NASA/TM—2008-215064 ARL–TR–4398

# Preliminary Analysis for an Optimized Oil-Free Rotorcraft Engine Concept

*Samuel A. Howard, Robert J. Bruckner, and Christopher DellaCorte*
*Glenn Research Center, Cleveland, Ohio*

*Kevin C. Radil*
*U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio*

March 2008

# NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 301–621–0134

- Telephone the NASA STI Help Desk at 301–621–0390

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2008-215064 ARL–TR–4398

# Preliminary Analysis for an Optimized Oil-Free Rotorcraft Engine Concept

*Samuel A. Howard, Robert J. Bruckner, and Christopher DellaCorte*
*Glenn Research Center, Cleveland, Ohio*

*Kevin C. Radil*
*U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio*

Prepared for
FORUM 63
sponsored by the American Helicopter Society International
Virginia Beach, Virginia, May 1–3, 2007

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

March 2008

This report contains preliminary findings, subject to revision as analysis proceeds.

*Level of Review*: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Available electronically at http://gltrs.grc.nasa.gov

# Preliminary Analysis for an Optimized Oil-Free Rotorcraft Engine Concept

Samuel Howard, Robert Bruckner, and Christopher DellaCorte
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Kevin C. Radil
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

Recent developments in gas foil bearing technology have led to numerous advanced high-speed rotating system concepts, many of which have become either commercial products or experimental test articles. Examples include Oil-Free microturbines, motors, generators and turbochargers. The driving forces for integrating gas foil bearings into these high-speed systems are the benefits promised by removing the oil lubrication system. Elimination of the oil system leads to reduced emissions, increased reliability, and decreased maintenance costs. Another benefit is reduced power plant weight. For rotorcraft applications, this would be a major advantage, as every pound removed from the propulsion system results in a payload benefit.

Implementing foil gas bearings throughout a rotorcraft gas turbine engine is an important long-term goal that requires overcoming numerous technological hurdles. Adequate thrust bearing load capacity and potentially large gearbox applied radial loads are among them. However, by replacing the turbine end, or hot section, rolling element bearing with a gas foil bearing many of the above benefits can be realized. To this end, engine manufacturers are beginning to explore the possibilities of hot section gas foil bearings in propulsion engines. This paper presents a logical follow-on activity by analyzing a conceptual rotorcraft engine to determine the feasibility of a foil bearing supported core. Using a combination of rotordynamic analyses and a load capacity model, it is shown to be reasonable to consider a gas foil bearing core section.

## Introduction

Consideration of gas foil bearing technology has recently been increasing with applications proposed or in production in turbochargers, power conversion units, small aero propulsion engines, auxiliary power units, and others.

Foil bearings, similar to the one shown in figure 1, are a special type of hydrodynamic sleeve bearing with a compliant surface on the inner diameter of the sleeve. In general, the compliant surface consists of two or more layers of superalloy sheetmetal, called foils. One layer provides stiffness (in this case the bumps act like springs), and the other is a smooth top layer providing the bearing surface. The gap between the top foil and the rotating journal, or shaft, is filled with a fluid. Typically, the fluid is air, but it can be just about any gas and some liquids. As the shaft rotates, the fluid becomes pressurized because of a wedge geometry that exists due to nonconcentricity of the shaft and sleeve. The pressure in the fluid film forces the foils to expand outward and separates the shaft from the top foil surface. The pressure is nonaxisymmetric and therefore generates a net force in the direction opposite the weight of the shaft. The pressure in the fluid film increases with the speed of the shaft, and eventually supports the full weight of the rotor. The compliance of the foil structure allows it to grow radially in response to centrifugal and thermal growth of the journal that would otherwise seize a rigid geometry bearing (ref. 1). As motion of

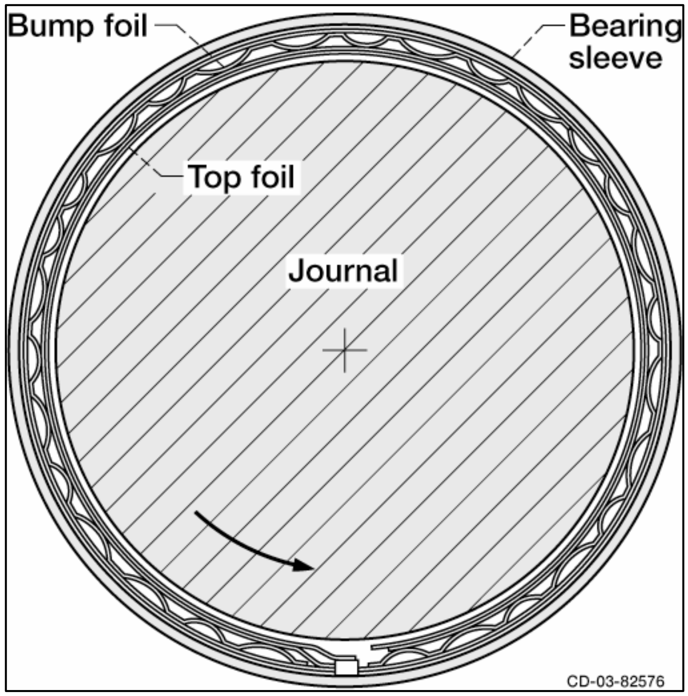

Figure 1.—Foil bearing schematic.

the shaft occurs relative to the sleeve, the bump and top foils deflect and rub against each other. The stiffness of the bumps controls the amount of deflection, and the rubbing adds Coulomb damping to the system (refs. 2 and 3). Thus, the foil structure gives the engine designer the ability to modify the stiffness and damping properties of the bearing, within certain limits, to meet the demands of the system rotordynamics (ref. 4). As in other Oil-Free applications, the elimination of the lubrication system results in higher specific power output, improved reliability, lower emissions, and less maintenance (ref. 5).

In previous programs intending to integrate gas foil bearing technology into various turbomachinery systems, a process has been developed and followed both by NASA and industry partners to bring new applications from concept to prototype with decreased risk of failure (ref. 6). The main steps are (1) Conduct a feasibility study to determine the potential for success and develop a detailed design, (2) Build and test candidate bearings on a component level, (3) Build and test a dynamically simulated version of the machine, and (4) Build and test a working prototype. Each step typically involves some iteration to arrive at a working design before moving onto the next step. The focus of the current paper is the first part of step one, and thus, presents a system level analysis of the feasibility of integrating gas foil bearings into a rotorcraft engine core.

## Optimized Engine Concept

When the entire rotorcraft power train is considered (the turboshaft engine and gearbox) in a systems approach, the optimized engine concept can reap the potential benefits of several technologies. Many of the previously discussed foil bearing advantages apply mainly to turbomachinery applications. In military rotorcraft however, the most significant benefit potentially comes from the optimization of the gearbox lubricant. In order to minimize logistical costs and efforts in the battlefield, many military rotorcraft routinely utilize the same lubricant in the engine and the gearbox, which is typically a compromise in both components. Because the demands (especially high temperatures) of oil lubricated ball bearings are more severe than that of gearbox and transmission, the engine requirements usually dictate the lubricant used, and the latter half of the power train typically suffers the most. Successful implementation of an Oil-Free rotorcraft engine due to advances in foil bearing technology would eliminate the need for engine lubrication. This would enable deployment of transmissions with an optimized lubrication system.

Laboratory tests have shown greater than 8-fold improvements in gear surface fatigue life using transmission optimized lubrication as compared to standard turbine oil (ref. 7). This concept would capture the benefits of a gas foil bearing supported turboshaft engine (lighter, more reliable, and more compact) as well as the benefits of longer surface fatigue life of the gearbox and transmission.

## Candidate Engine Architecture

A typical rotorcraft turboshaft engine layout is configured with a turbine driving a compressor on a high-speed rotor, and a lower speed power turbine driving an output shaft coupled to a transmission. Figure 2 shows a cartoon of this typical layout. For this conceptual optimized Oil-Free engine, a geometry based on a production engine is used to conduct a rotordynamic feasibility study. The purpose of this analysis is to build on a previous concept of gas foil bearings at the hot end of both the generator core, and the power turbine rotors of a rotorcraft engine (ref. 8). There are several technical challenges, which will be discussed later, to be solved before the goal of an entirely Oil-Free optimized engine can be successful. For this analysis, it is assumed that these technical challenges will eventually be addressed, thus the main objective is to determine if gas foil bearing technology is capable of meeting the rotordynamic needs of a typical rotorcraft engine core.

The first step in determining the potential of foil bearings in an existing engine is to construct a model with conventional rolling element bearings that are currently used in the engine. The goal is to build a baseline model that closely matches the observed behavior of the engine in terms of critical speeds (both natural frequencies and mode shapes) and mass properties (overall mass, polar and transverse inertias, and center of mass). The model was built for the candidate engine and checked against these criteria. Figure 3 shows the engine model in the baseline condition as graphically represented in the rotordynamics analysis software (ref. 9). The bearing locations and added masses/disks are shown in the figure. Table 1 lists the first three critical speeds and mass of the NASA baseline model along with the corresponding error of each compared to the actual engine behavior. The mode shapes are not shown, but they agree well with data supplied by the manufacturer. With good correlation between the NASA baseline computer model and the actual engine behavior, modifications to the geometry for foil bearing insertion can proceed.

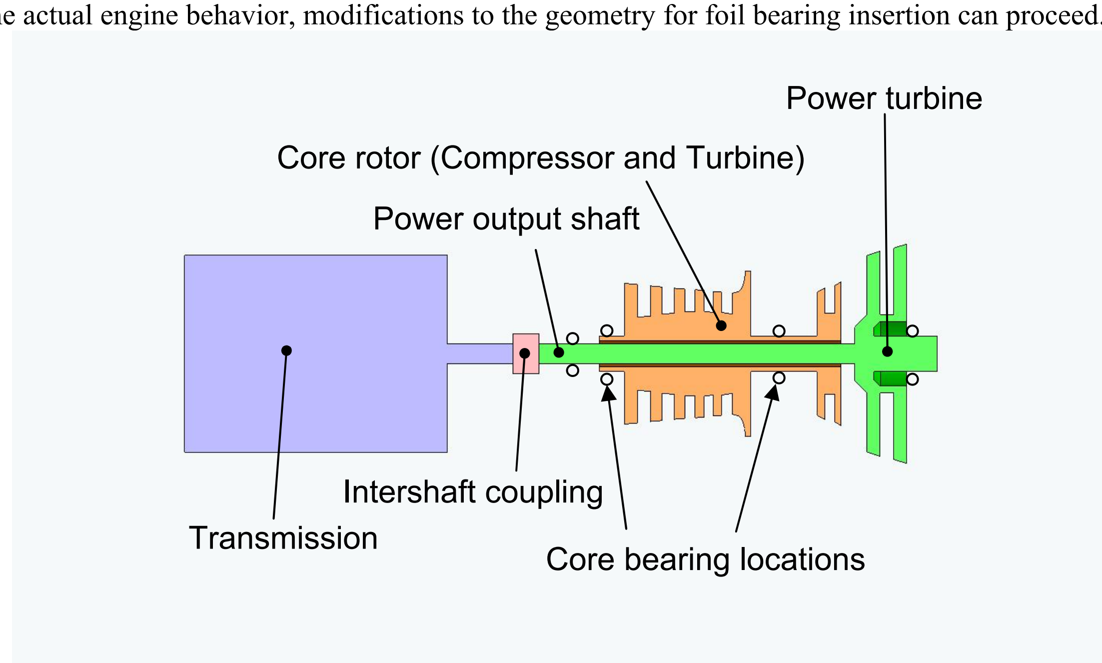


Figure 2.—Cartoon layout of a typical rotorcraft propulsion system.

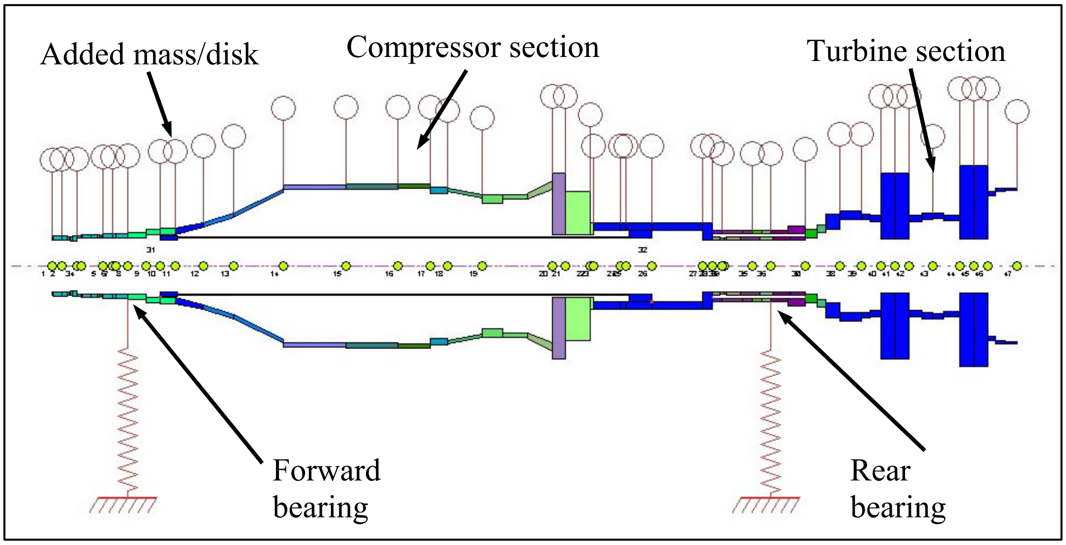

Figure 3.—Rotordynamic model of the baseline engine core configuration.

TABLE 1.—CRITICAL SPEED AND MASS COMPARISONS OF BASELINE MODEL TO ACTUAL ENGINE

| | Baseline model predicted values | Error compared to actual engine, percent |
|---|---|---|
| 1st critical speed | 6260 rpm | 0.6 |
| 2nd critical speed | 12700 rpm | 3.5 |
| 3rd critical speed | 26600 rpm | 1.2 |
| Mass | 21.9 kg | –1.7 |

## Rotordynamic Modeling With Gas Foil Bearings

In preliminary engine studies of this type, there are two main considerations to determine if gas foil bearing integration is feasible: adequate load capacity and acceptable rotordynamic behavior. These two criteria, taken alone, are not sufficient to proceed with an engine design because they do not consider other important design details such as material stress limits, physical space requirements/tradeoffs, secondary airflow, and others. However, if the steady-state loads are manageable from a foil bearing perspective, vibration amplitudes remain low while traversing the critical speeds, and stability is achieved up to the maximum speed, a given application then warrants further consideration and more advanced analysis.

Two potential configurations were analyzed in this study to determine feasibility. The first is simply the same geometry as the baseline rotor (fig. 3) with gas foil bearing properties substituted for the rolling element bearing properties of the baseline rotor. To properly size the bearing, the gas foil bearing rule of thumb developed previously (ref. 10) is used based upon steady state rotor loads. Based upon the model, the predicted steady state bearing loads of the engine are 44.8 N on the fore bearing, and 170 N on the aft bearing. Using the load capacity rule of thumb with load capacity coefficient of 1.0 (an advanced bearing design), and the 170 N load on the aft bearing, a 76.0 mm diameter by 50.8 mm long bearing would be lightly loaded at the minimum operating speed of 30,000 rpm, and the minimum speed for supporting the load (lift-off speed, again using the rule of thumb) would be around 2,000 rpm. For the fore bearing, a 50.8 by 50.8 mm bearing would meet the load requirement and have a lift-off speed for the given load around 1,200 rpm. Due to the necessity to sustain dynamic loads under operation, such as maneuver g-loads, and based upon recently developed power loss models (ref. 11) that suggest light nominal loads are more thermally stable, some load capacity margin is desirable. With the bearing sizes chosen above, the load capacity requirement is met with extra margin, the lift-off power requirements will be low (due to low lift-off speed), and thermal stability is more likely.

The rotordynamic analyses presented here are based upon linearized gas foil bearing dynamic force coefficients calculated using a computer code developed under a NASA grant to Pennsylvania State University (refs. 12 and 13). The computer code is used to calculate the stiffness and damping coefficients for the bearings with the given radial loads, at three different speeds to feed into the rotordynamic analysis software. Table 2 lists the rotordynamic coefficients used for the initial configuration.

TABLE 2.—BEARING DYNAMIC FORCE COEFFICIENTS USED IN THE FIRST OIL-FREE MODEL
[Calculated using carpino (refs. 12 and 13).]

| Speed, rpm | Kxx(N/m) | Kxy(N/m) | Kyx(N/m) | Kyy(N/m) |
|---|---|---|---|---|
| | Cxx(Ns/m) | Cxy(Ns/m) | Cyx(Ns/m) | Cyy(Ns/m) |
| Forward bearing (50.8 by 50.8 mm, 44.8 N load) | | | | |
| 10000 | 6.73E+06 | 3.84E+05 | 5.44E+05 | 7.52E+06 |
| | 4.08E+02 | –3.13E+01 | 1.35E+01 | 3.83E+02 |
| 30000 | 5.37E+06 | 1.29E+05 | 6.89E+05 | 6.11E+06 |
| | 4.21E+02 | –7.12E+01 | 9.75E+01 | 3.96E+02 |
| 50000 | 5.18E+06 | –3.72E+05 | 7.09E+05 | 6.11E+06 |
| | 4.68E+02 | –1.59E+02 | 2.51E+02 | 4.11E+02 |
| Rear bearing (76.0 by 50.8 mm, 170 N load) | | | | |
| 10000 | 1.88E+07 | 1.66E+06 | 1.80E+06 | 1.31E+07 |
| | 4.46E+02 | –8.89E+00 | 3.73E+01 | 4.66E+02 |
| 30000 | 1.41E+07 | 5.15E+05 | 1.17E+06 | 1.22E+07 |
| | 4.51E+02 | –6.30E+01 | 1.15E+02 | 4.80E+02 |
| 50000 | 1.28E+07 | –1.50E+05 | 1.54E+06 | 1.12E+07 |
| | 5.40E+02 | –1.28E+02 | 2.09E+02 | 4.96E+02 |

The critical speed analysis of this configuration indicates that there are two critical speeds below the operating speed range. The first is a rigid body critical speed and occurs at around 7,000 rpm. The second is a bending critical speed and occurs at around 19,800 rpm. The third critical speed occurs at 140 percent of the maximum speed of the engine, so it is not a concern. Since the ground idle speed (minimum operating speed) is above the second critical speed, and the third natural frequency is well above the maximum operating speed, the entire speed range is clear of natural frequencies. This is desirable because foil bearings typically offer less damping than oil lubricated rolling element bearings and squeeze film dampers. However, this is not sufficient to ensure the engine configuration can work with foil bearings. One must also consider stability. Either of the natural frequencies occurring below the operating speed range could become excited within the operating speed range and cause instability.

The rotordynamic analysis software can also be used to calculate stability. The log decrement is a measure of the decay of a transient vibration of the system. If the log decrement is positive, the vibration decays in time. If it is negative, the vibration grows in time and is an indication of instability. The computer code calculates the log decrement for each of the natural frequencies and plots them as a function of speed. The lowest speed at which the log decrement of any of the natural frequencies becomes negative is called the threshold speed of instability, and is the maximum speed at which the engine can safely operate. Figure 4 shows the log decrement plot for the first rotor configuration. As one can see, the log decrement of the first three critical speeds is positive, indicating that the engine is stable throughout its speed range.

The first configuration analyzed, which is the same as the baseline engine, satisfies the criteria defined as being feasible and warranting further study. However, one concern with this design that would require more detailed consideration in follow-on analyses is the fact that it results in supercritical operation. This means that the bending critical speed is below the operating speed. This is important because although the natural frequency does not exist within the speed range of interest, and it is a stable mode up to the maximum speed, the machine still has to pass through the natural frequency on its way to

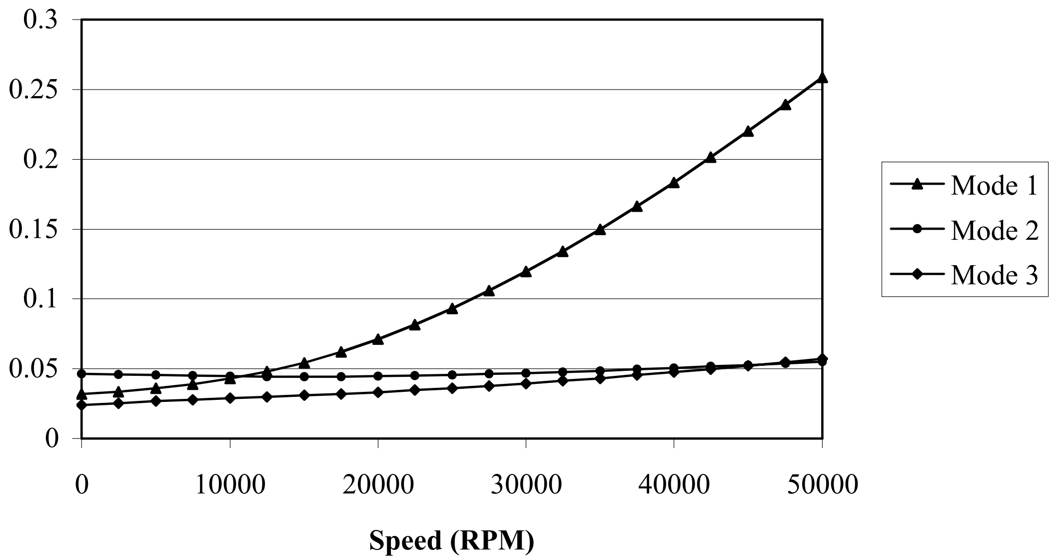


Figure 4.—Stability plot of the baseline engine core configuration with foil bearings.

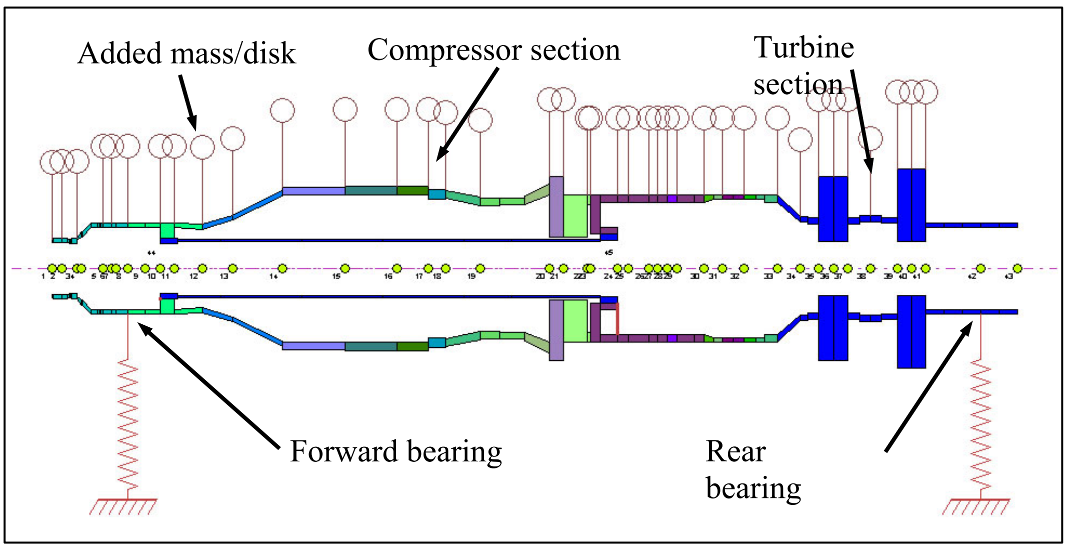


Figure 5.—Rotordynamic model of the stiffened engine core configuration.

the operating speed range. The concern is the amplitude of vibration at the compressor and turbine locations. Depending upon the amplitude of these vibrations, the required tip clearances could become large, thereby adversely affecting engine performance. Amplitude of vibration is a concern when passing through any natural frequency, but more so when the mode shape involves bending because the displacements at the aerodynamic components are typically larger in bending mode shapes than rigid mode shapes. For this reason, it is usually desirable to push the bending natural frequency above the operating speed range in foil bearing supported machinery.

In order to analyze a system with a bending mode shape outside the operating speed range, a second model was constructed and is shown in figure 5. In this model, the engine shaft is made stiffer and the aft bearing is relocated behind the turbine. Significant layout changes, such as these, are possible only if the Oil-Free version of the engine is assumed to be a complete redesign. With that assumption, one has the freedom to make the shaft stiffer by reducing the span between the compressor and the turbine, and by increasing its outer diameter. This modification required that the aft foil bearing be moved behind the turbine because there is insufficient real estate at the old bearing location to accommodate a larger sized bearing. The compressor section is made stiffer as well by increasing the wall thickness. The turbine design remains identical to the first model and the baseline engine.

With these changes, the bearing loads are different, requiring re-sizing of the bearings. The load on the front bearing is now 104 N and the rear bearing is now 130 N. With the load more evenly distributed, the same size bearings are used in both locations, 64.0 mm diameter by 50.8 mm long. As before, this size gives low lift-off speeds of 1900 and 2300 rpm, respectively. The bearings would operate in a lightly loaded condition throughout the operating speed range, ensuring dynamic load capacity and thermal stability. The new bearing dynamic force coefficients are listed in table 3.

TABLE 3.—BEARING DYNAMIC FORCE COEFFICIENTS USED IN THE SECOND OIL-FREE MODEL
[Calculated using carpino (refs. 12 and 13).]

| Speed, rpm | Kxx(N/m) | Kxy(N/m) | Kyx(N/m) | Kyy(N/m) |
|---|---|---|---|---|
| | Cxx(Ns/m) | Cxy(Ns/m) | Cyx(Ns/m) | Cyy(Ns/m) |
| Forward bearing (64.0 by 50.8 mm, 104 N load) | | | | |
| 10000 | 1.24E+07 | 1.07E+06 | 1.21E+06 | 1.02E+07 |
| | 4.58E+02 | –5.37E+01 | –1.30E+01 | 4.55E+02 |
| 30000 | 9.72E+06 | 1.71E+05 | 8.40E+05 | 9.33E+06 |
| | 4.34E+02 | –5.47E+01 | 1.11E+02 | 4.32E+02 |
| 50000 | 8.83E+06 | –2.92E+05 | 1.13E+06 | 8.66E+06 |
| | 5.21E+02 | –1.37E+02 | 2.29E+02 | 4.54E+02 |
| Rear bearing (64.0 by 50.8 mm, 130 N load) | | | | |
| 10000 | 1.49E+07 | 1.38E+06 | 1.52E+06 | 1.11E+07 |
| | 4.38E+02 | –2.65E+01 | 1.02E+01 | 4.34E+02 |
| 30000 | 1.11E+07 | 2.90E+05 | 9.17E+05 | 1.01E+07 |
| | 4.21E+02 | –6.28E+01 | 1.07E+02 | 4.37E+02 |
| 50000 | 9.95E+06 | –1.95E+05 | 1.21E+06 | 9.22E+06 |
| | 4.91E+02 | –1.30E+02 | 2.13E+02 | 4.48E+02 |

Analysis of the second model indicates that there are now two rigid body critical speeds below the minimum speed of the engine, one at 7,100 rpm, and one at 13,200 rpm. The bending critical speed is increased to 51,000 rpm. This gives a 15 percent margin above the maximum operating speed. Like the previous configuration, the operating speed range is clear of natural frequencies. However, stability is still a concern. Figure 6 is a plot of the log decrements for this configuration's first three modes. Again, all are positive indicating stability throughout the range. As mentioned before, part of a more detailed design analysis would need to include monitoring tip clearances when passing through the first two modes, but that is less of a concern with this configuration.

## Technical Hurdles

Several technical hurdles exist that need to be addressed for success of a concept such as an Oil-Free engine coupled to an optimized transmission. The most important area is thrust load management. The models presented here did not include thrust bearing analysis. Foil thrust bearing technology is not nearly as advanced as foil journal bearing technology resulting in thrust bearing designs that have low load capacity and suffer from thermal instability problems. Typically, the solution to this problem has been to pressure balance the thrust loads of each rotor as much as possible so that the thrust bearings do not have to sustain large loads. This is most likely possible in this application for the core shaft. However, to realize the full potential of the optimized transmission concept, the entire engine must be oil-free. The power turbine shaft has no compressor with which to balance the thrust loads in the turbine. One possible solution in a rotorcraft application would be for the transmission to be coupled to the engine with a thrust

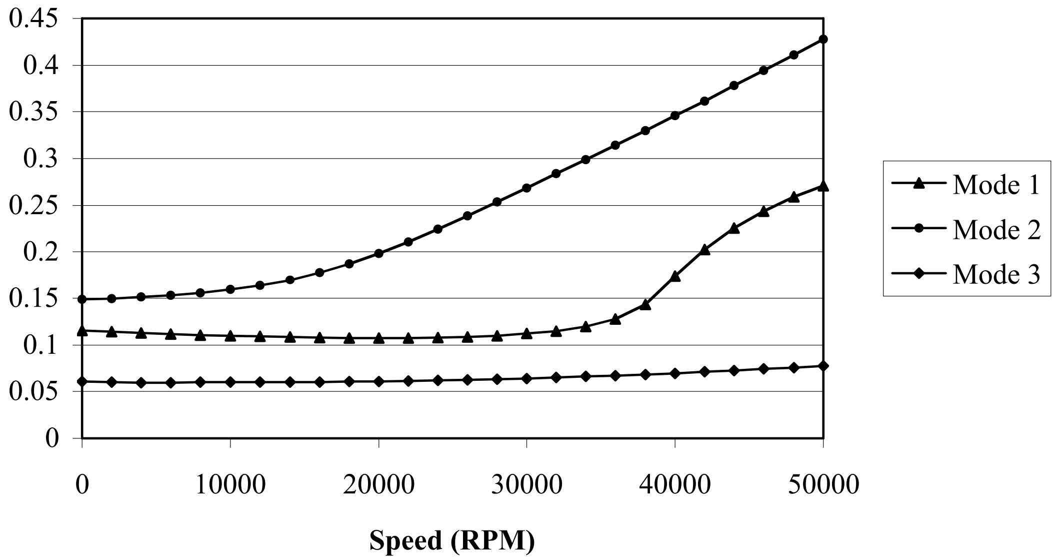


Figure 6.—Stability plot of the stiffened engine core configuration with foil bearings.

carrying coupling (possible a quill shaft) and let the transmission carry the thrust load of the low-spool rotor. However the thrust loads are managed, it remains an area that requires attention.

Another limiting technology is in bearing analysis tools. The computations to compute bearing rotordynamic coefficients are very complex, involving compressible fluid dynamics coupled with nonlinear structural dynamics, including frictional contact forces, membrane effects, thermal effects, etc. The tools to accurately predict these bearing properties, including all the necessary physics, do not yet exist. The current foil bearing prediction models are adequate for preliminary analysis, but are insufficient for advanced, detailed design work. Efforts to address this problem are underway, but for now, this deficiency forces much empirical based design that is costly and time consuming.

Elimination of the gear-driven starter/generator is another area that needs attention. The current fleet of rotorcraft engines typically use starter motors with bevel gears to drive the core for starting. These gear contacts put radial loads on the shaft that would be hard to sustain for a foil bearing supported rotor, especially at low speed during starting. Some work has been done on integral starter/generators that would be mounted directly on the shaft to eliminate this problem, but more work is needed.

## Conclusions

The proposed concept of mating an Oil-Free gas turbine engine, using air lubricated foil bearings, with a transmission using gearbox specific oil offers potential savings of weight, emissions, and maintenance, as well as longer transmission life. A correlated baseline model of an existing rotorcraft engine was analyzed in two configurations to determine if foil bearing technology could possibly be used based upon loads and dynamic considerations. A more detailed analysis is needed to properly address all concerns, but the initial study indicates that the concept is plausible from the standpoint of an Oil-Free gas generator section. The radial load capacity of foil journal bearings is adequate for the rotorcraft engine size class. The critical speeds can be designed to be outside of the operating speed range. Further, both Oil-Free core configurations are predicted to be stable throughout the operating speed range. More advanced analysis and testing is needed to generate detailed designs, but there are no obvious roadblocks to suggest the concept is not plausible. Considering the potential payoffs of an optimized propulsion system, moving forward with this concept is a worthwhile endeavor.

# References

1. Gross, W.A., *Gas Film Lubrication*. John Wiley and Sons, New York, NY, p. 11.
2. Heshmat, H., "Advancements in the Performance of Aerodynamic Foil Journal Bearings: High Speed and Load Capability," *Transactions of the ASME J. of Tribology*, 116, 287–295 (1994).
3. Agrawal, G.L., "Foil Air/Gas Bearing Technology—an Overview," in *Proceedings of Turbo Expo: Power for Land, Sea, and Air 1997 (IGTI)*, ASME, Orlando, FL, 1997, Paper No. 97-GT-347.
4. Rubio, D., and SanAndres, L., "Bump-Type Foil Bearing Structural Stiffness: Experiments and Predictions," in *Proceedings of Turbo Expo: Power for Land, Sea, and Air 2004 (IGTI)*, ASME, Vienna, Austria, 2004, Paper No. GT 2004-53611.
5. Bruckner, R.J., "A Propulsion System Analysis of Oil Free Turbomachinery for Aviation Turbofan Engines," Presented at *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Ft. Lauderdale, FL, 2004, Paper No. AIAA–2004–4189.
6. Heshmat, H., Walton, J.F., DellaCorte, C., and Valco, M.J., "Oil-Free Turbocharger Demonstration Paves Way to Gas Turbine Engine Applications," in *Proceedings of Turbo Expo: Power for Land, Sea, and Air 2000 (IGTI)*, ASME, Munich, Germany, 2000, Paper No. 2000-GT-620.
7. Townsend, D.P., and Shimski, J., *Evaluation of the EHL Film Thickness and Extreme Pressure Additives on Gear Surface Fatigue Life*, NASA TM 106663, NASA Lewis Research Center, Cleveland, OH, 1994.
8. Spring, S.D., Kaminske, M., Leone, S., Drexel, M.V., Ertas, B.H., Ames, E.C., Agrawal, G., Burr, D., and Brophy, M., "Application of Compliant Foil Air Bearings for Oil Free Operation of Advanced Turboshaft Engines," Presented at the *AHS 62nd Annual Forum*, Phoenix, AZ, 2006.
9. Chen, W.J., and Gunter, E.J., *DyRoBeS Reference Manual on Rotor Bearing Dynamics*, version 11, RODYN Vibration Analysis, Inc., Charlottesville, VA, 2006.
10. DellaCorte, C., and Valco, M.J., "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications," *STLE Tribology Transactions* 43, 795–801 (2001).
11. DellaCorte, C., Radil, K.J., Bruckner, R.J., and Howard, S.A., *A Preliminary Foil Gas Bearing Performance Map*, NASA/TM—2006-214343, NASA Glenn Research Center, Cleveland, OH, 2006.
12. Carpino, M., and Talmadge, G., "A Fully Coupled Finite Element Formulation for Elastically Supported Foil Journal Bearings," *STLE Tribology Transactions* 46, 560–565 (2003).
13. Carpino, M., and Talmadge, G., "Prediction of Rotordynamic Coefficients in Gas Lubricated Foil Journal Bearings with Corrugated Sub-Foils," *STLE Tribology Transactions* 49, 400–409 (2006).

| REPORT DOCUMENTATION PAGE | | | | | | *Form Approved* *OMB No. 0704-0188* |
|---|---|---|---|---|---|---|
| The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS. | | | | | | |
| **1. REPORT DATE** *(DD-MM-YYYY)* 01-03-2008 | | **2. REPORT TYPE** Technical Memorandum | | | | **3. DATES COVERED** *(From - To)* |
| **4. TITLE AND SUBTITLE** Preliminary Analysis for an Optimized Oil-Free Rotorcraft Engine Concept | | | | | | **5a. CONTRACT NUMBER** |
| | | | | | | **5b. GRANT NUMBER** |
| | | | | | | **5c. PROGRAM ELEMENT NUMBER** |
| **6. AUTHOR(S)** Howard, Samuel, A.; Bruckner, Robert, J.; DellaCorte, Christopher; Radil, Kevin, C. | | | | | | **5d. PROJECT NUMBER** |
| | | | | | | **5e. TASK NUMBER** |
| | | | | | | **5f. WORK UNIT NUMBER** WBS 877868.02.07.03.01.01 |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** National Aeronautics and Space Administration<br>John H. Glenn Research Center at Lewis Field<br>Cleveland, Ohio 44135-3191 | | | | | | **8. PERFORMING ORGANIZATION REPORT NUMBER** E-16290 |
| **9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)** National Aeronautics and Space Administration<br>Washington, DC 20546-0001<br>and<br>U.S. Army Research Laboratory<br>Adelphi, Maryland 20783-1145 | | | | | | **10. SPONSORING/MONITORS ACRONYM(S)** NASA; ARL |
| | | | | | | **11. SPONSORING/MONITORING REPORT NUMBER** NASA/TM-2008-215064; ARL-TR-4398 |
| **12. DISTRIBUTION/AVAILABILITY STATEMENT** Unclassified-Unlimited<br>Subject Category: 07<br>Available electronically at http://gltrs.grc.nasa.gov<br>This publication is available from the NASA Center for AeroSpace Information, 301-621-0390 | | | | | | |
| **13. SUPPLEMENTARY NOTES** | | | | | | |
| **14. ABSTRACT** Recent developments in gas foil bearing technology have led to numerous advanced high-speed rotating system concepts, many of which have become either commercial products or experimental test articles. Examples include Oil-Free microturbines, motors, generators and turbochargers. The driving forces for integrating gas foil bearings into these high-speed systems are the benefits promised by removing the oil lubrication system. Elimination of the oil system leads to reduced emissions, increased reliability, and decreased maintenance costs. Another benefit is reduced power plant weight. For rotorcraft applications, this would be a major advantage, as every pound removed from the propulsion system results in a payload benefit. Implementing foil gas bearings throughout a rotorcraft gas turbine engine is an important long-term goal that requires overcoming numerous technological hurdles. Adequate thrust bearing load capacity and potentially large gearbox applied radial loads are among them. However, by replacing the turbine end, or hot section, rolling element bearing with a gas foil bearing many of the above benefits can be realized. To this end, engine manufacturers are beginning to explore the possibilities of hot section gas foil bearings in propulsion engines. This paper presents a logical follow-on activity by analyzing a conceptual rotorcraft engine to determine the feasibility of a foil bearing supported core. Using a combination of rotordynamic analyses and a load capacity model, it is shown to be reasonable to consider a gas foil bearing core section. | | | | | | |
| **15. SUBJECT TERMS** Rotary wing aircraft; Turboshafts; Foil bearings; Gas bearings | | | | | | |
| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | | **19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov) |
| **a. REPORT** U | **b. ABSTRACT** U | **c. THIS PAGE** U | UU | 15 | | **19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390 |

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18