gas turbine engines where bearing temperatures often exceed 500 °C (refs. 7 and 13). PS300 is a plasma sprayed coating comprised of a metal binder with chrome oxide hardening and solid lubricant phases. It has been proven effective as a shaft lubricant for gas generator core foil bearings in microturbines and in other engine and lab testing (ref. 7). (see fig. 6).

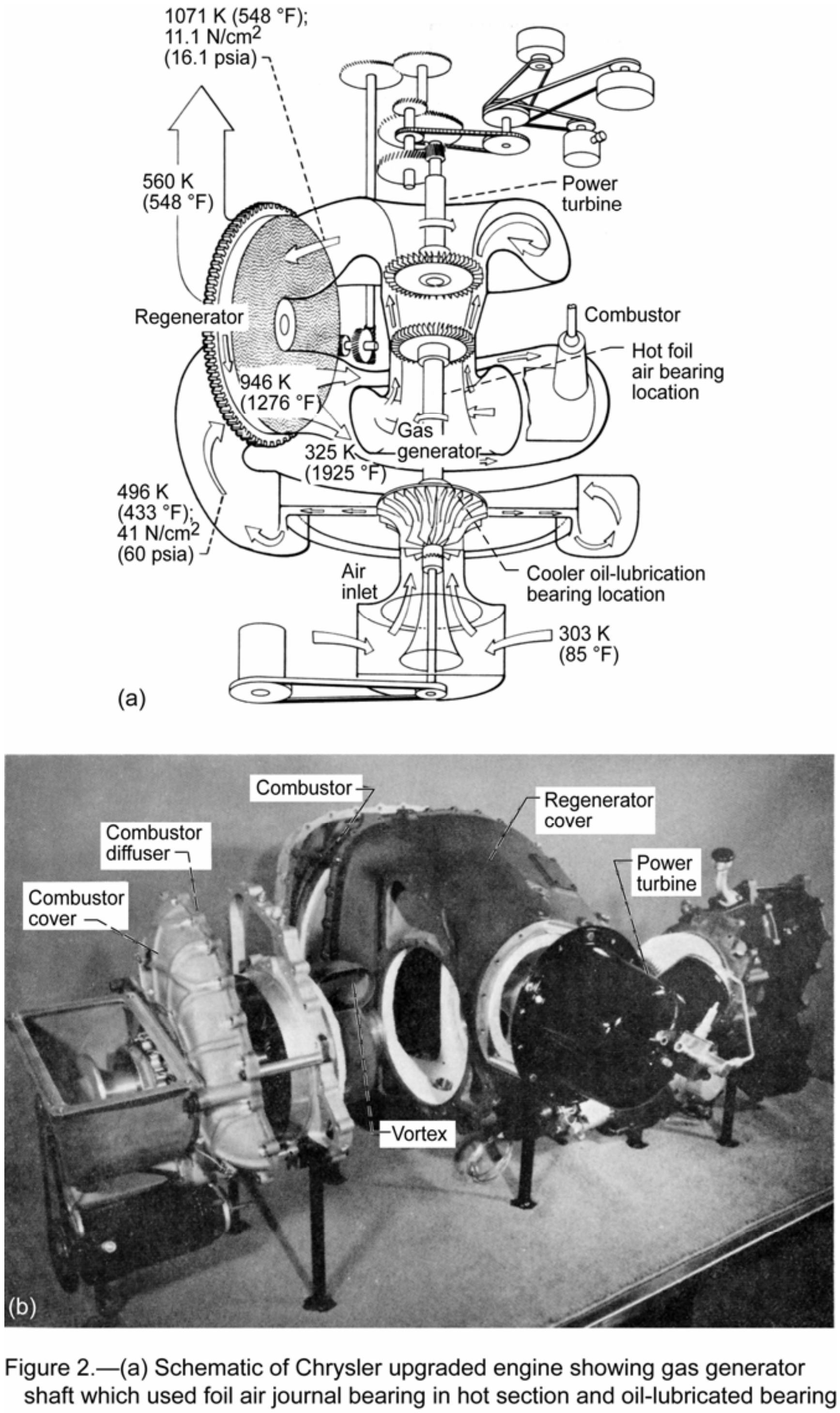

Figure 2.—(a) Schematic of Chrysler upgraded engine showing gas generator shaft which used foil air journal bearing in hot section and oil-lubricated bearing for compressor section. (b) Expanded display of Chrysler upgraded engine.

Figure 3.—Foil bearing hardware after testing on turbine engine core shaft. Adapted from reference 10.

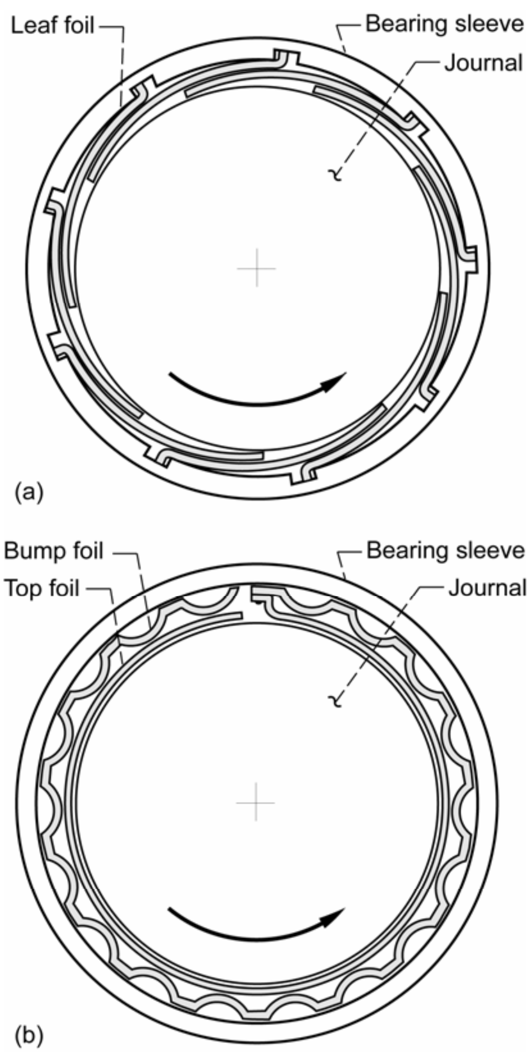

Figure 4.—Schematic example of typical foil bearings with axially and circumferentially uniform elastic support elements. (a) Leaf-type foil bearing. (b) Bump-type foil bearing.

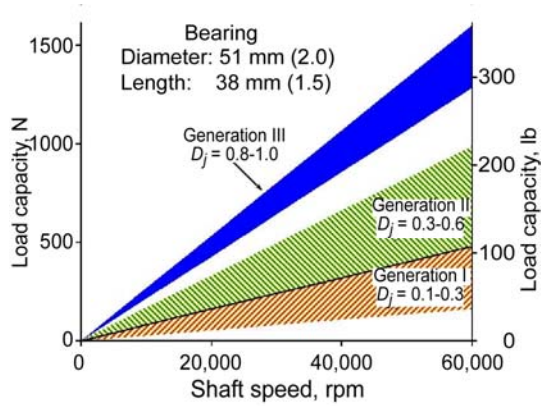

Figure 5.—Foil bearing load capacity increases with speed. Adapted from reference 5.

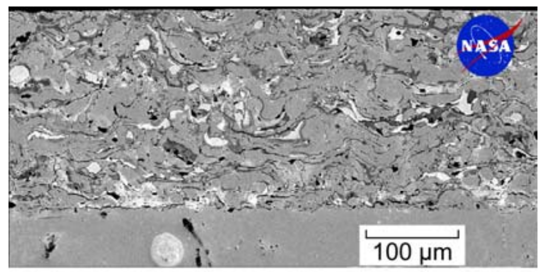

Figure 6.—Cross section photomicrograph of PS304 shaft coating used for foil bearings to 650 °C

Successful integration of foil gas bearings to rotorcraft engines requires careful management of bearing loads, bearing power loss (thermal stability) and matching of bearing stiffness and damping to rotordynamics. Foil bearing stiffness, damping and load capacity are limited and this results in the need to develop an engine design in which the bearingrequirements are within known bearing capabilities. Load capacity, power loss and stiffness are described in the literature and the successful deployment of foil bearings in terrestrial microturbines indicates that these bearings can meet shaft loading and other requirements in the absence of large environmental loads (ref. 14). To address transients expected in rotorcraft applications additional approaches such as advanced thermal management (bearing cooling) and load capacity enhancement may be required.

Research to integrate foil bearings for closed Brayton cycle power turbines generally locate the bearings inside a pressure vessel to avoid the need for seals and prevent working fluid contamination (ref. 15). In these instances, the foil bearings are operating at ambient pressures above one atmosphere and often in working fluids other than air. To field such systems, research into bearing performance at high pressures and in various fluids has been undertaken.

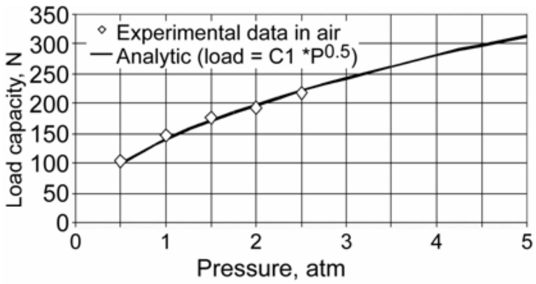

Figure 7.—Foil Bearing load capacity as a function of pressure showing a load capacity increase roughly proportional to ambient pressure raised to the square root power.

The results have shown that foil bearing load performance improves with increases in ambient pressure (ref. 16). Figure 7 shows that increasing the bearing cavity pressure by a factor of 2, increases the load capacity by 50 percent. Since rotorcraft gas turbines often operate with higher than ambient internal pressures, designs to intentionally pressurize bearing cavities to increase load capacity represents a viable path to meet transient load requirements.

Thermal management in the absence of oil, used in conventional engines as a coolant, could present a challenge. Despite having generally low friction, foil bearings do produce finite amounts of heat that must be carried away to maintain thermal stability (ref. 14). Foil bearing thermal stability must be maintained either through direct conduction through the bearing and shaft structure, via convection to the working fluid or, as is most often the case, through a combination of the two. Foil bearing thermal management studies in which two different bearing cooling schemes were employed to maintain foil bearing thermal stability are described in the literature (ref. 17). In the first method, shown in figure 8(a), air was forced through the foil bearing by pressuring one side of the bearing cartridge slightly above ambient pressure. Cooling flow thus passes both behind the foil structure and possibly along the shaft surface in the thin hydrodynamic lubricating film. This technique does provide effective cooling and is employed in many commercial foil bearing supported systems. It has an unintended consequence in that this approach often leads to lower bearing temperatures than shaft temperatures. The resulting radial thermal gradient causes an increase in bearing preload due to thermal expansion of the shaft into the bearing (ref. 18). The increased load can thus lead to increased power loss and ultimately thermal runaway and bearing seizure.

The second thermal management approach studied was shaft cooling. In this method, shown in figure 8(b), a jet of air was directly impinged against the inside diameter of the shaft, which was hollow as most flight weight systems are, to carry away heat from

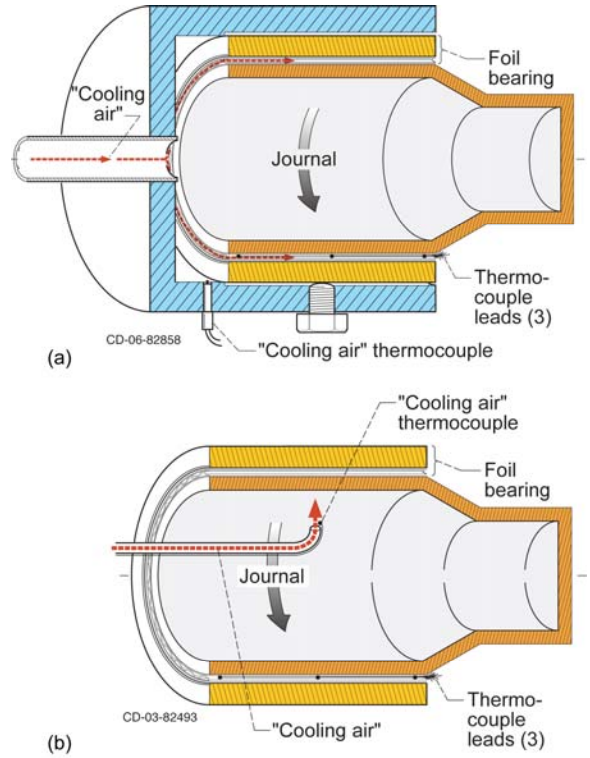

Figure 8.—(a) Axial cooling method with bearing inside can. Air flow is through bearing support structure. (b) Direct cooling method with guide tube oriented towards journal ID surface.

the shaft that was conducted from the gas film. With this method, the shaft tends to operate cooler than the bearing. This radial thermal gradient results in a slight reduction in bearing preload and reduced power loss. This is a thermally stable situation. In successful oil-free applications, like microturbine engines, a combination of carefully managed shaft and bearing bleed flow is used to ensure adequate thermal management (ref. 19). Clearly, based upon foil bearings' sensitivity to ambient pressure and the need to balance frictional heat with cooling, an extensive secondary airflow assessment will be part of a successful oil-free gas turbine engine program.

Results and Discussions: (Gearbox Power Density)

It has long been recognized that higher viscosity oils with additive packages tailored specifically for gears can result in improved gearbox lubrication (refs. 4, 20, and 21). Among the most demanding contacts within a gearbox are the gear teeth and bearing ball-race contacts. These are highly loaded contacts that rely on thin film elastohydrodynamic lubrication to prevent metal-metal asperity touching which can lead to wear, damage and fatigue type failures. Studies to estimate and, in some cases, measure potential gearbox improvements possible with higher viscosity and gear specific lubricants have been undertaken (refs. 4 and 20). The results consistently show that higher viscosity lubricants lead to higher fatigue life. Improvements to additive chemistry can also improve performance (ref. 21). There are several important reasons why implementing a change in oil has not been universal.

One challenge is that employing different oil in the gearbox than the engine necessitates a separate oil system and an increased burden on logistics as two types of oil will be needed. Additional maintenance and reliability concerns for the second oil system will also surface. Another challenge is that while increasing the gearbox lubricant's viscosity will improve fatigue life it can lead to other less desirable outcomes. For instance, higher oil viscosity leads to higher churning, pumping and viscous power loss elsewhere in the gearbox. Also, cooling oil flow rates vary inversely with viscosity. This means that using a higher viscosity oil will reduce oil flow rate for a given system making heat transfer and cooling of key, hard to reach, components like gear teeth difficult (ref. 22).

Fortunately, the concept under study here is to eliminate the need for an engine oil system, not simply to utilize separate systems as had been considered in the past (refs. 2 and 3). For the optimized propulsion system, no second oil system is needed. Rather, a downsized transmission-only system lubrication package is required. Thus no extra weight or cost is endured. On the other hand, gearbox designers must develop new lubrication systems to accommodate higher viscosity gear oil. Oil pumps, supply lines and controls will have to be adapted to minimize parasitic power needs and to provide adequate flow for thermal management. Innovative shrouding and gearbox oil scavenging may also be needed to reduce churning and windage losses (ref. 23).

In the literature, Townsend and Shimski indicated that simply increasing gear oil viscosity by 30 percent resulted in improvements in fatigue life by over 2.0 times (ref. 24). Other sources show that increasing viscosity combined with improving oil additives tailored for gears exhibited fatigue life improvements of over 8 times (ref. 25). Fatigue life is a key indicator of transmission health and is greatly affected by a variety of factors including construction materials, surface finish, operating temperature and loading. Increasing the lubricant viscosity and tailoring the additive package for gearboxes increases fatigue life. The opportunity exists to increase the loading to achieve an acceptable fatigue life but with a much higher power density. Research on spur gears demonstrated the relationship between load level and life. In these tests, the fatigue life based upon a pitting damage criterion followed an inverse relationship with load raised to the fifth power (ref. 25). Using data from the literature cited above, gear loads could be increased from 20 to 50 percent while retaining an acceptable fatigue life. Higher loading would then result in potential downsizing and weight savings for the transmission.

Clearly, making such major changes to gear loading and lubrication will have a cascading effect on the rest of the transmission. Thermal management, windage losses and structural loading are all affected by changes to lubricant viscosity. Oil system design would need to be refined to accommodate a higher viscosity fluid as well (ref. 26). In other words, a completely new transmission using a "clean sheet" design will be needed to arrive at an optimized gearbox suitable for mating to the proposed oil-free engine.

Summary

Based upon this overview, it is apparent that an Oil-Free turboshaft engine can be designed to mate with an advanced gearbox that provides both shaft speed reduction and low spool axial load support for the engine. Such an "Optimized Propulsion System" offers tangible benefits for rotorcraft, yet research challenges and questions remain.

Long term and intermediate goal research must be conducted on a variety of fronts before such a system is demonstrated. Hot core bearing development and tests, integral starter-generators, advanced axial load carrying couplings and possibly new centerlines are among the topics that will need to be addressed. Nonetheless, the potential weight savings offered by such an approach merits consideration. Further, deployment of oil-free bearing technology into rotorcraft will help mature the technology for larger more advanced systems such as turbofans and potentially space power generation systems as well.

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