Conceptual Design and Feasibility of Foil Bearings for Rotorcraft Engines: Hot Core Bearings

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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 overview 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. In addition, system level foil bearing testing capabilities at NASA Glenn Research Center are presented along with analysis work being conducted under NRA Cooperative Agreements.

Conceptual Design and Feasibility of Foil Bearings for Rotorcraft Engines: Hot Core Bearings

by

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Outline

- Rotordynamic analysis of an Optimized Oil-Free Rotary Wing Engine
- Oil-Free rotor system testing at NASA Glenn Research Center
- Overview of current NASA Research Announcement funded Oil-Free Rotary Wing Activities
- Summary Remarks

Rotordynamic analysis of an Optimized Oil-Free Rotary Wing Engine

Oil-Free Technology Integration Approach

1) Rotor System Conceptual Design & Feasibility Study

2) Bearing Development & Testing

3) Rotordynamic System Simulation

4) Oil-Free Technology Demonstration

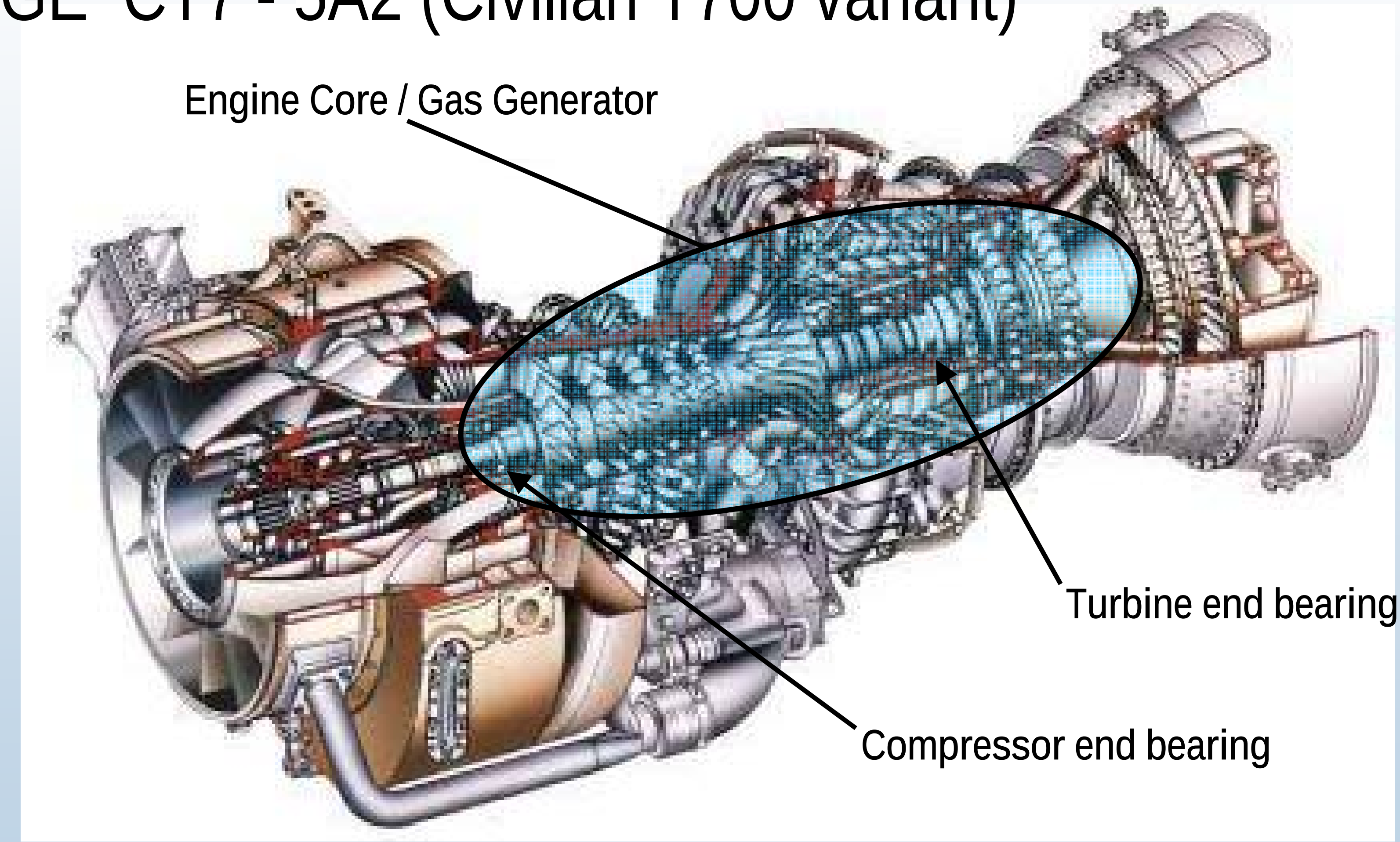
- *Approach successfully employed in Oil-Free turbocharger project*
- *Approach successfully practiced by industry in turboalternator and turbocompressor projects*

Oil-Free Rotorcraft Concept

- **Others are currently investigating foil bearings at the turbine end of a rotorcraft engine core (Spring, et.al., 2006).**
- **The purpose of the current study is to show that foil bearing technology is rotordynamically capable of rotor support at both ends by analyzing a generic rotorcraft engine core.**
- **Some technical challenges exist that require attention to make the optimized engine concept a reality, but we believe foil bearing technology is ready for this size class.**

Common Rotary Wing Turboshaft Engine

- GE CT7 - 5A2 (Civilian T700 variant)

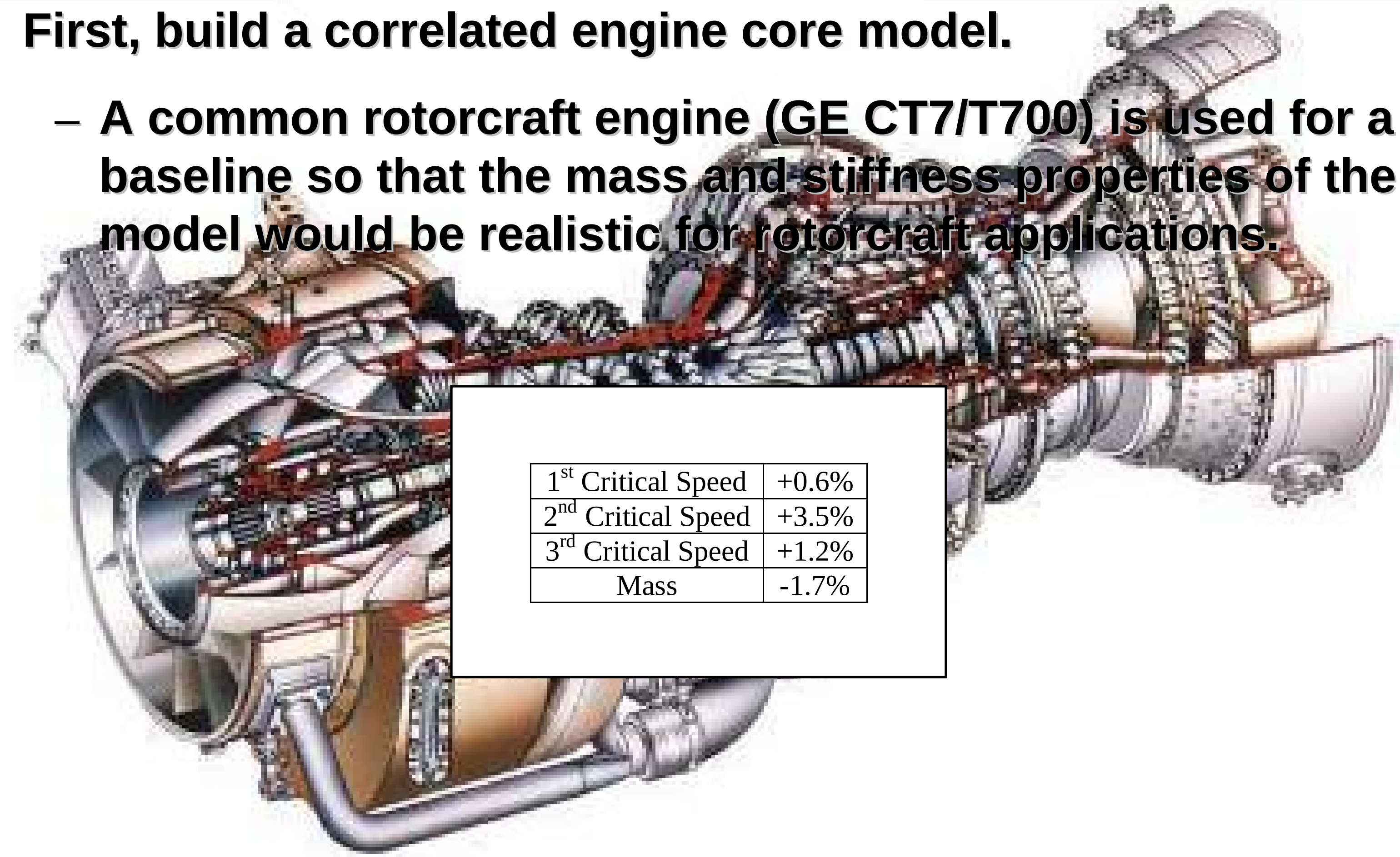


Rotordynamic System Conceptual Design

- **The steps in the analysis process:**
  - **Build a correlated model of an engine core that has some relevance to rotorcraft (GE CT7/T700).**
  - **Modify the engine core model to account for foil bearing dynamic force coefficients.**
    - **This step includes choosing foil bearing sizes to accommodate the loads.**
    - **Also includes modifying the layout if needed to improve the response.**
  - **Analyze various designs for rotordynamic acceptability.**

Rotordynamic System Conceptual Design

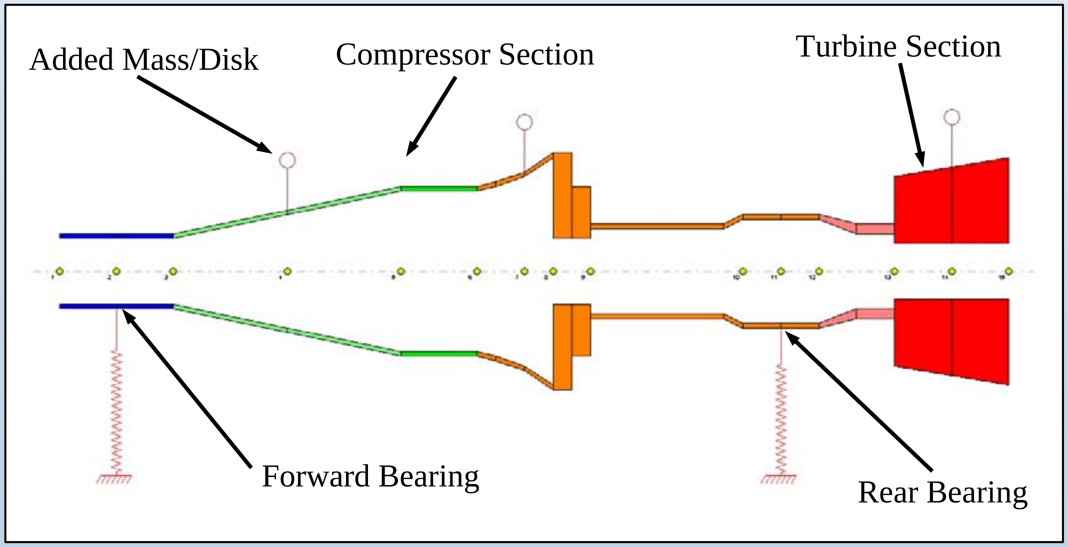
- **First, build a correlated engine core model.**
  - **A common rotorcraft engine (GE CT7/T700) is used for a baseline so that the mass and stiffness properties of the model would be realistic for rotorcraft applications.**



1st Critical Speed	+0.6%
2nd Critical Speed	+3.5%
3rd Critical Speed	+1.2%
Mass	-1.7%

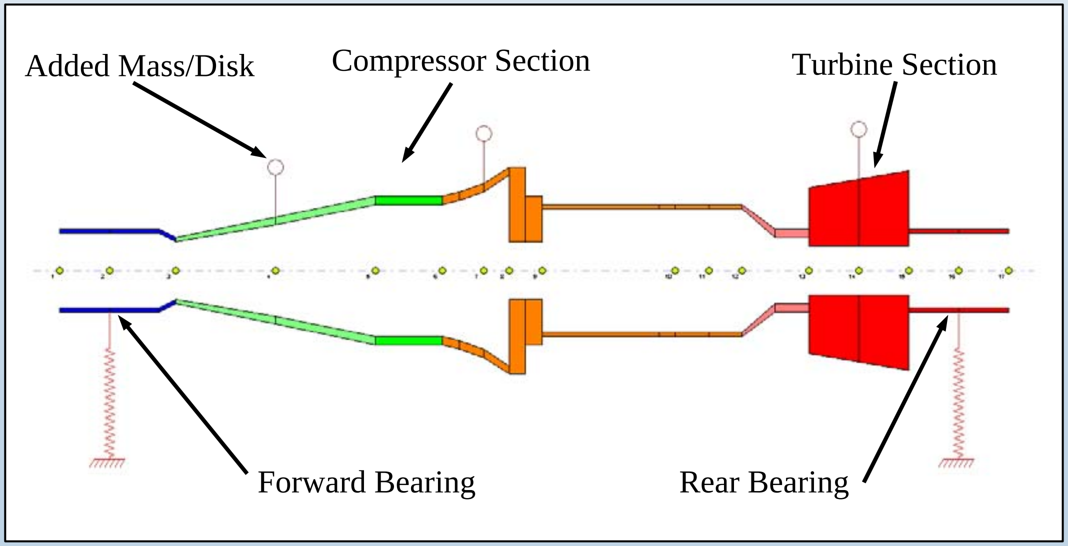
Rotordynamic System Conceptual Design

- **After the baseline model was developed, and its dynamic behavior matched to the existing engine, two modified layouts for integration of foil bearings were analyzed.**
- **The first layout is an overhung turbine design similar to the original engine layout. A cartoon of its rotordynamic model shows approximate bearing locations relative to the compressor and turbine.**



Rotordynamic System Conceptual Design

- **The overhung design has a relatively small cross section in the middle and therefore, operates supercritical (bending mode below the operating speed).**
- **The second layout is a straddle mount design which is stiffened to move the bending mode above the operating speed range. This is not necessary, but is more typical of foil bearing supported machines.**



Foil Bearing Load Capacity Rule of Thumb

- **In 2000, DellaCorte and Valco developed a load capacity rule of thumb.**

- **This simple, empirically derived correlation allows designers to estimate acceptable bearing loads for a given size and speed.**

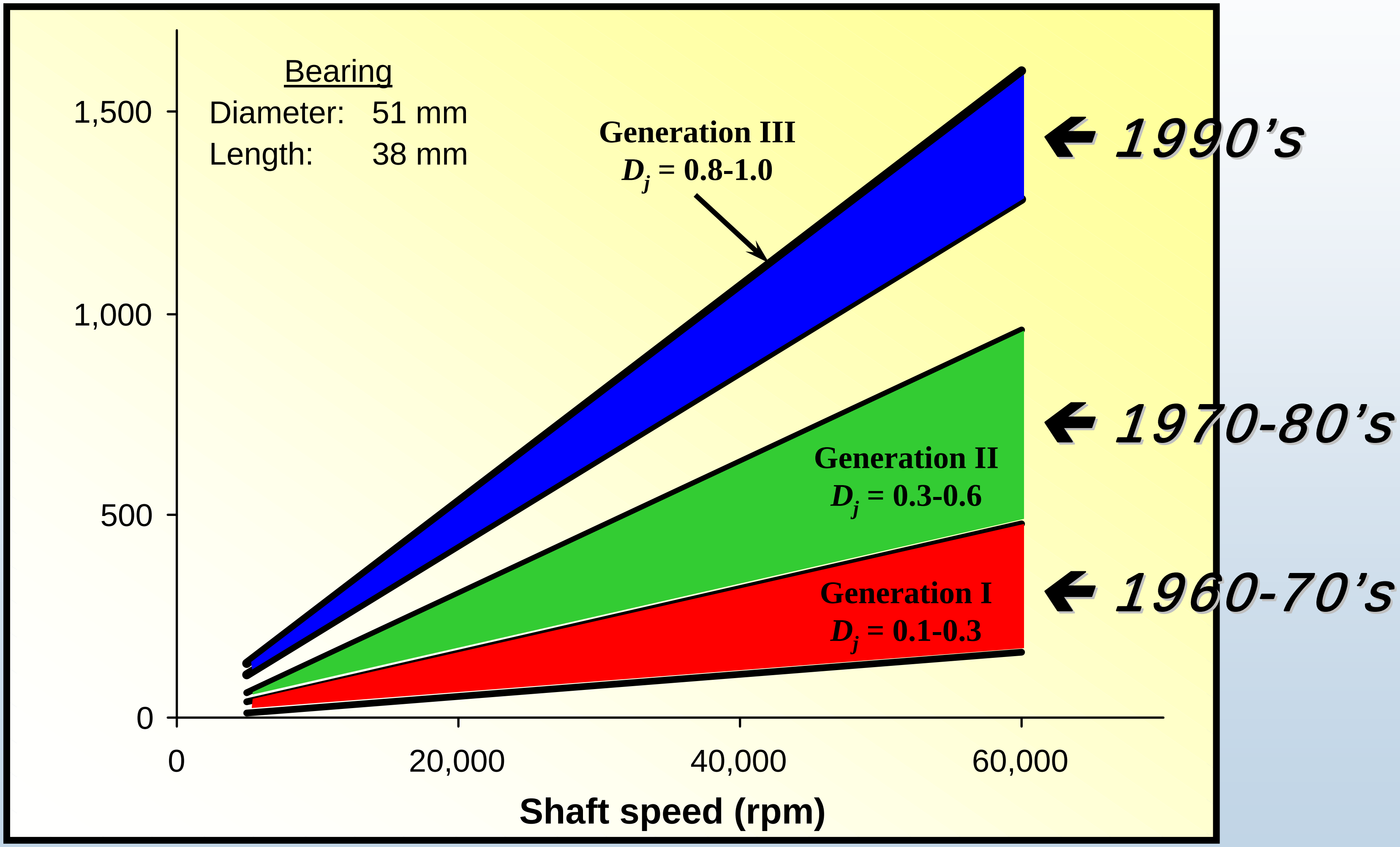
$$Load = \mathrm{D_j}\ x\ (\omega\ x\ D)\ x\ (L\ x\ D)$$

$$where\ D = Diameter\,(inches), L = Length\,(inches), \omega = krpm, \mathrm{D_j} = Load\ Capacity\ Coefficient$$

- **Foil Bearings can be broken down into three generations based upon their geometry and associated load capacity coefficients…**

Source: DellaCorte & Valco, "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications, NASA/TM-2000-209782, ARL-TR-2334, Oct 2000

Foil Bearing Load Capacity
Generation I, II, & III



Rotordynamic System Conceptual Design

- **Foil bearing dynamic force coefficients are calculated with the static loads predicted by the rotordynamic model.**

- **A computer code developed under a NASA grant to Penn State University is used to calculate bearing stiffness and damping coefficients for use in the model (Carpino and Talmadge, 2006).**

Overhung Layout Bearing Data

Speed (RPM)	Kxx(N/m) / Cxx(Ns/m)	Kxy(N/m) / Cxy(Ns/m)	Kyx(N/m) / Cyx(Ns/m)	Kyy(N/m) / Cyy(Ns/m)
Forward Bearing (50.8 mm x 50.8 mm)				
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 mm x 50.8 mm)				
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

Source: 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).

Rotordynamic System Conceptual Design

- **The first three critical speeds of each layout are calculated and compared to the operating speed of the engine core.**

- **Both layouts offer speed ranges clear of critical speeds.**
- **The advantage is minimizing vibration amplitudes during operation.**
- **Lower critical speeds are traversed quickly.**

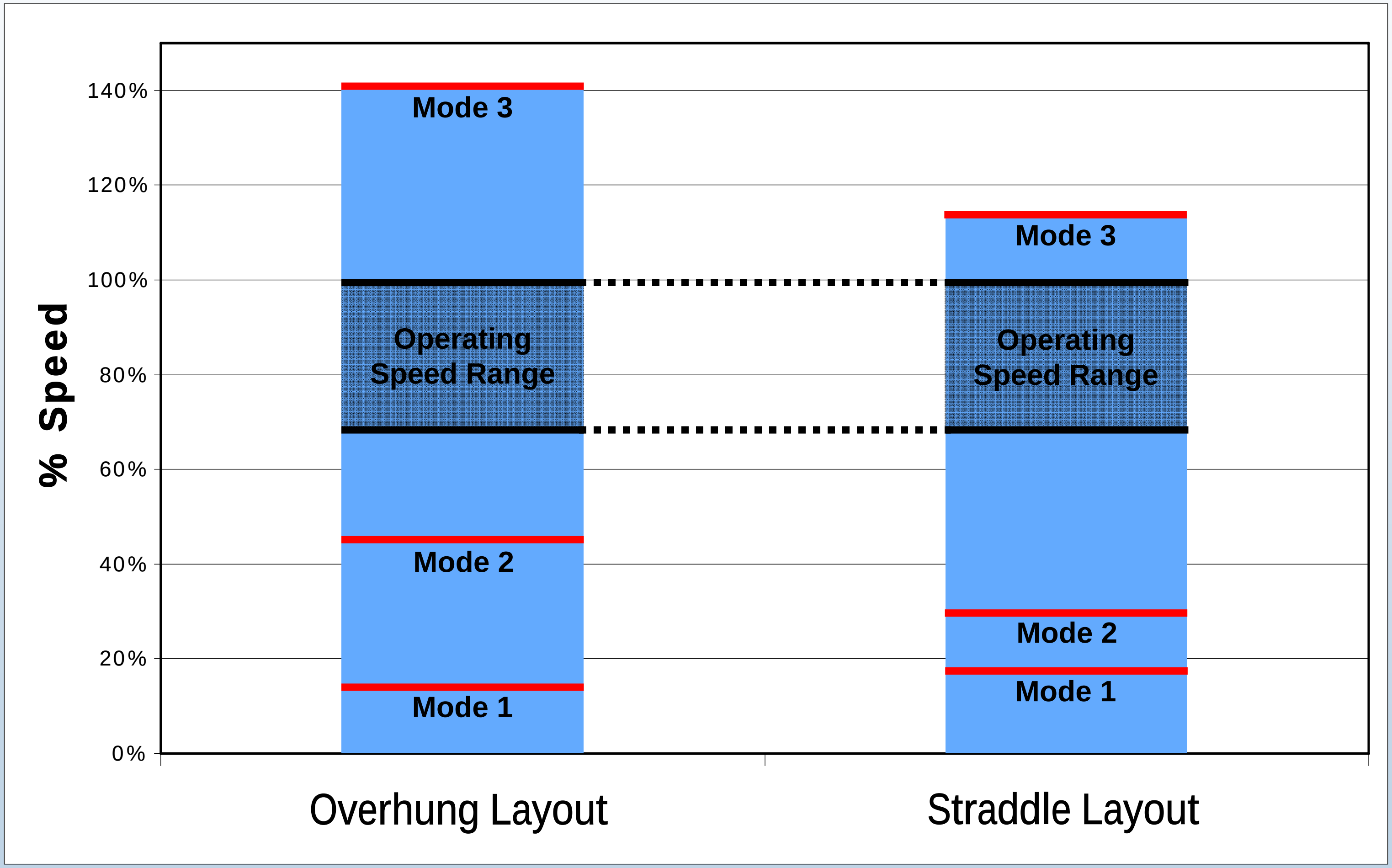
Straddle Layout Bearing Data

Speed (RPM)	Kxx(N/m) Cxx(Ns/m)	Kxy(N/m) Cxy(Ns/m)	Kyx(N/m) Cyx(Ns/m)	Kyy(N/m) Cyy(Ns/m)
Forward Bearing (64.0 mm x 50.8 mm)				
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 mm x 50.8 mm)				
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

Source: 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).

Rotordynamic System Conceptual Design

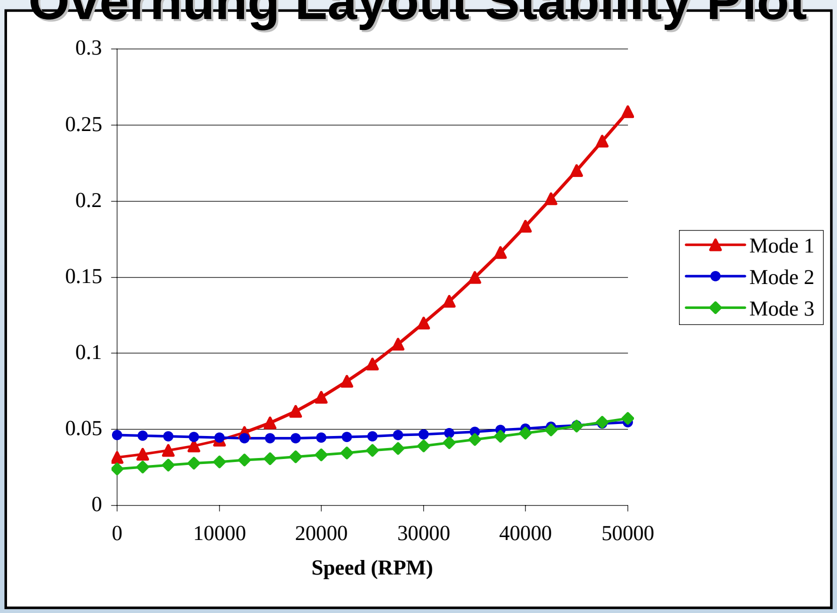
Critical speed locations in operating speed range.



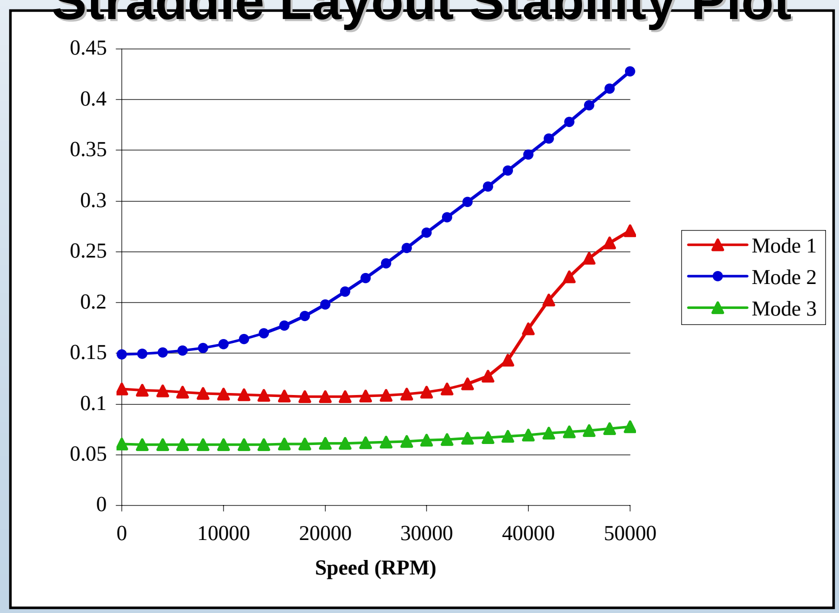
Rotordynamic System Conceptual Design

- **While the critical speed map looks good for both layouts, that is not sufficient to consider a design feasible.**
- **Stability also needs to be considered.**

Overhung Layout Stability Plot



Straddle Layout Stability Plot



Oil-Free rotor system testing at NASA Glenn Research Center

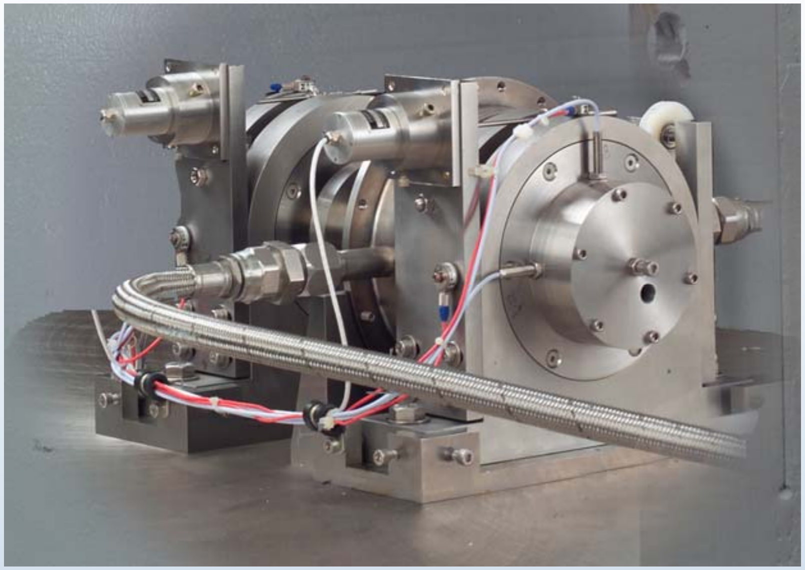
System Level Testing for Oil-Free Rotor Craft Propulsion

- Historically, much of the gas foil bearing testing and data in the literature is based upon component level tests.
  - Load capacity
  - Torque
  - Coating research
  - Stiffness and Damping
- For successful integration of gas foil bearings into engines, system level testing is needed.
  - Misalignment
  - Unbalance
  - Thermal Management
  - Stiffness and Damping

Oil-Free Rotor System Testing

Misalignment

- **A Simulator Rig was conceived and built to test the rotordynamic behavior of simulated turbomachine rotors ("dummy" compressor and turbine wheels).**
- **Current testing includes a study of the effects of misalignment of the two foil journal bearings supporting the rotor.**

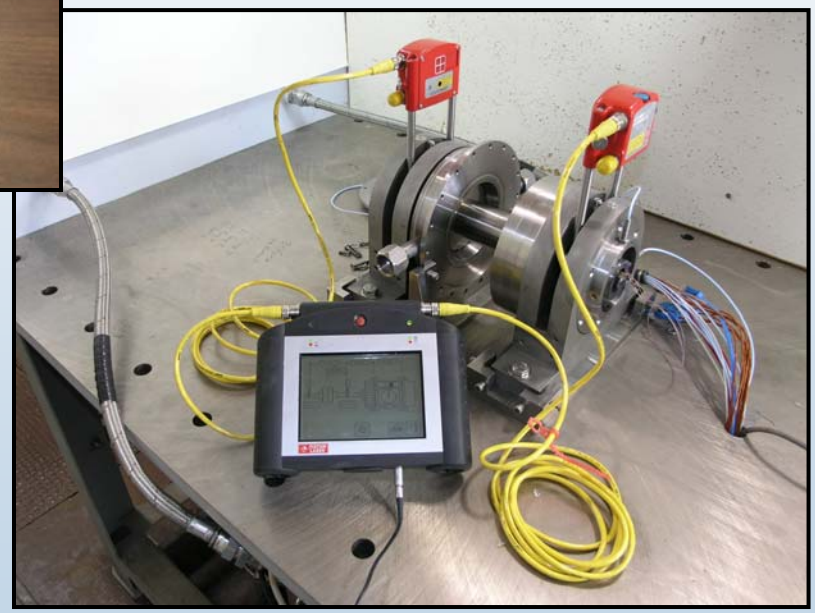


- **A laser alignment system is used to introduce lateral misalignment between the two foil journal bearings (so far up to 0.035").**
- **Bearing temperature, rotor coast down time, and dynamic response are measured to observe any effects from the misalignment.**

Oil-Free Rotor System Testing

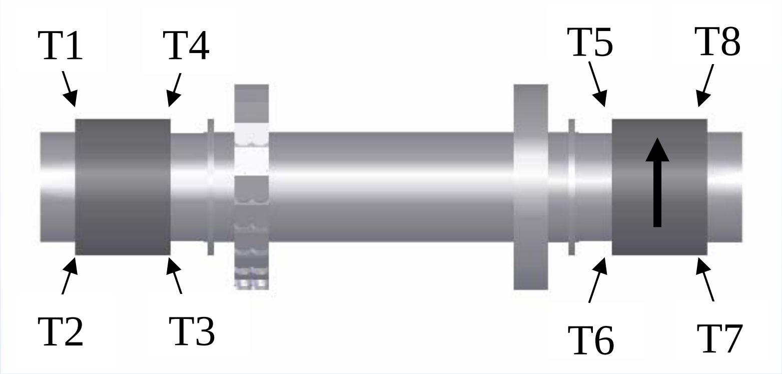
Misalignment

Rotor and bearings used in misalignment tests.

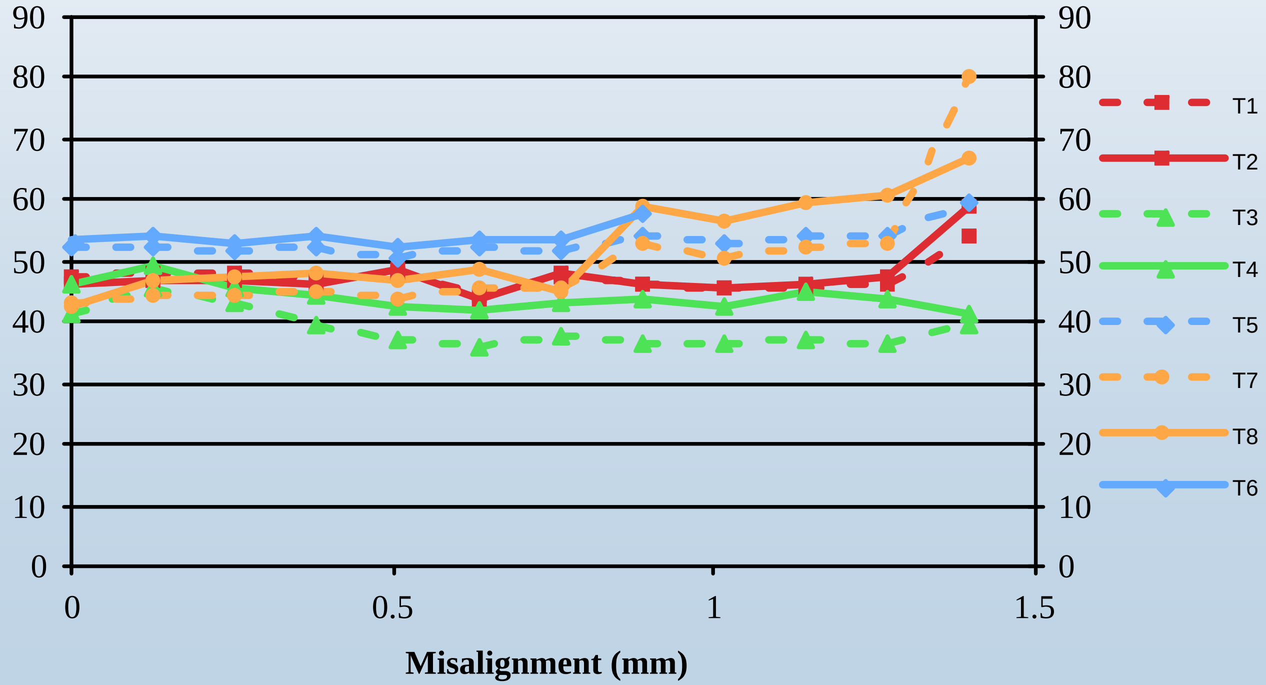


Laser alignment system used to measure the extent of misalignment

Oil-Free Rotor System Testing
Misalignment



Edge Temperature vs. Misalignment



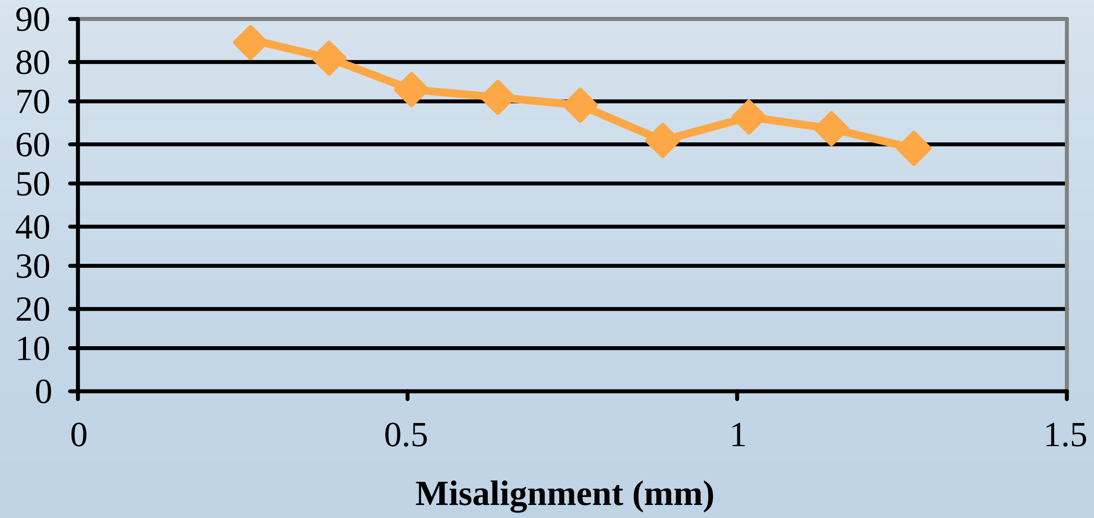
Oil-Free Rotor System Testing
Misalignment

- **Misalignment Results:**
  - **The edge temperature does not increase significantly with misalignment until failure is imminent.**
  - **The failure mode suggests a decrease in load capacity with increased misalignment.**
  - **Misalignment tolerance is expected to decrease with increased static load.**
  - **At light loads, typical of high-speed turbomachinery, foil bearings can withstand extreme misalignment with little detrimental impact (20x higher than REB).**

Oil-Free Rotor System Testing
Misalignment

- **Direct measurement of torque/power loss is currently not possible, but a decrease in coast down time indicates higher power loss with increased misalignment**

Coast Down Time vs. Misalignment



Overview of current NASA Research Announcement funded Oil-Free Rotary Wing Activities

Overview of Current NRA Oil-Free Research

- Advanced Gas Foil Bearing Analysis Tools Needed
  - Foil gas bearings are in widespread use in low temperature, benign environments in Air Cycle Machines (ACM)'s and cryogenic turboexpanders, selected micro-turbines and emerging in turbocharger applications.
  - Historical technical hurdles preventing Oil-Free RC application:
    - Dearth of foil bearing test capability (espec. @ high temp + high speed)
    - Effective, long life solid lubricants for start-stop transients
    - Inadequate manufacturing base (limited knowledge, mysterious art vs understood technology)
    - Lack of predictive design tools (applications driven by "break and bust").

Overview of Current NRA Oil-Free Research

Application Needs Summary:

- Several major OEMS currently investing to integrate foil bearings into hot sections for RC engines
  - Relying upon “black box” guidance from small foil bearing manufacturers
  - Applying “hope” and “guess” approach to hardware testing.
- All have articulated the need for open source, first principals-computationally based and validated predictive design tools for foil bearings.

Overview of Current NRA Oil-Free Research

Subtopic A.3.1.3:

- Oil-Free Engine Technology (Foil Gas Bearing Modeling)
- Objective:
  - Develop first-principles and computer based hydrodynamic models of journal bearings with elastic foundations that include thermal effects and non-linear structural coulomb friction effects and result in more accurate models of bearing behavior.

Overview of Current NRA Oil-Free Research

- Pennsylvania State University, “Thermal Effects in Gas Lubricated Foil Journal Bearing Performance.”
  - Earlier NRA (01-04) resulted in accurate isothermal foil bearing model recognized as current SOA.
  - Complete understanding of the thermal effects in foil bearings and gaps in current model.
  - PI has personal hands-on experience in manufacturing and integration leading to an appreciation of model output needs of OEMs.
  - Several value added “extra” strengths:
    - Two pronged solution approach, continuous and iterative, to reduce computational risk
    - Model designed to handle subtle engine integration issues like shaft misalignment
    - Model is independent of empirical inputs making experimental corroboration rigorous
    - Use of innovative perturbation technique used to extract stiffness and damping coefficients
    - PI has past successful experience designing experimental cases for model that can be readily accomplished using existing NASA facilities.

Overview of Current NRA Oil-Free Research

- Texas A&M University - Texas Engineering Experiment Station, “Prediction of Foil Bearing Performance: A Computational Model Anchored to Test Data.”
  - Outstanding literature review showing thorough understanding of foil bearing operation and existing modeling history.
  - Innovative simplifying approach to develop versatile and manageable code
    - Lumped thermal parameter with side cooling flow
    - 1-D finite element model for the top foil
  - Several value added “extra” strengths:
    - Empirical validation using TAMU facilities at elevated temperatures
    - Utilizes anchoring experiments to estimate (unknowable) friction effects
    - Unique and proven effective Excel based GUI’s to link Fortran codes to user
    - Model to be part of an existing and accepted suite of turbomachinery design codes already in use by OEMs through the Turbomachinery Research Consortium (TRC)

Conclusions

- **An Oil-Free rotorcraft engine coupled to a transmission using oil formulated for highly loaded gears represents an opportunity for an optimized propulsion system.**
- **Such a propulsion system would benefit from less complexity, better reliability, less maintenance, and longer life.**
- **Foil bearing technology is found to be feasible for the core of a rotorcraft class turboshaft engine, and the optimized Oil-Free engine concept warrants further analysis.**
- **Preliminary misalignment testing is completed that indicates gas foil bearings can tolerate significant amounts of misalignment compared to rolling element bearings.**
- **NRA-funded Gas Foil Bearing analysis tool development is underway.**

Acknowledgements

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www.grc.nasa.gov/WWW/Oilfree