Speaker/Presenter Contact Information:
Name: Dr. Christopher DellaCorte
Affiliation: NASA
Mailing Address: Mail Stop 23-2, 21000 Brookpark Road, Cleveland, OH 44135
Phone Number: 216-433-6056
E-mail address: christopher.dellacorte@nasa.gov

If you have any restrictions on when you need to present, please list them here.
I cannot present on the morning of May 1st. I prefer the afternoon of the 1st but could accommodate sometime on the 2nd if required.

Please indicate the Mechanical Working Group Panel affiliation this presentation should be listed under:
Aerospace Power Panel

Title: Oil-Free Turbomachinery Technologies for Long-Life, Maintenance-Free Power Generation Applications

Abstract:

Turbines have long been used to convert thermal energy to shaft work for power generation. Conventional turbines rely upon oil-lubricated rotor supports (bearings, seals, etc.) to achieve low wear, high efficiency and reliability. Emerging Oil-Free technologies such as gas foil bearings and magnetic bearings offer a path for reduced weight and complexity and truly maintenance free systems. Oil-Free gas turbines, using gaseous and liquid fuels are commercially available in power outputs to at least 250kWe and are gaining acceptance for remote power generation where maintenance is a challenge. Closed Brayton Cycle (CBC) turbines are an approach to power generation that is well suited for long life space missions. In these systems, a recirculating gas is heated by nuclear, solar or other heat energy source then fed into a high-speed turbine that drives an electrical generator. For closed cycle systems such as these, the working fluid also passes through the bearing compartments thus serving as a lubricant and bearing coolant. Compliant surface foil gas bearings are well suited for the rotor support systems of these advanced turbines. Foil bearings develop a thin hydrodynamic gas film that separates the rotating shaft from the bearing preventing wear. During start-up and shut down when speeds are low, rubbing occurs. Solid lubricants are used to reduce starting torque and minimize wear. Other emerging technologies such as magnetic bearings can also contribute to robust and reliable Oil-Free turbomachinery. In this presentation, Oil-Free technologies for advanced rotor support systems will be reviewed as will the integration and development processes recommended for implementation.

Oil-Free Turbomachinery Technologies for Long-Life, Maintenance-Free Power Generation Applications

by
Dr. Christopher DellaCorte
Glenn Research Center at Lewis Field
Cleveland, Ohio

May 1st, 2013
IAPG
Cleveland, OH

Background

NASA's goals to Revolutionize Aviation and enhance Access to Space are supported by the development of revolutionary Oil-Free Turbomachinery Propulsion and Energy systems.

Definition

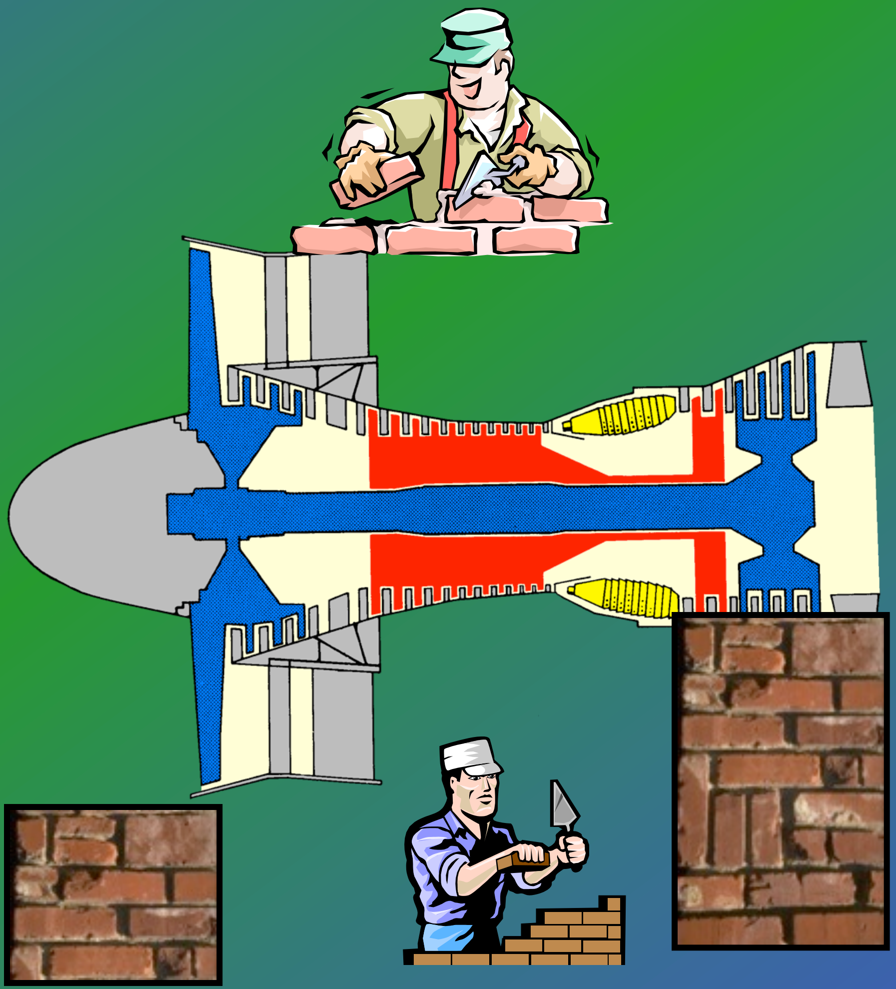
Oil-Free Turbomachinery is defined as "high speed rotating equipment operating without oil lubricated rotor supports…bearings, dampers, seals…"

Approach

Capitalize on recent breakthroughs in Foil Air Bearings, Tribological Coatings and Analytical Modeling to enable high speed, high temperature Oil-Free Turbomachinery systems.

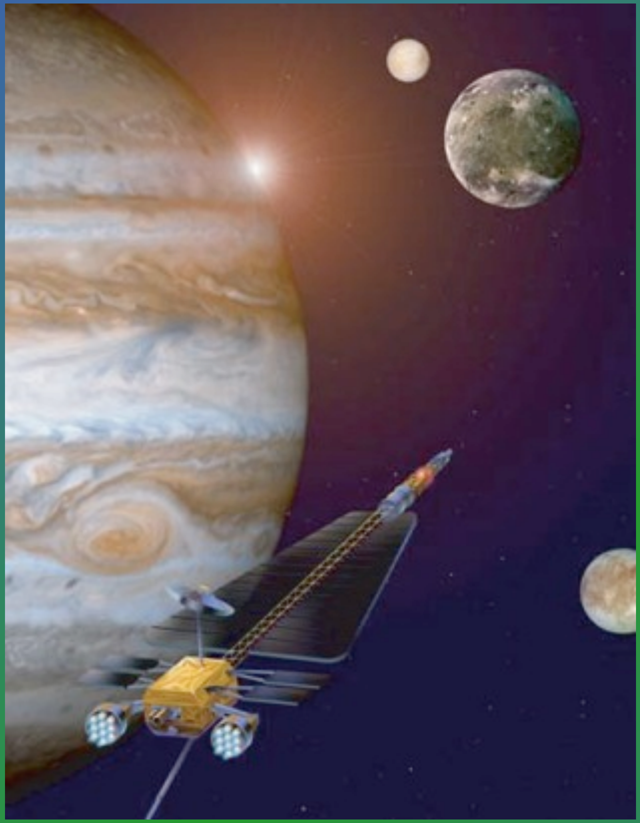
Turbomachinery Rotor Support System

- **The rotor support system is the foundation upon which the engine** *(compressor, combustor, turbine)* **is built**

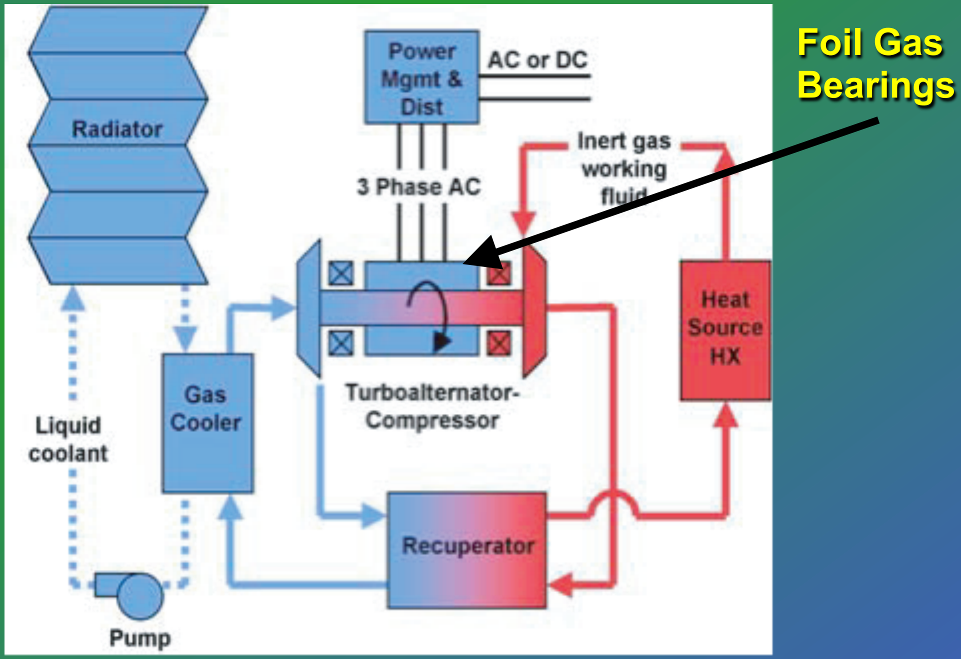


Oil-Free Turbomachinery

Nuclear Power for Space Applications

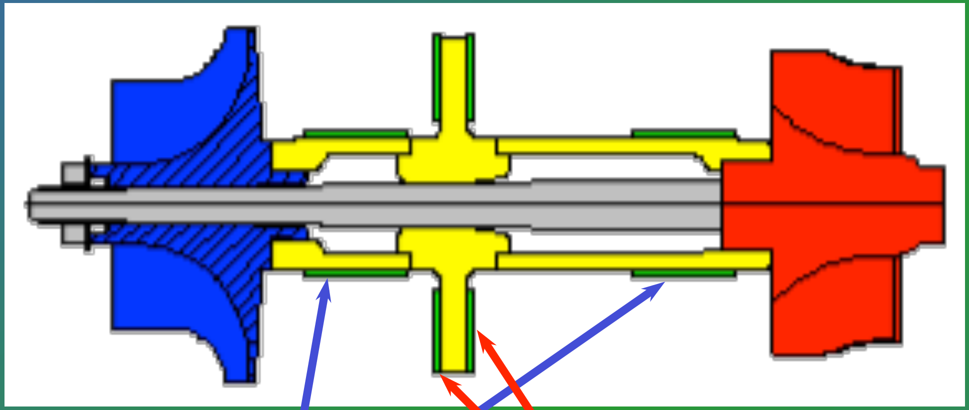


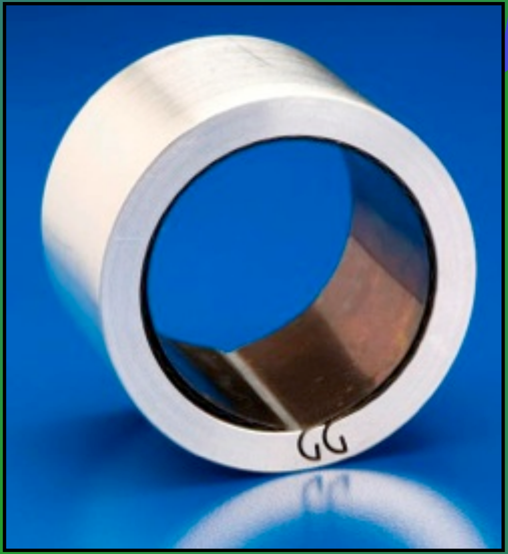
Artist's Conception of JIMO, Jupiter Icy Moon Orbiter



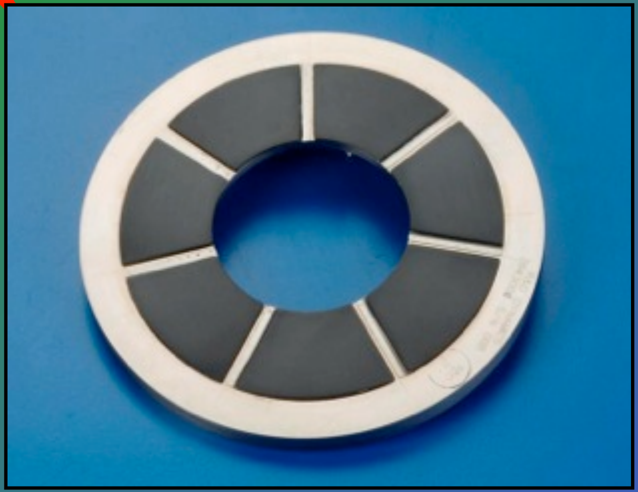
Power system uses foil gas bearings for Oil-Free turbine

Journal & Thrust Foil Bearings





Journal Foil Bearing



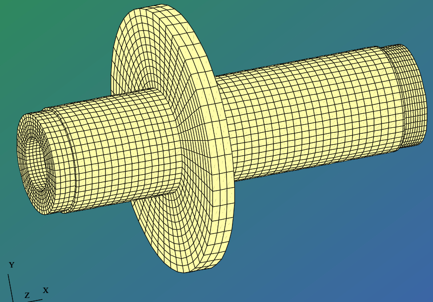
Thrust Foil Bearing

Enabling Technology Breakthroughs

- **Advanced Foil Bearings**
  - Load capacity has doubled

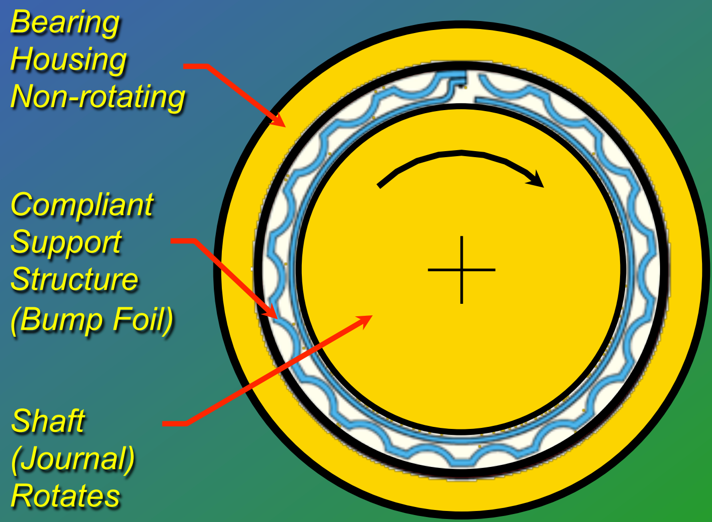
- **High-Temperature Solid Lubricant Coating**
  - NASA PS400, 100,000 start/stops, 25 °C to 650 °C

- **Analytical & Rotordynamic Modeling**
  - Less time, risk & cost from concept to application

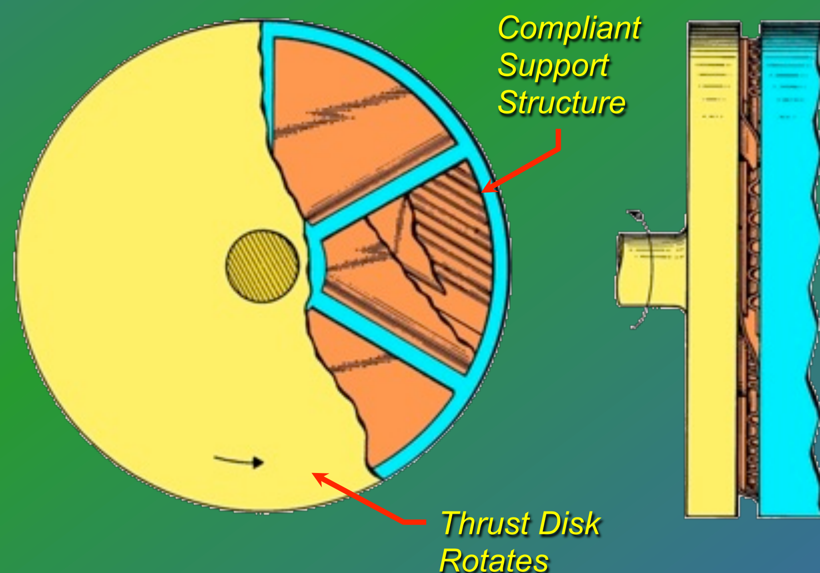


Enabling Technology: Advanced Foil Bearings

Foil Journal Bearing



Foil Thrust Bearing



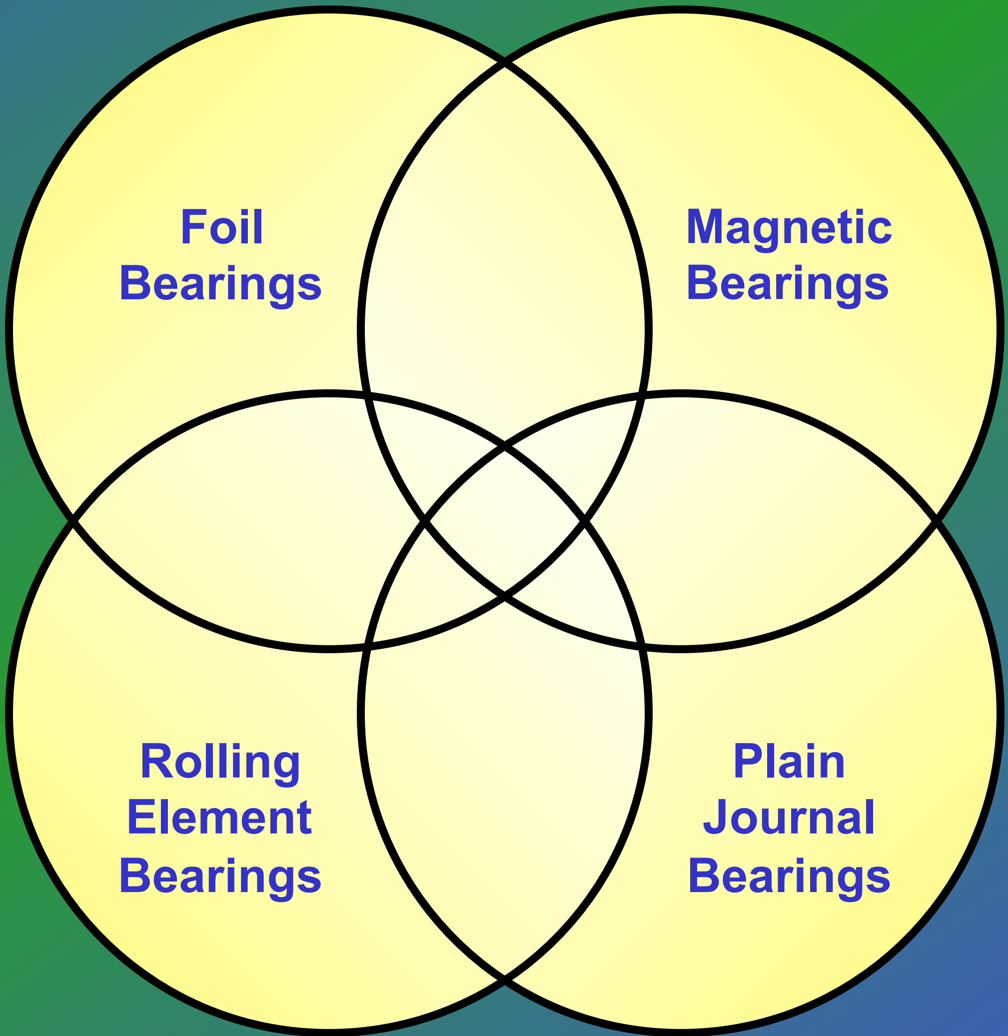
Foil Bearing Benefits:

- ✓ Self-acting hydrodynamic "float on air" ➔ No external pressurization
- ✓ No DN speed limit ➔ Higher power density
- ✓ No lube/tanks/coolers/plumbing/filters ➔ Lower weight
- ✓ Operate to 650 °C ➔ Higher efficiency
- ✓ Compliant "spring" foil support ➔ Accommodate misalignment & distortion
- ✓ No maintenance ➔ Reduce operating costs

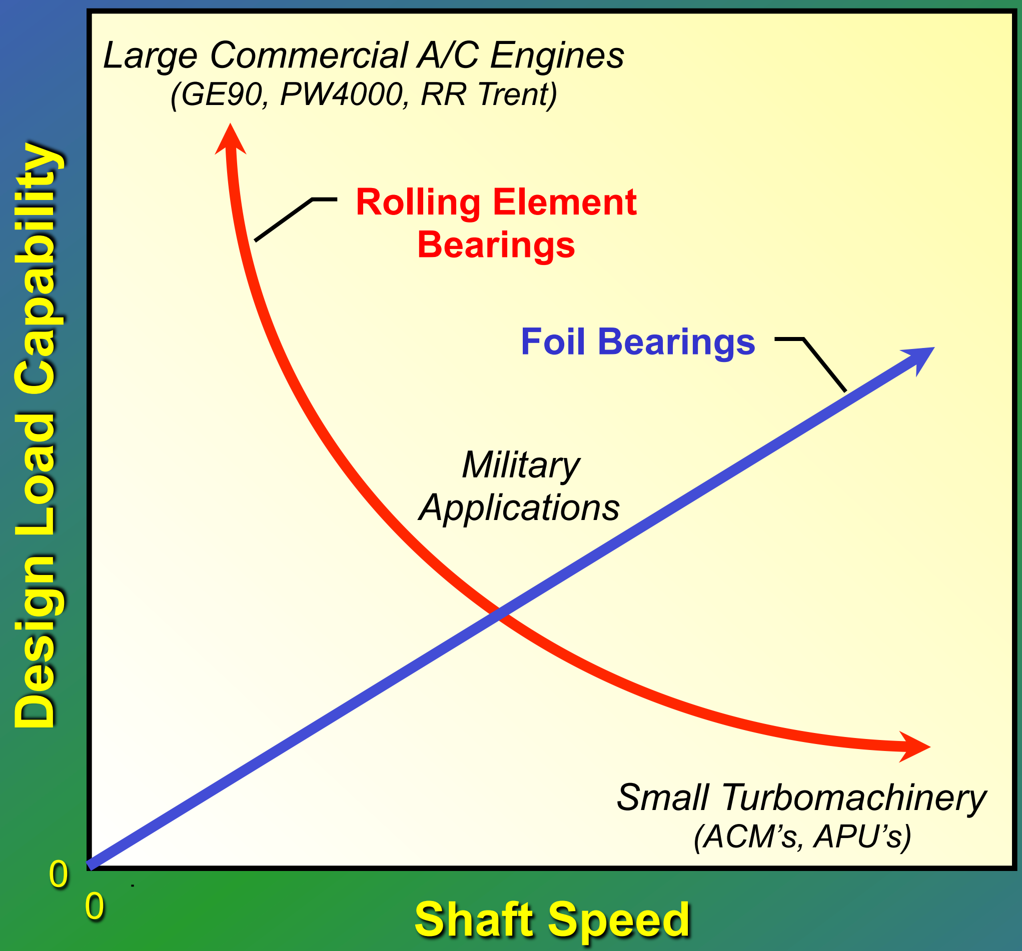
Source, Thrust Bearing Sketch: Fortmann, US Patent #4,082,375, Apr. 4, 1978

Bearing Characteristics

Commonality & Unique Features



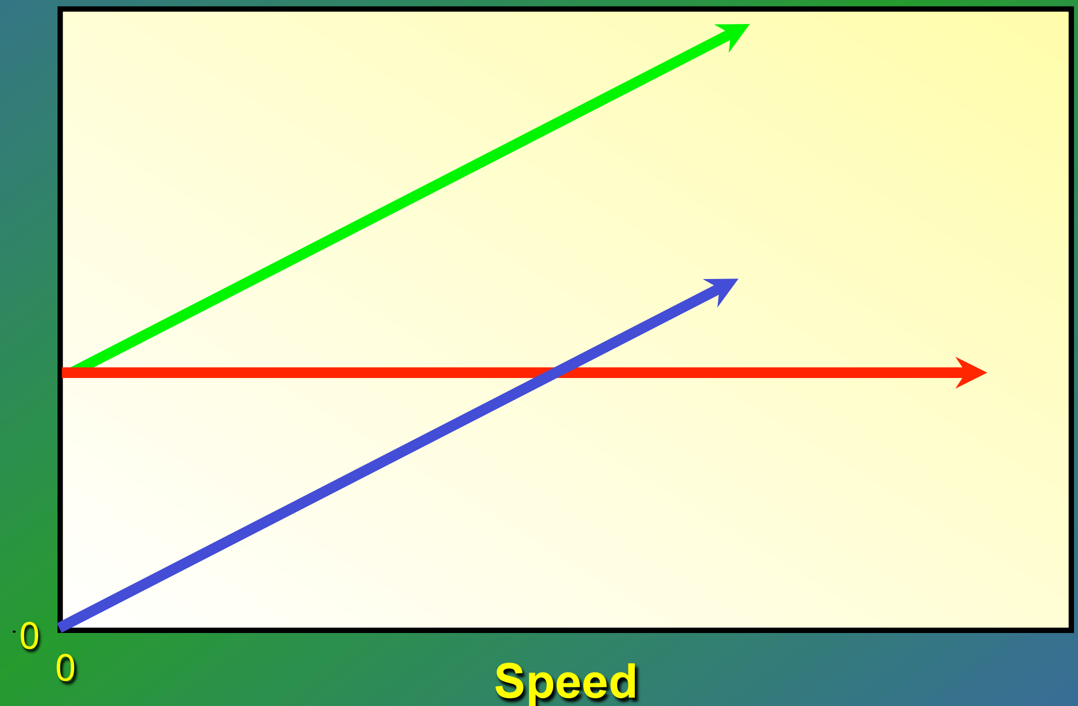
Bearing Characteristics Comparison



- Foil bearings cannot retrofit into large engines – new engine designs needed
- Foil bearings need solid lubricant at startup/shutdown
- Foil bearings outperform rolling element bearings at high speeds

Bearing Characteristics Comparison – Mag & Foil

- Magnetic Bearings Load Capacity
- Foil Air Bearings Load Capacity
- Hybrid Foil/Mag Load Capacity



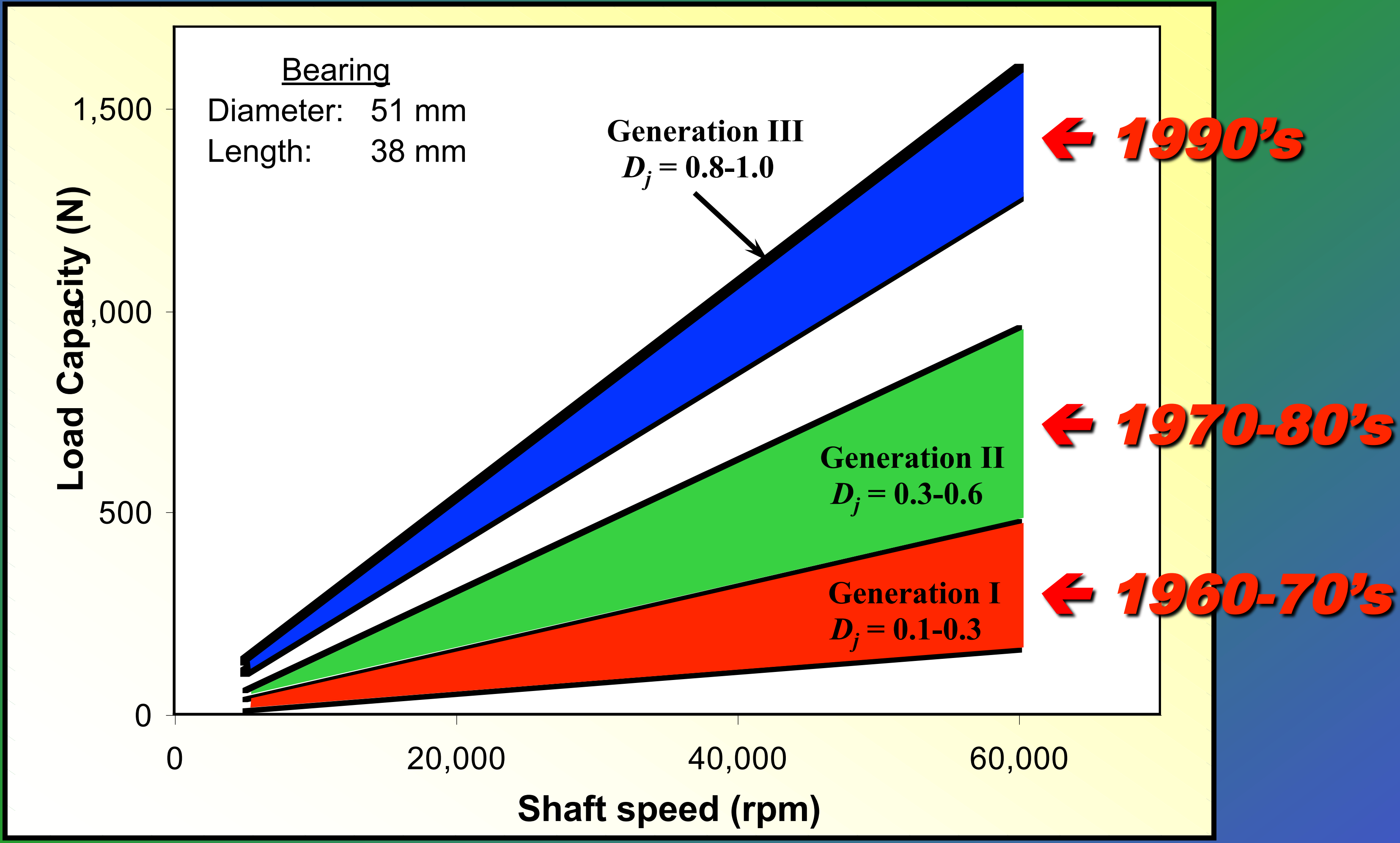
Magnetic Bearing Load Capacity

- Independent of shaft speed
- Controllable stiffness and damping
- Susceptible to shock overloads
- Requires back-up bearing

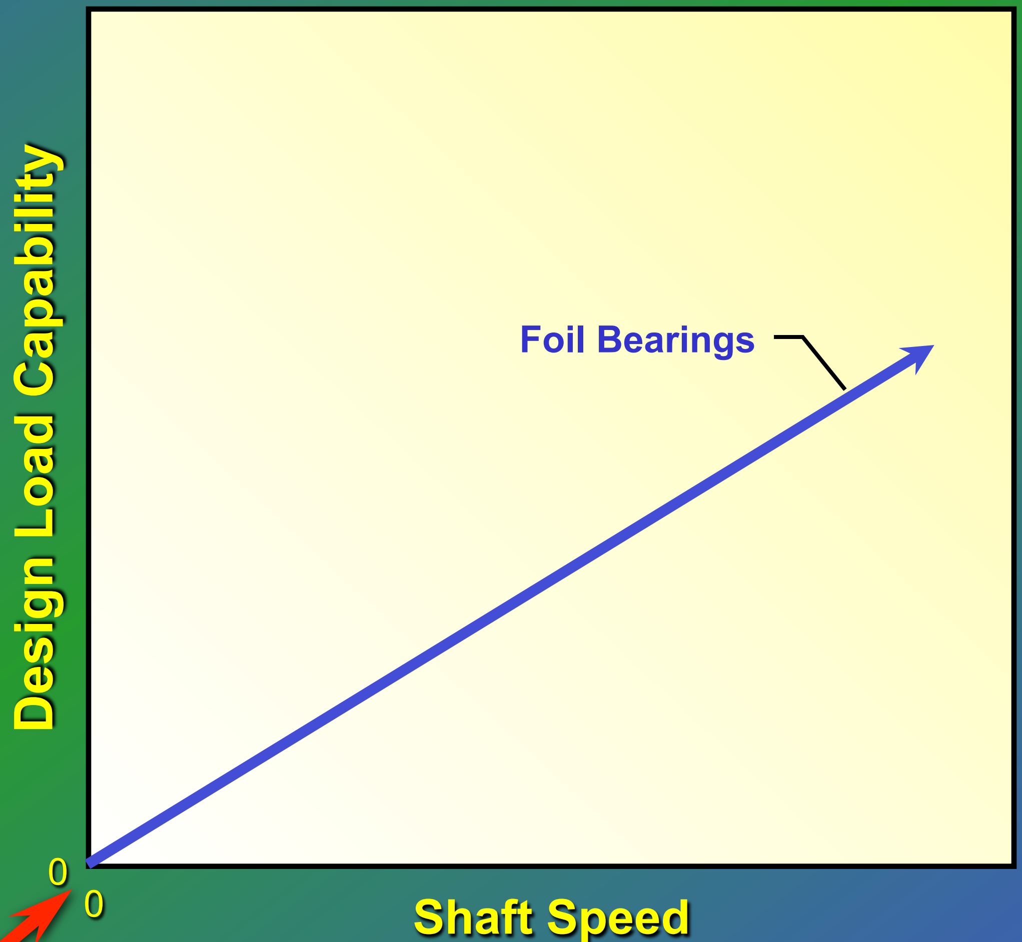
Foil Bearing Load Capacity

- Very low at low speeds
- Increases linearly with speed

Foil Bearing Load Capacity – Generation I, II, & III



Foil Bearing Load Capacity Characteristics



Solid lubricant coating needed for long life

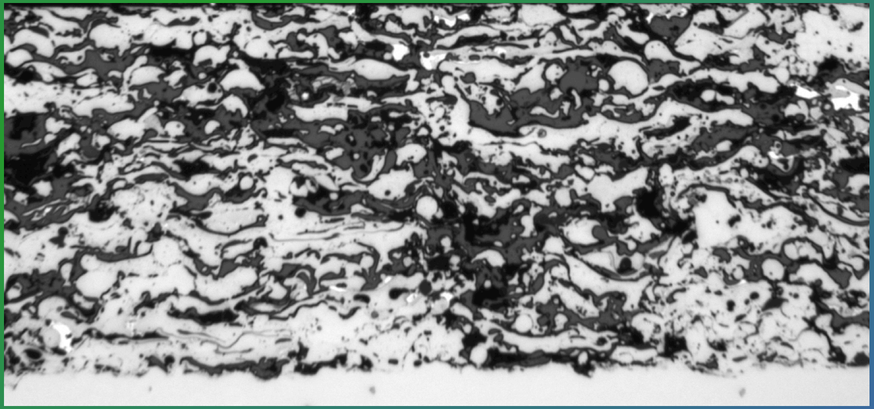
PS400 High-Temperature Solid Lubricant Coatings

- Provide start/stop wear protection for foil bearings
- Operate from cold start to 650°C
- No vaporization or emissions

NASA PS400 *US Patent No. ???*

70% NiMoAl	Binder
20% Cr_2O_3	Hardener
5% BaF_2/CaF_2	Hi-Temp Lube
+ 5% Ag	Low-Temp Lube

= Wide temperature spectrum solid lubricant coating



. . . PS400, the latest generation coating has been proven in maintenance-free, trouble-free engine tests for over 20,000hr

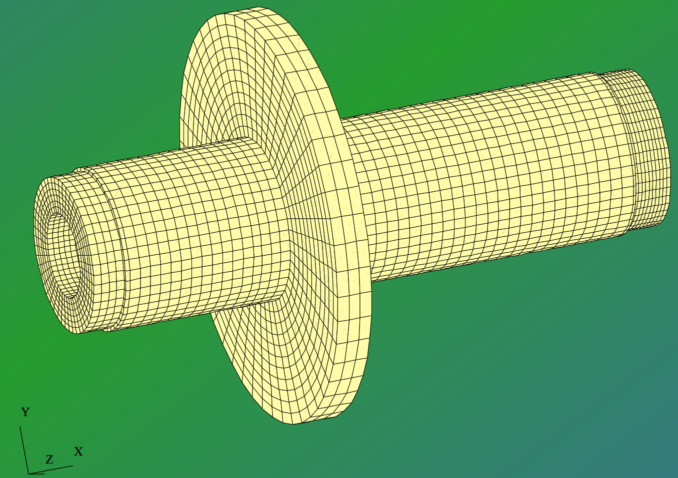
Glenn Research Center Foil Bearing Test Rig

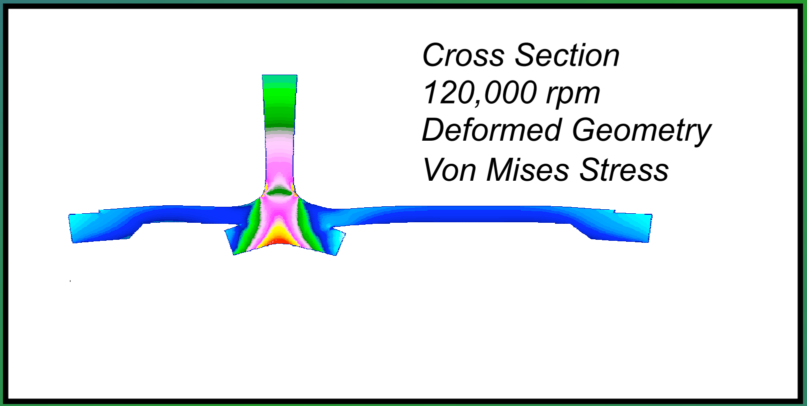
(oven cover opened for photograph)

Enabling Technology: Analytical & Rotordynamic Modeling

Advances in . . .

- Finite Element Methods
- Rotordynamic Analysis
- Hydrodynamic Gas Film Calculations



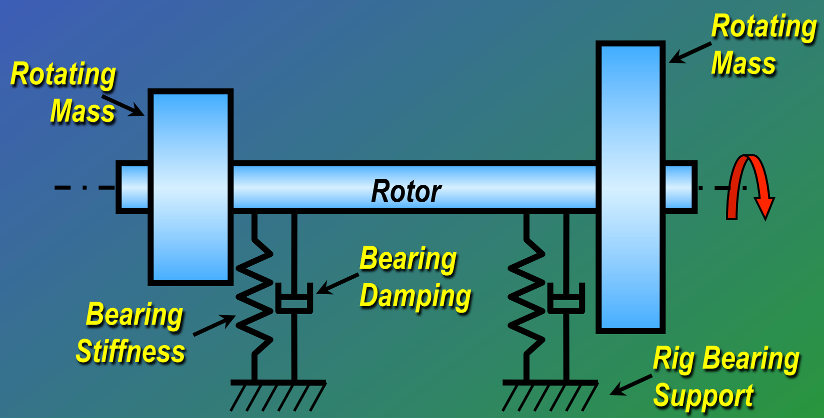


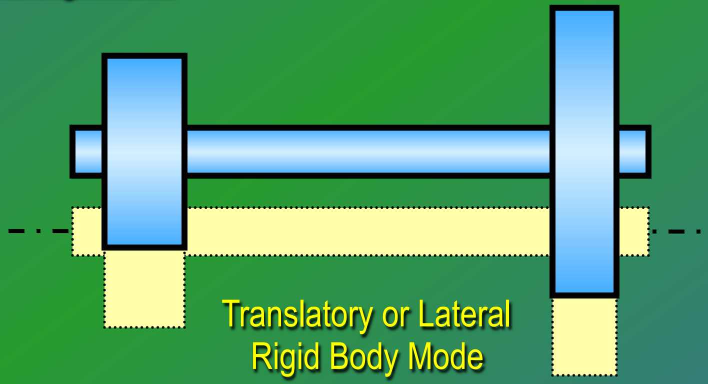
Allow prediction of . . .

- Bearing Characteristics *(stiffness, damping)*
- Mechanical and Thermal Distortions and Stresses
- Rotordynamic Performance

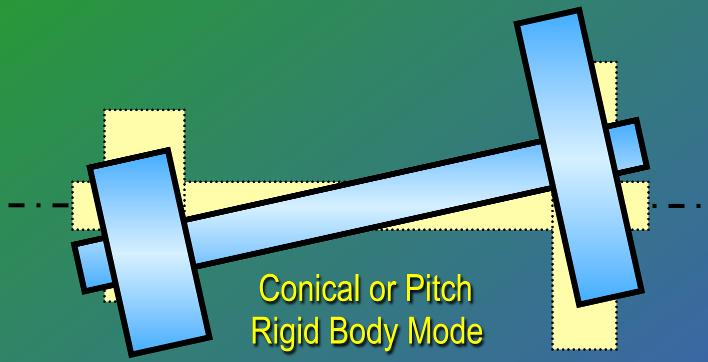
. . . Concurrent analytical methods provide the opportunity to "test" new designs without a risky "make & break" hardware approach

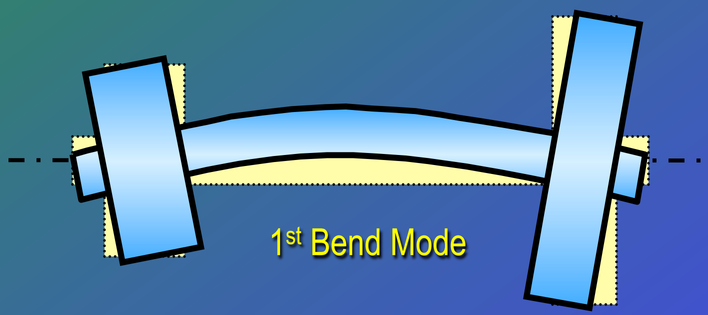
Rotordynamic Analysis





- **Rotor system critical speeds and natural frequencies** *(modes)* **are controlled by:**
  - **Shaft/disk masses and locations**
  - **Shaft geometry and material** *(stiffness)*
  - **Bearing stiffness** *(including rig structural stiffness)*
  - **Bearing damping**
  - **Operating speed**
- **Goal is to design a rotor system** *(shaft & bearings)* **that provides stable operation across the operating range**





Oil-Free Turbomachinery Technology Path

Air Cycle Machines (ACM's)

1970's

- Clean Oil-Free Cabin Air
- High Reliability
- Maintenance Free

Turbocompressors

1980's

- No Process Fluid Contamination
- Cryogenic Capability
- Long Life

Turbogenerators

1999

- Low Emissions
- Lightweight
- Maintenance Free

Turbochargers

2010

- Mounting Orientation Freedom
- No Particulate Emissions
- High Temperature

Small Gas Turbine Engines

2015

- High Speed
- Low Cost
- Maintenance Free

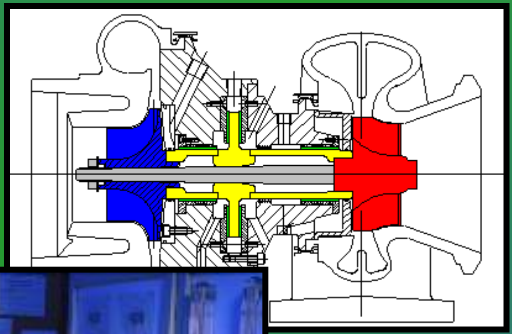
Mid-Range & Large Engines

2020

- High Temperature & High Speed
- Design Architecture Freedom
- Revolutionary Engines

...Starting a Turbomachinery Revolution...

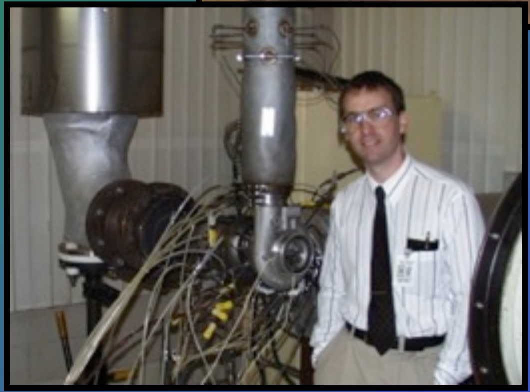
Oil-Free Technology Integration Approach



1) Rotor System Conceptual Design & Feasibility Study

2) Bearing Integration & Testing

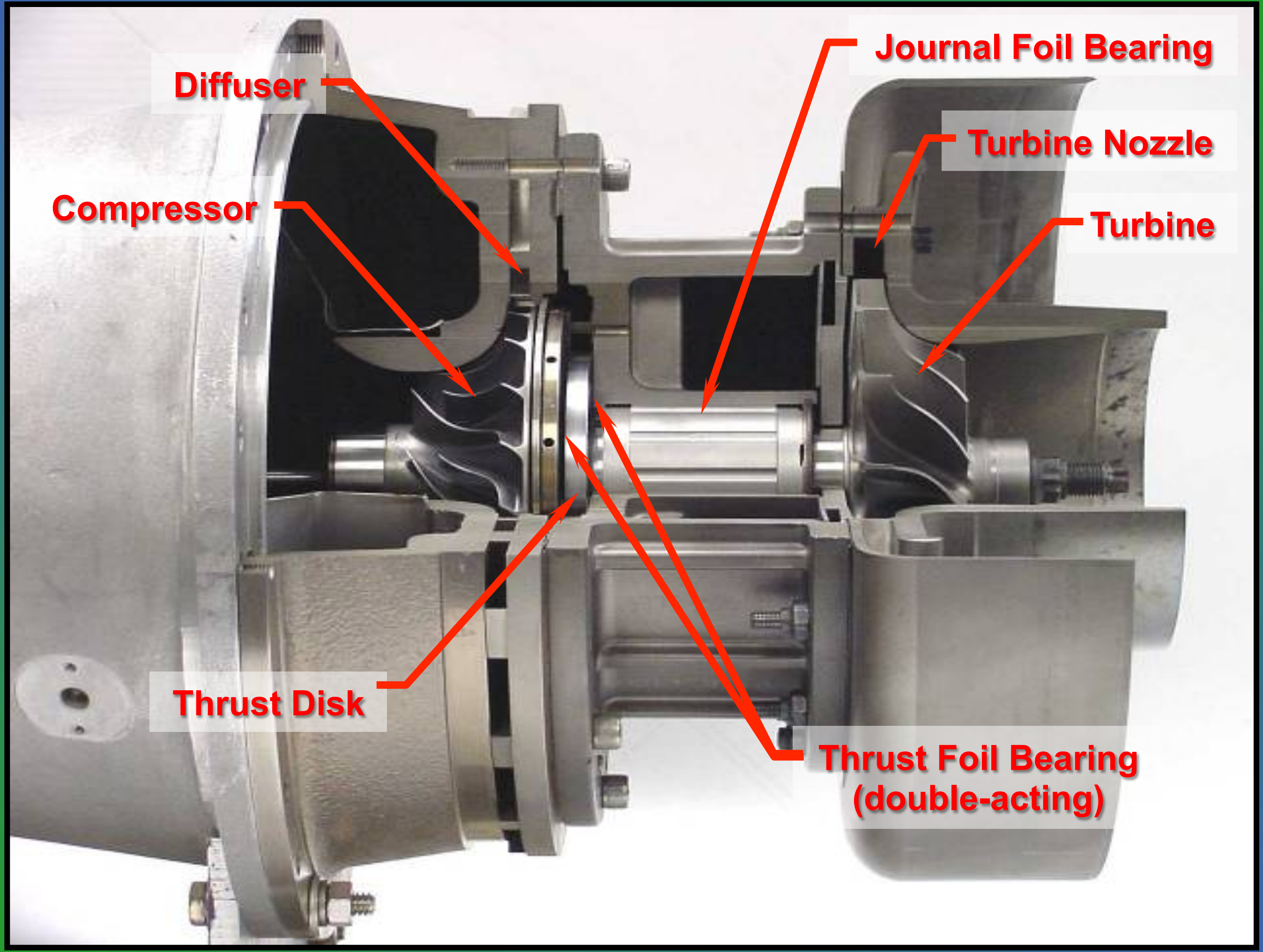
3) Rotordynamic System Simulation



4) Oil-Free Technology Demonstration

Where is Oil-Free Turbomachinery Headed?

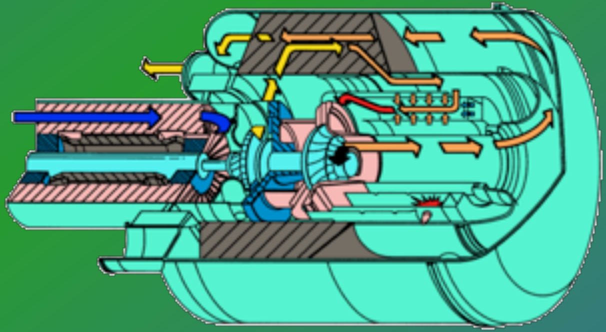
Capstone 30kW MicroTurbine



Capstone turbines used as coatings test bed at NASA. PS304 coated shaft tests initiated in 1998.

NASA GRC Operating Capstone MicroTurbine

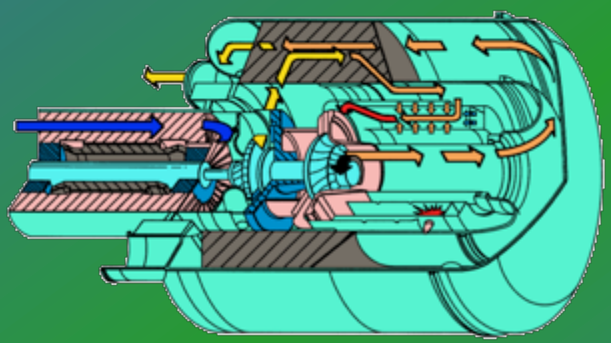
- 30 kW unit installed
- In use since 2001 to develop PS300. Results led to PS400 development
- Currently, NASA PS400 coating on engine shaft surfaces



- Engine tests drive coating development.

Capstone MicroTurbines: 30kWe to 1MWe

- 30 kWe marketed since ~1999
- 60kWe model ~2003
- 200kWe model ~2009
- Multiple units palletized together for 1MWe systems



- Advanced development on higher power, higher efficiency systems.

Oil-Free Turbomachinery Program

Automotive OEM's are going Oil-Free

TOYOTA CRDL., INC.
TECHNICAL NEWS

Air Bearing for Automotive Turbocharger

Minoru Ishino

1. Introduction

The application of oil-free bearings such as air or magnetic types to automotive turbochargers is expected to realize a reduction in mechanical losses while eliminating oil consumption. As a result, engines fitted with oil-free turbochargers will offer an improved response and lower fuel consumption and exhaust emissions. We have designed compliant foil air bearings with uniquely shaped dampers for the journal and thrust bearings of small-sized turbochargers (**Figs. 1** and **2**).

2. Method

First, we undertook a rotational test of a prototype turbocharger with air bearings. The results of this test revealed the need to increase the load capacity of the thrust air bearing relative to that of the journal bearing. To solve this problem, we used 3D computational fluid dynamics to analyze the effects of the film thickness distribution between the bearing and runner surfaces of the thrust air bearing on the generated pressure distribution, so as to increase the load capacities of the bearing.

3. Results and conclusion

Numerical analyses revealed three effective methods of increasing the load capacity, namely, increasing the size of the fluid charge in the bearing, generating the maximum pressure at the center of the bearing surface, and preventing the leakage of the fluid in the radial direction of the bearing surface. To realize these three improvements, we devised a new thrust bearing design with a shallow squared groove leading from the leading edge to the center of the bearing surfaces of the topmost foil. **Figure 3** shows the calculated pressure distributions on the surfaces of the thrust bearings both with and without the groove. The grooved bearing allows fluid to enter the bearing surface over a wider area and increases the amount of fluid by 70% relative to that without the groove. Because the groove does not link the circumferential edges or interrupt the center of the bearing surface, there is basically no radial leakage of fluid in the groove and the maximum pressure is generated at the center of the bearing. Numerical analyses with the grooved foil bearing indicated a 1.5-times increase in the maximum pressure and a 2.5-times increase in the load capacity, relative to the conventional bearing. **Figure 4** shows a trial version of the improved bearing together with a conventional version, both of which were installed in a turbocharger and then evaluated experimentally. A turbocharger with the improved bearing has been run at a rotational speed up to 200,000 rpm.

(Report recieved on Jul. 3, 2006)

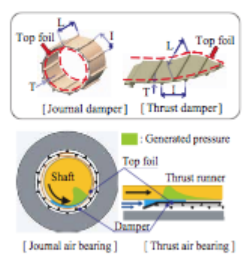


Fig. 1 Compliant foil bearings.

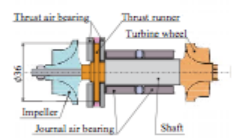


Fig. 2 Construction of air bearings for turbocharger.

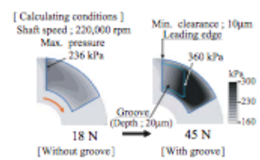


Fig. 3 Comparison of load capacity (calculated).

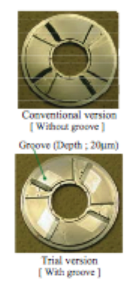


Fig. 4 Test peaces of compliant foil thrust bearing.

This news is reported on R&D Review of Toyota CRDL Vol.41 No.3.

Oil-Free Turbomachinery Program

- Turbochargers are emerging
- High volume application will improve manufacturing
- Competition will drive technology forward.
- New bearings designed for high volume and low cost.
- Significant development for Oil-Free turbomachinery.

US007108488B2

(12) **United States Patent**
Larue et al.

(10) **Patent No.: US 7,108,488 B2**
(45) **Date of Patent: Sep. 19, 2006**

(54) **TURBOCHARGER WITH HYDRODYNAMIC FOIL BEARINGS**

(75) Inventors: **Gerald Duane Larue**, Torrance, CA (US); **Sun Goo Kang**, Los Angeles, CA (US); **Werner Wick**, Torrance, CA (US)

(73) Assignee: **Honeywell International, Inc.**, Morristown, NJ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/812,281**

(22) Filed: **Mar. 26, 2004**

(65) **Prior Publication Data**

US 2005/0210875 A1 Sep. 29, 2005

(51) **Int. Cl.**

F02B 17/00	(2006.01)
F02B 33/44	(2006.01)
F16C 32/06	(2006.01)
F02B 35/00	(2006.01)
B61F 17/00	(2006.01)

(52) **U.S. Cl.** **417/407**; 60/605.1; 384/103; 384/105; 384/106

(58) **Field of Classification Search** 417/407; 384/103–106, 535, 119, 160; 123/572, 559.2; 60/684, 605.1
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,375,046	A	*	3/1968	Marley	384/105
3,740,163	A	*	6/1973	Schinnerer et al.	417/407
4,167,295	A	*	9/1979	Glaser	384/105
4,170,389	A		10/1979	Eshel	384/104
4,402,618	A		9/1983	Fortmann et al.	384/107
4,573,808	A	*	3/1986	Katayama	384/114
4,608,827	A	*	9/1986	Hasegawa et al.	60/605.1
4,850,721	A	*	7/1989	Malabre et al.	384/106
5,014,518	A	*	5/1991	Thomson et al.	60/684
5,102,305	A	*	4/1992	Bescoby et al.	417/407
5,131,807	A		7/1992	Fischer et al.	417/407
5,140,968	A	*	8/1992	Doan	123/572
5,427,455	A	*	6/1995	Bosley	384/103
5,529,464	A	*	6/1996	Emerson et al.	384/106
5,857,332	A		1/1999	Johnston et al.	417/407
5,890,881	A	*	4/1999	Adeff	417/407

(Continued)

FOREIGN PATENT DOCUMENTS

GB 2335710 9/1999

(Continued)

OTHER PUBLICATIONS

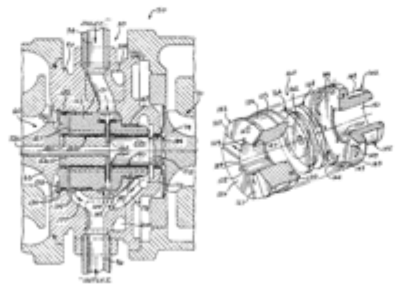
Copy of International Search Report & Written Opinion for PCT Application No. PCT/2005/010145; Filed Mar. 28, 2005; Date of Completion Jun. 27, 2005; Date of Mailing Sep. 21, 2005.

Primary Examiner—Thai-Ba Trieu
(74) *Attorney, Agent, or Firm*—Chris James

(57) **ABSTRACT**

A turbocharger includes a foil bearing assembly mounted in a center housing between a compressor and a turbine of the turbocharger. The bearing assembly forms a unit installable into the center housing from one end thereof, and the center housing is a one-piece construction. The bearing assembly includes a foil thrust bearing assembly disposed between two foil journal bearings. The journals foils are mounted in annular bearing carriers fixedly mounted in the center housing. A radially inner portion of a thrust disk of the thrust bearing assembly is captured between a shaft and a shaft sleeve of the turbocharger. The center housing defines cooling air passages for supplying cooling air to the foil bearings, and optionally includes a water jacket for circulating engine coolant through the center housing.

10 Claims, 4 Drawing Sheets



Oil-Free Turbomachinery Program

- **Capstone C30 turbine generator integrated with full size minivan**
- **Plug-in hybrid approach (batteries, controls, regenerative braking) yields impressive performance**
- **First Oil-Free car, a sign of the future, never needs service.**

Photo Release -- Capstone C30 Successfully Integrated Into Ford Vehicle by Langford Performance Engineering Ltd. 6/11/09 2:15 PM

GlobeNewswire
A NASDAQ OMX COMPANY

Login Register
HOME SERVICES NEWSROOM ABOUT US CONTACT US Search

Capstone

Source: Capstone Turbine Corporation

Photo Release -- Capstone C30 Successfully Integrated Into Ford Vehicle by Langford Performance Engineering Ltd.

CHATSWORTH, Calif., June 11, 2009 (GLOBE NEWSWIRE) -- Capstone Turbine Corporation (www.capstoneturbine.com) (Nasdaq:CPST), the world's leading clean technology manufacturer of microturbine energy systems, today announced that its C30 liquid fueled microturbine has been successfully integrated into a Ford S-Max people carrier in the United Kingdom.

A photo accompanying this release is available at http://www.globenewswire.com/newsroom/prs/?pkgid=6263

To see a promotional video of the "Whisper" please click on the following link: http://www.capstoneturbine.com/whisper_promo.wmv

Langford Performance Engineering (www.lpengines.com), headquartered in Wellingborough England, designed and modified the Ford S-Max seven seat crossover vehicle into a series hybrid plug in vehicle with a C30 under the hood as an electric range extender. Langford reports that the "Whisper Eco-Logic" car gets up to 80 mpg in early stage demonstration testing.

"The Ford modified by Langford is an extremely practical solution and one that Langford has been working on for over two years," said Jim Crouse, Capstone's Executive Vice President, Sales and Marketing. "The design characteristics of Capstone's turbine permits ultra low emissions, high fuel economy, multi fuel capability, no coolants or lubricating oil, and little to no maintenance in an automotive application," added Crouse.

"Our Whisper Eco-Logic vehicle is a plug in electric car with an on board turbine generator to keep the batteries charged and extend the range of the car beyond that of a typical electric vehicle," said Dick Langford, Langford's Founder and Managing Director. "This sets it apart from the hybrids now available such as the Lexus and Toyota which use conventional 4 stroke engines to provide both vehicle drive and battery charging. In early demonstration testing the car is getting up to 80 miles per gallon and travels 40 miles on electric power before the Capstone turbine generator starts up and charges the lithium ion batteries," added Langford.

"Capstone was founded on the concept of a C30 powering hybrid vehicles so it is extremely gratifying to see the Langford Ford with a C30 under the hood," stated Darren Jamison, Capstone's President and Chief Executive Officer. "Langford did an exceptional job integrating the turbine, power electronics and batteries into the vehicle without impacting any of the seven seats or increasing the overall vehicle weight," added Jamison.

Langford Engineering will be marketing and demonstrating the plug in hybrid vehicle in hopes of further developing this concept with a suitable automotive partner who could commercialize the product for U.S. use and capitalize on a portion of the Obama administration's $2.4 billion outlined in the stimulus fund to get more electric vehicles on U.S. roads.

Images

Capstone Powered Hybrid Electric Vehicle

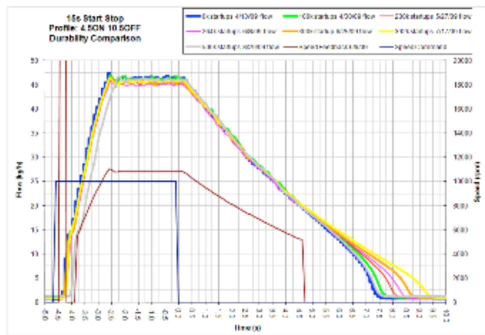
Other Company Press Releases

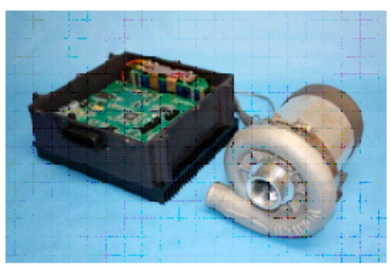
- Capstone Signs First C1000 Factory Protection Plan Pushing Long Term Service Backlog Over $11 Million - Jun 9, 2009
- Capstone Expands Southeast Asia Distribution -- Names Aqua Nishihara Its Distributor in Thailand - Jun 2, 2009
- Capstone Turbine to Announce Fourth Quarter & Fiscal Year 2009 Results On June 15, 2009 - Jun 1, 2009
- Capstone Completes Underwriters Laboratories (UL) Scheduled Testing of the C200 Product - Jun 1, 2009
- Capstone Receives Order for C200 Microturbines for

http://www.globenewswire.com/newsroom/news.html?d=167104 Page 1 of 2

Foil Bearing Life: Neuros Oil-Free Blower Bearings 1,000,000+ cycles

Title	Neuros Air Foil Bearings Successfully Passed 500,000 cycles of Start/Stop Durability Test	**View**	650
Name	Neuros co,. Ltd	**Date**	2009-09-03

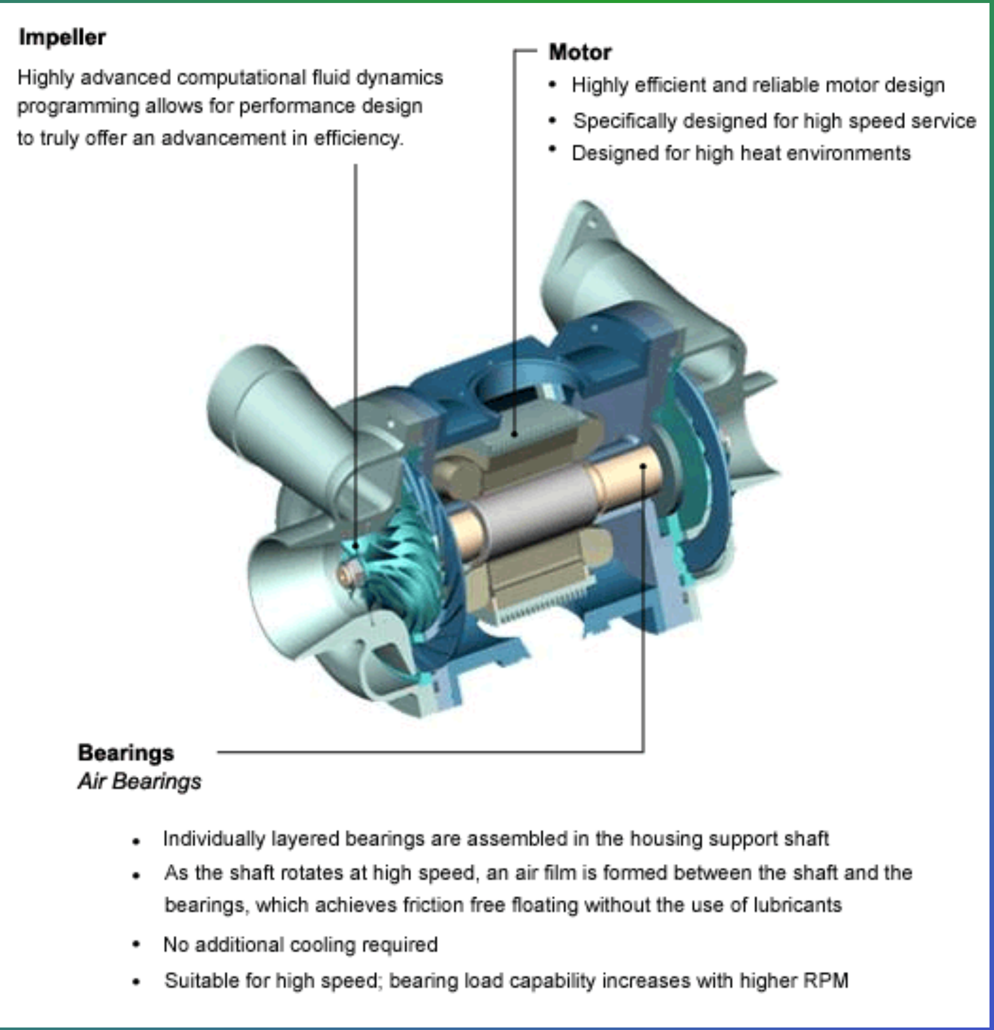




*Neuros Air Foil Bearings Successfully Passed 500,000 cycles of Start/Stop Durability Test

Neuros air foil bearings have been employed in a 15kW air compressor under development for application to automotive PEM Fuel Cells. The bearings passed 500,000 cycles of start/stop durability test without any kind of abnormal symptom on Aug. 24 2009, which is absolutely a world new record in terms of durability cycle numbers for air foil bearings. The test, started on Apr. 13 2009, has been conducted for nearly four months with scheduled teardown inspections, and continues until the end of the life. This experimental result proudly contributes to widening the application spectrum of air foil bearings.

Oil-Free Turbomachinery Program



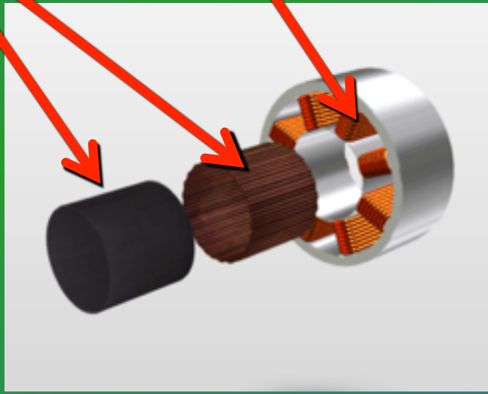
Air compression industry OEM's are going Oil-Free

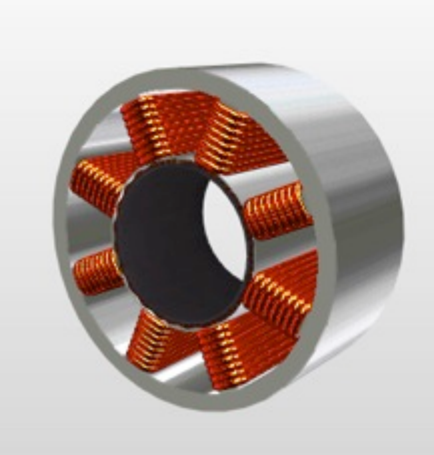
Findings

- Foil bearing development programs to support compressor industry and emerging turbine industry.
  - Example: Smart bearings developed that combine electromagnetic damper with foil bearing; an outgrowth of MiTi-NASA pioneering work from 2001.

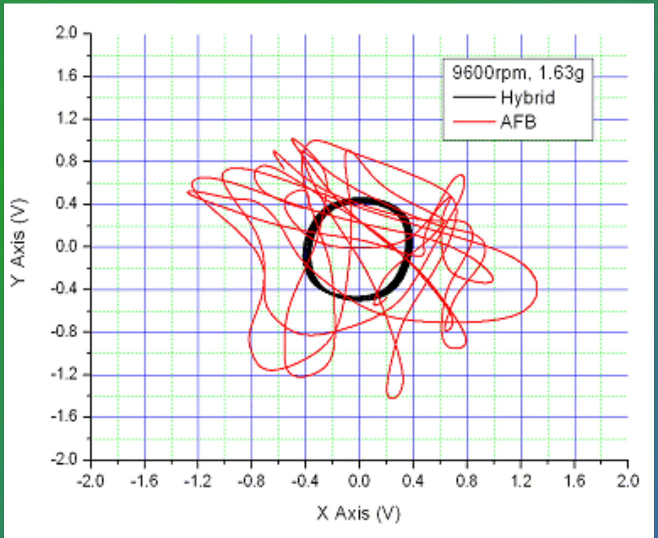
Foils

EM Damper





Smart Bearing actively damps vibrations and controls shaft orbit



Smart EMD bearing exploded (top) and assembled (bottom

Summary

- Oil-Free technology is enabling for high speed rotors of ever increasing size and complexity.
- Research over the last three decades led to a strong understanding of the governing principles, limits and design rules for foil bearing application.
- Driven largely by Oil & Gas industry, magnetic bearing application has matured and can readily be used alongside gas bearings for future systems.
- As more commercial applications for Oil-Free turbomachinery systems mature, technology will develop and advance.

…Starting a Turbomachinery Revolution…