Oil-Free Enabling Technology:

Gas Foil Bearings

by

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GOAL

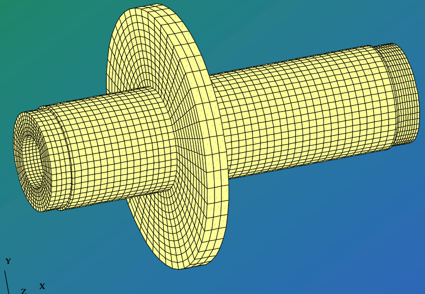
Transfer Oil-Free technologies into widespread industrial applications to enable their maturation and eventual growth “back into” aerospace.

Enabling Technology Breakthroughs

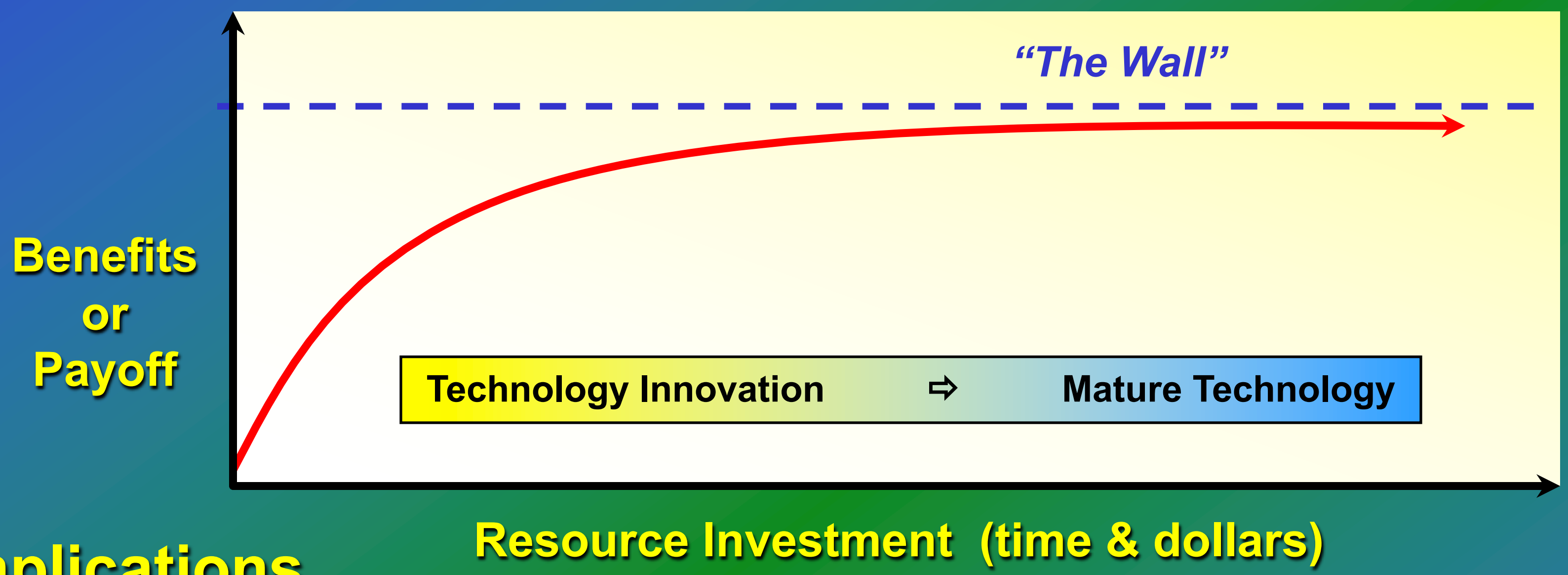
- **Advanced Foil Bearings**
  - Load capacity has doubled

- **High-Temperature Solid Lubricant Coating**
  - NASA PS400, low cost, durable, subzero to 1400°F

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



Technology Learning Curve



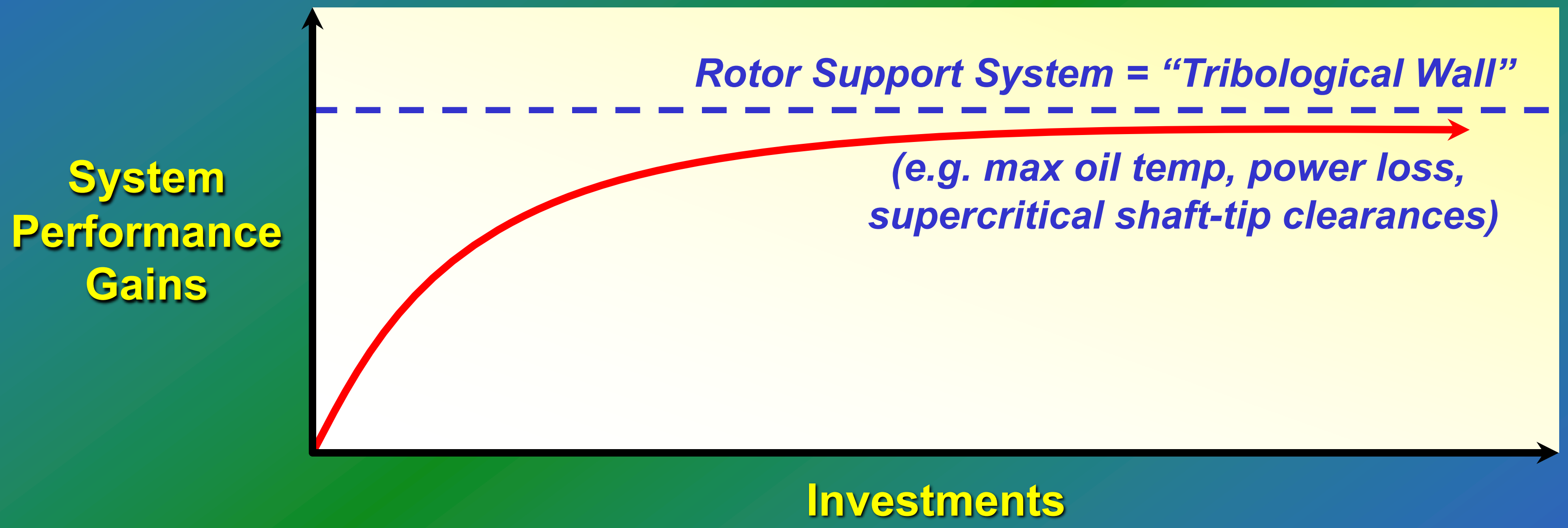
Implications

- When technology matures performance stagnates
- Profit margins drop leading to less innovation
- Technology is copied by competition
- Lower cost suppliers win market share

How can this be prevented/reversed?

Problem: Technology Maturation

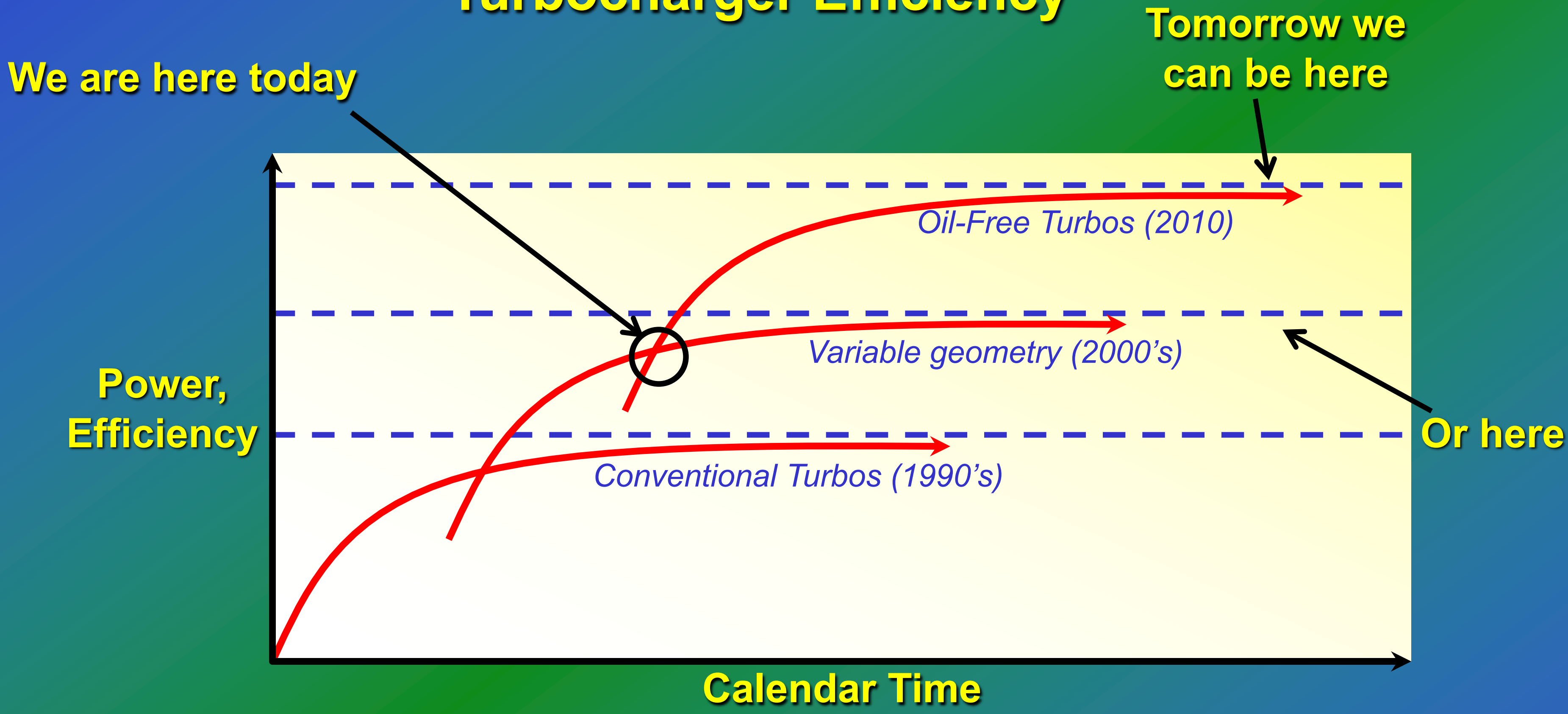
- Rotor support system has been largely unchanged for decades contributing to a maturation of turbocharger technology and performance



Solution:

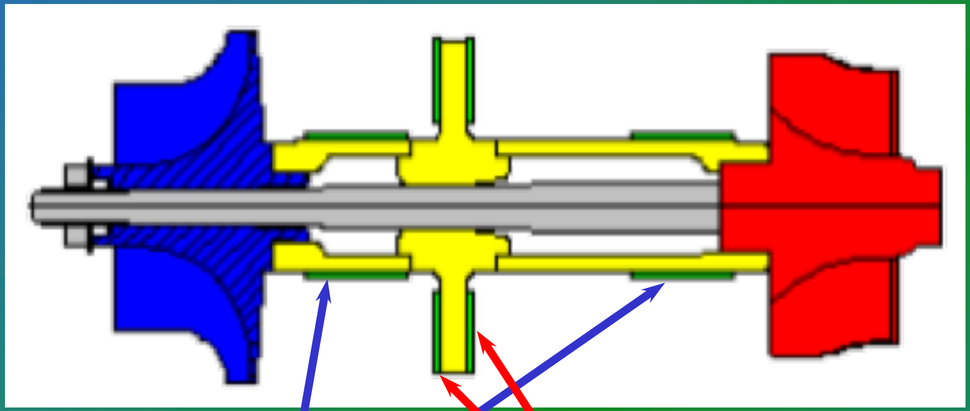
Technology maturation limits can only be overcome through adoption of new foundation technologies

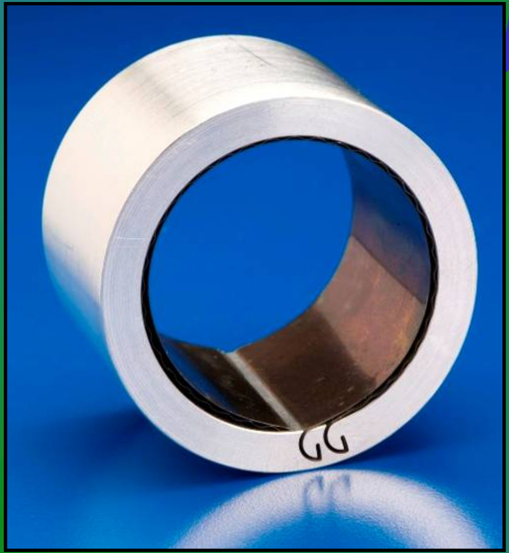
Turbocharger Efficiency



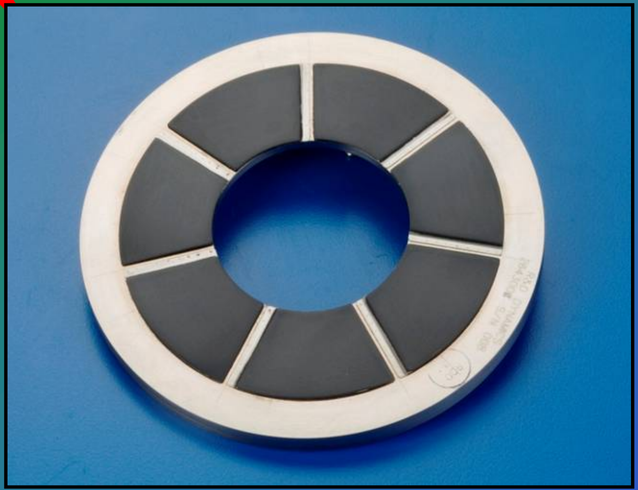
Investing in Oil-Free technology today will determine where your products will be in five years

Journal & Thrust Foil Bearings





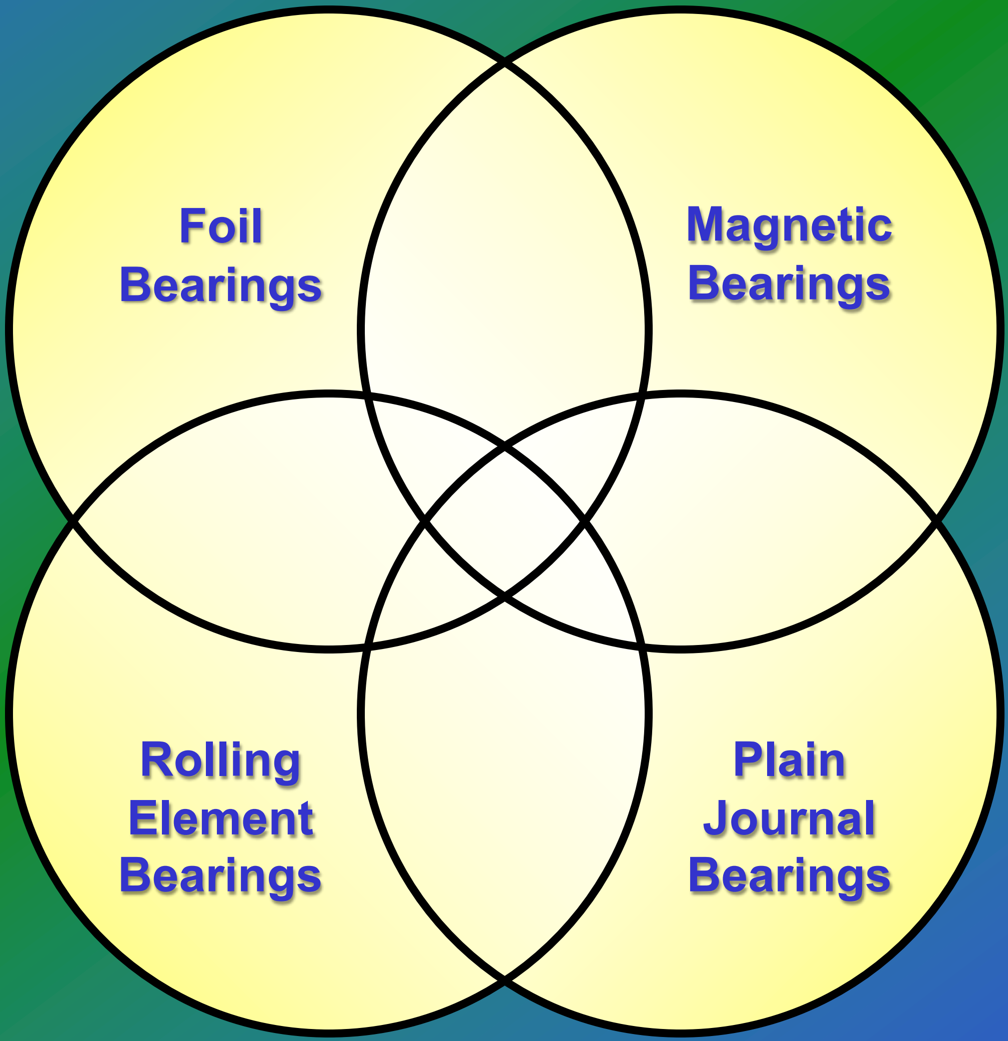
Journal Foil Bearing



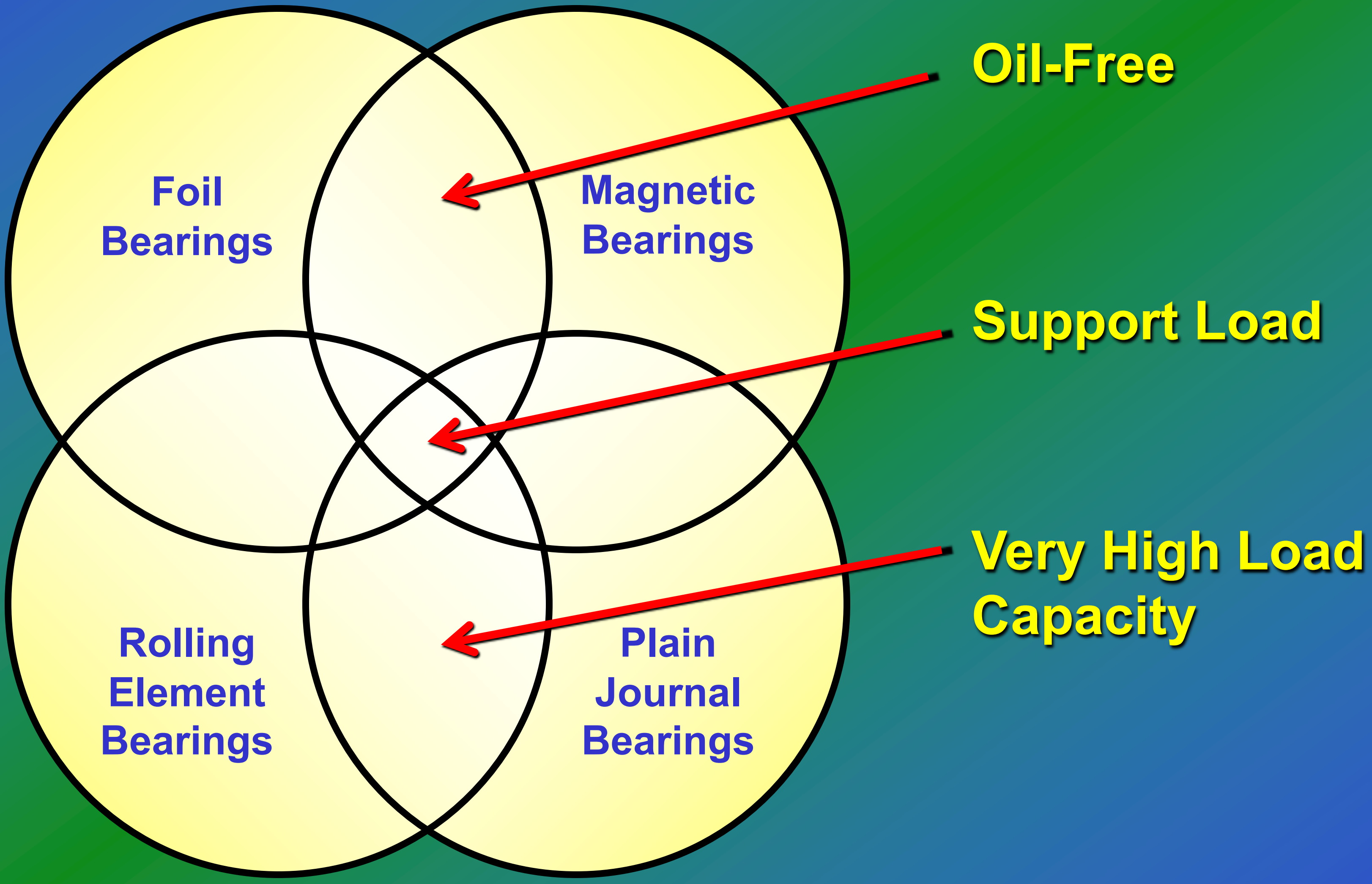
Thrust Foil Bearing

Bearing Characteristics

Commonality & Unique Features



Common Features

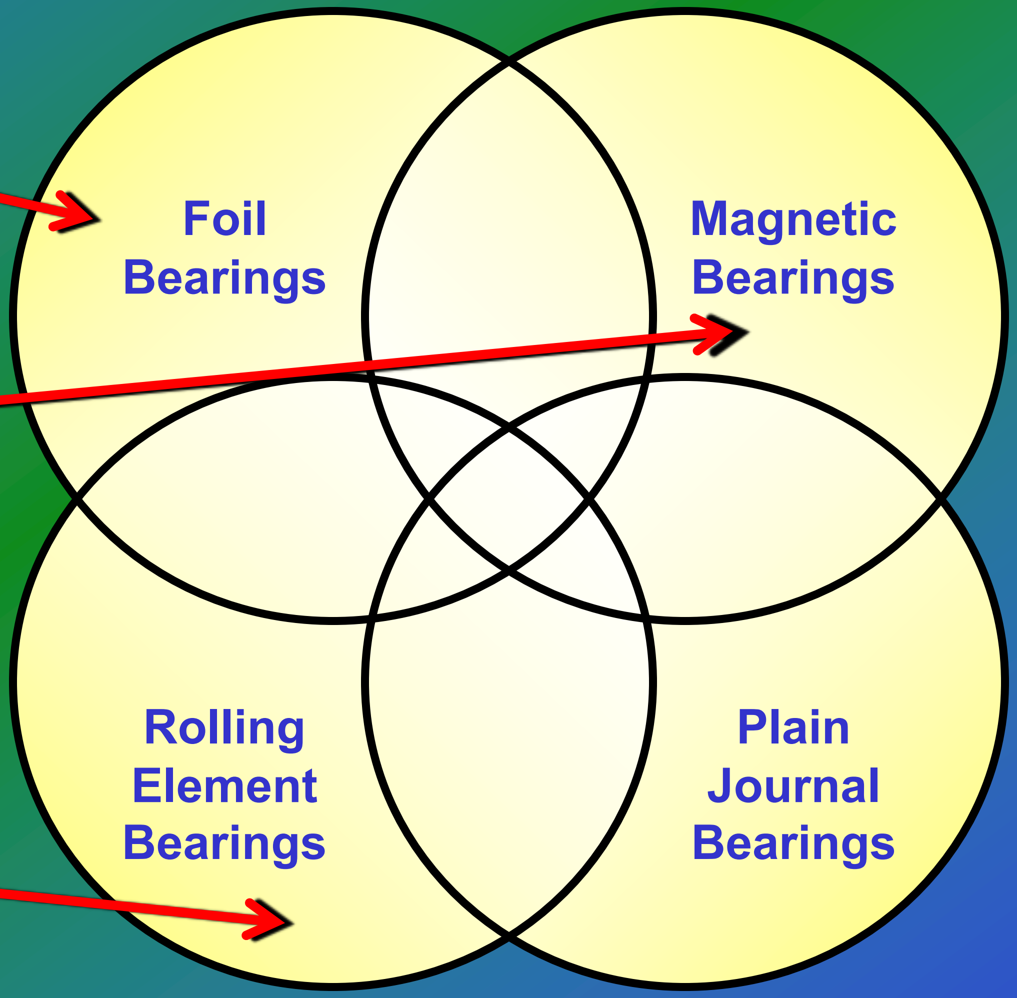


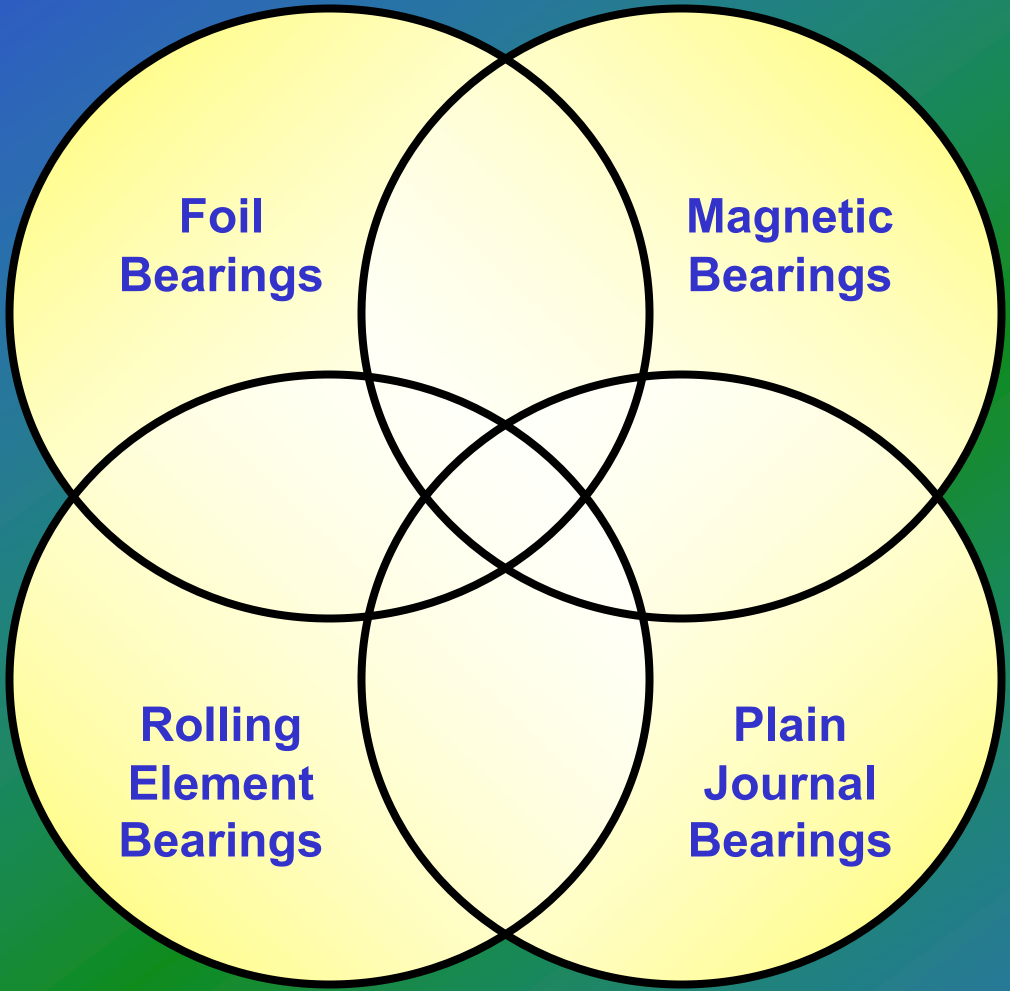
Unique Features

High/Low Temperature, lightweight, high-speed

Active stiffness and damping

Shock and overloads (short time) ok.

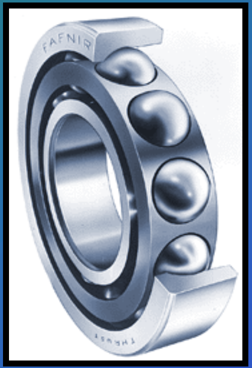




Cannot simply replace one bearing type for another without major redesign.

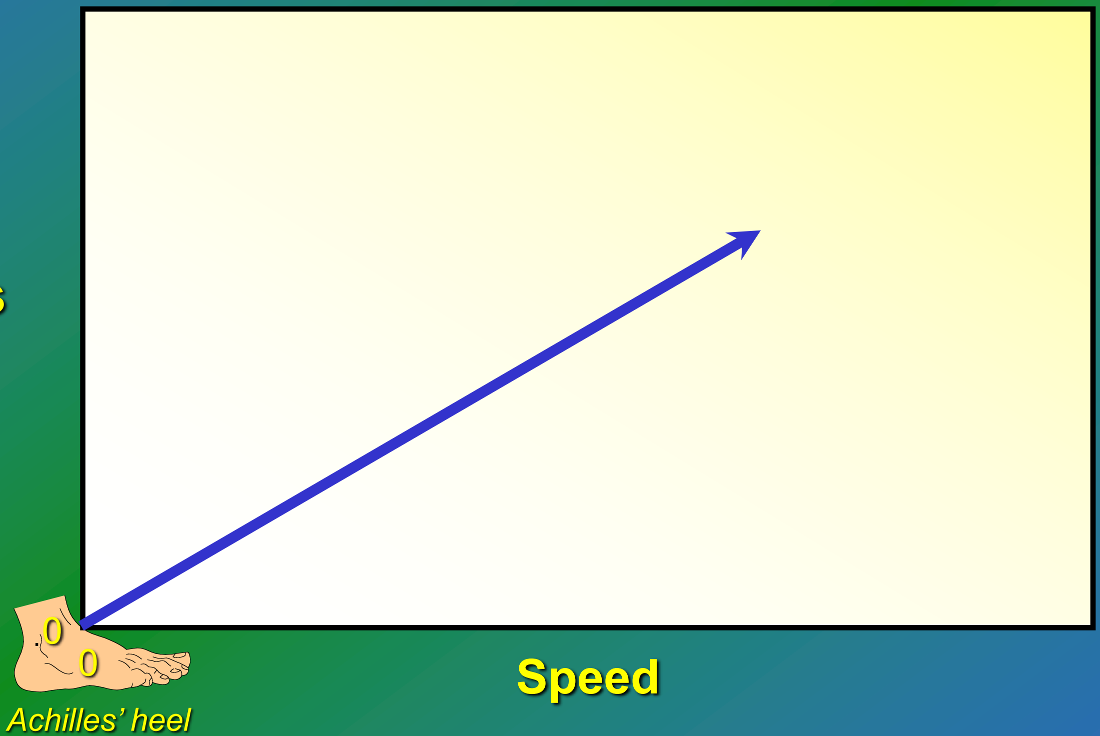
Rolling Element Bearing Speed Ranges

✦ Low Speed	< 10,000 DN
✦ Medium Speed	10,000 DN to 1 MDN
✦ High Speed	1 MDN to 2 MDN
✦ Ultra High Speed	> 2 MDN



Bearing Characteristics -- Foil Air Bearings

- Foil Air Bearings Load Capacity

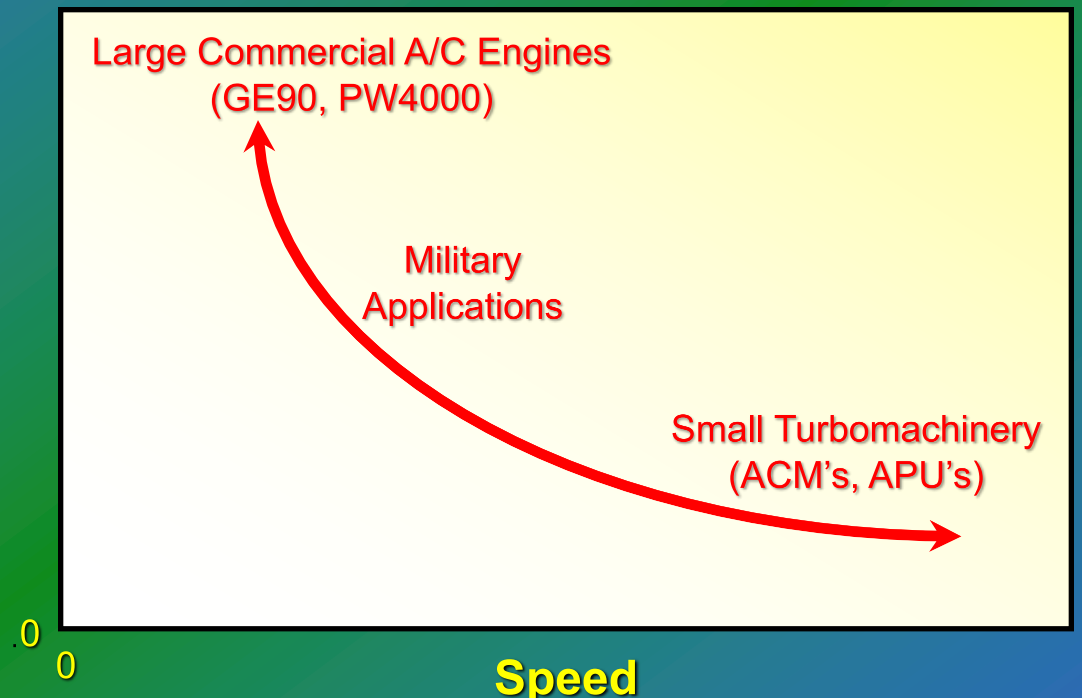


Foil Bearings

- Load capacity very low at low speeds
- Load capacity increases linearly with speed
- Foil bearings have no practical speed limitations (DN)
- Require no external systems (pressurization)

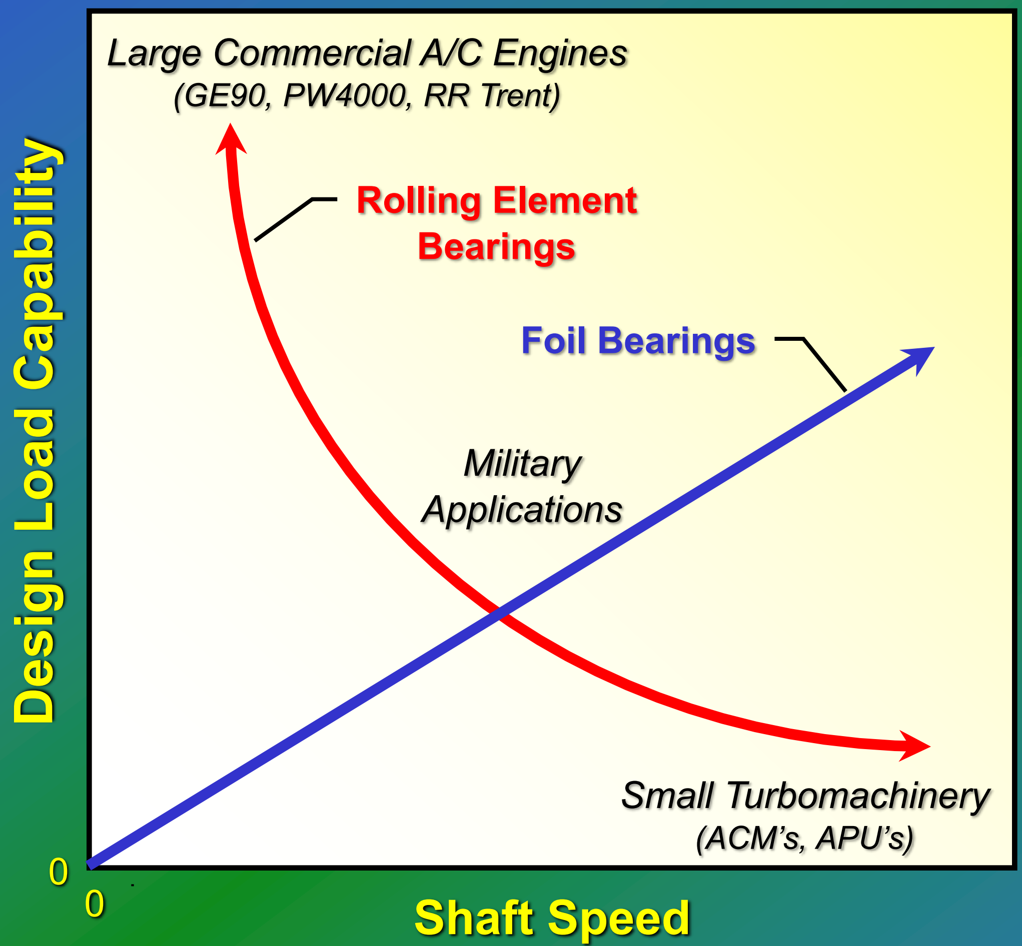
Bearing Characteristics -- Rolling Element Bearings

- **Rolling Element Brgs Maximum Load for Long Fatigue Life**



- **Oil-Lubricated Rolling Element Bearings**
  - **DN limits drive shaft diameters to minimum**
  - **High loads at low to moderate speeds**
  - **Light loads at very high speeds** *(> 2.5 MDN)*
  - **Small diameters lead to flexible shaft, large tip clearances**

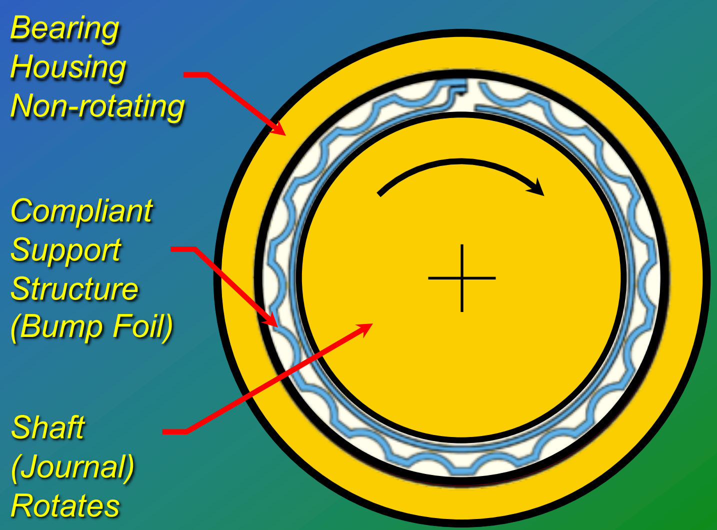
Bearing Characteristics Comparison



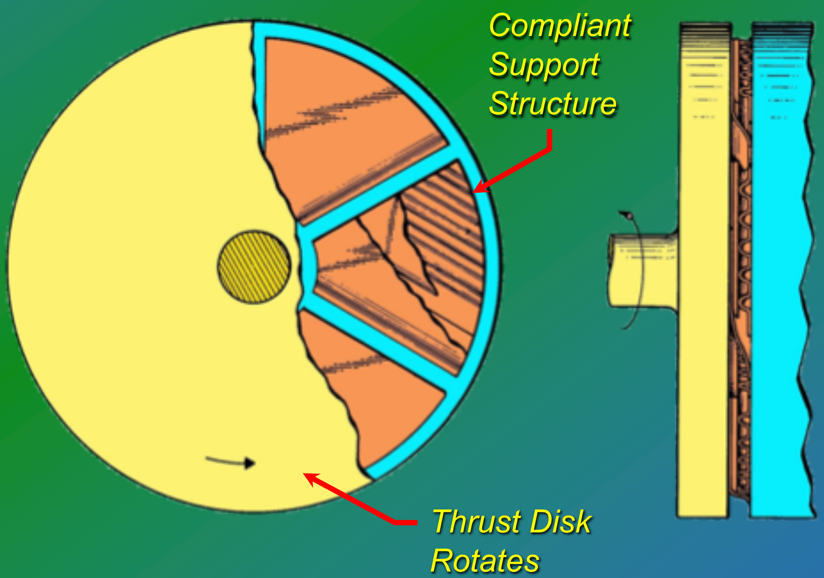
- Foil bearings do not retrofit into existing machines – changes needed
- Foil bearings need solid lubricant at startup/shutdown
- Foil bearings outperform rolling element bearings at high speeds

Enabling Technology: Advanced Foil Bearings

Foil Journal Bearing



Foil Thrust Bearing

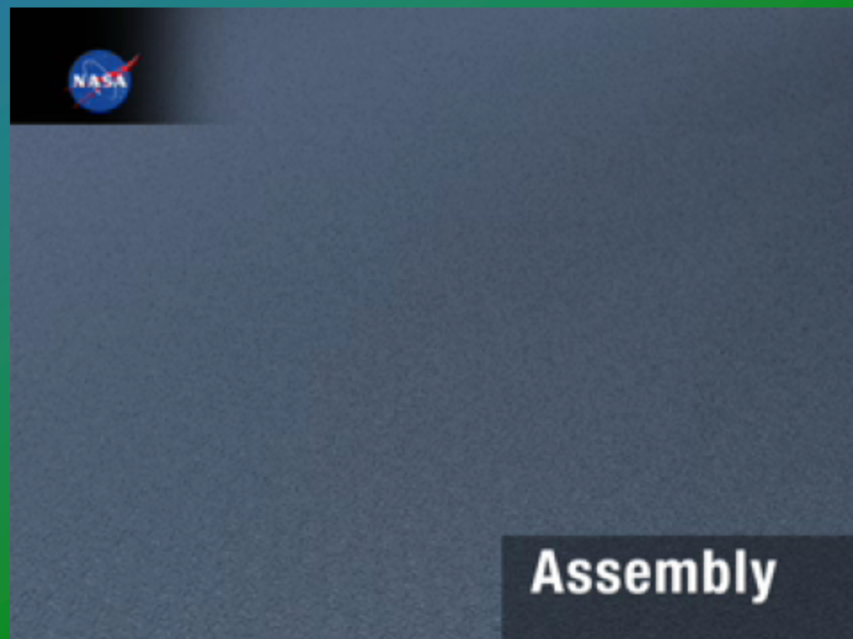


Foil Bearing Benefits:

- ✓ Self-acting hydrodynamic "float on air"
- ✓ No DN speed limit
- ✓ No lube/tanks/coolers/plumbing/filters
- ✓ Operate to 1200°F
- ✓ Compliant "spring" foil support
- ✓ No maintenance

- ➔ No external pressurization
- ➔ Higher power density
- ➔ Lower weight
- ➔ Higher efficiency
- ➔ Accommodate misalignment & distortion
- ➔ Reduce operating costs

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


NASA
Assembly

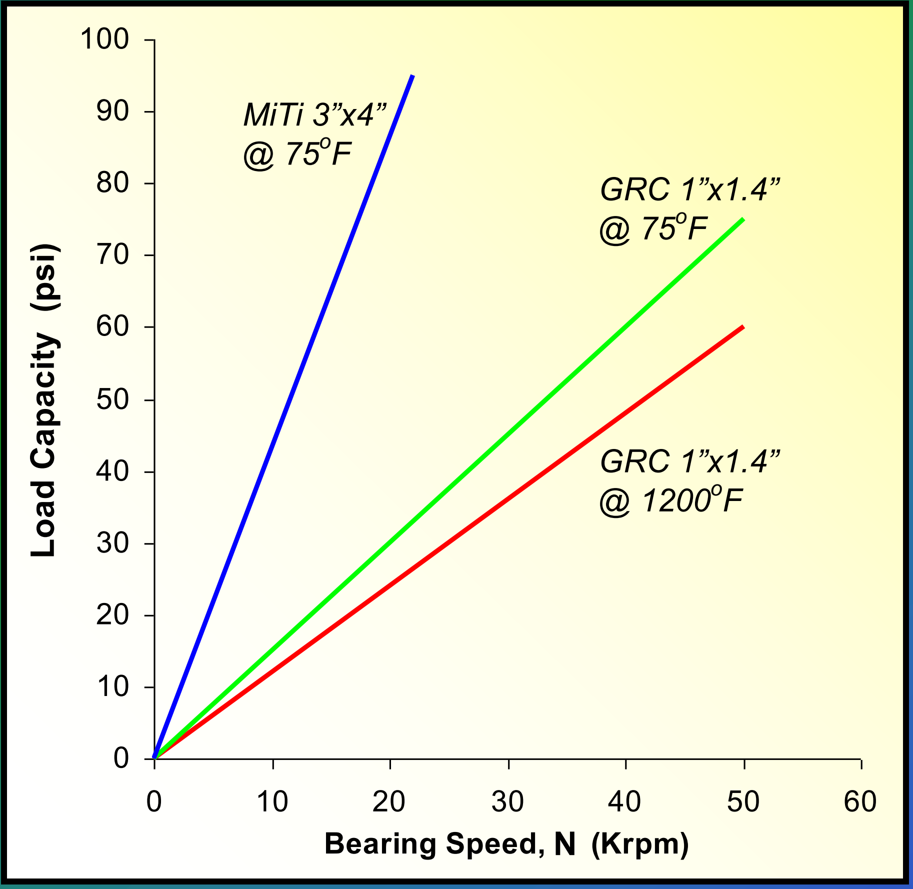
Load Capacity – Foil Air Bearings

Rule of Thumb

. . . a journal foil bearing will support about one pound
per square inch of projected area
per inch of bearing diameter
per thousand rpm

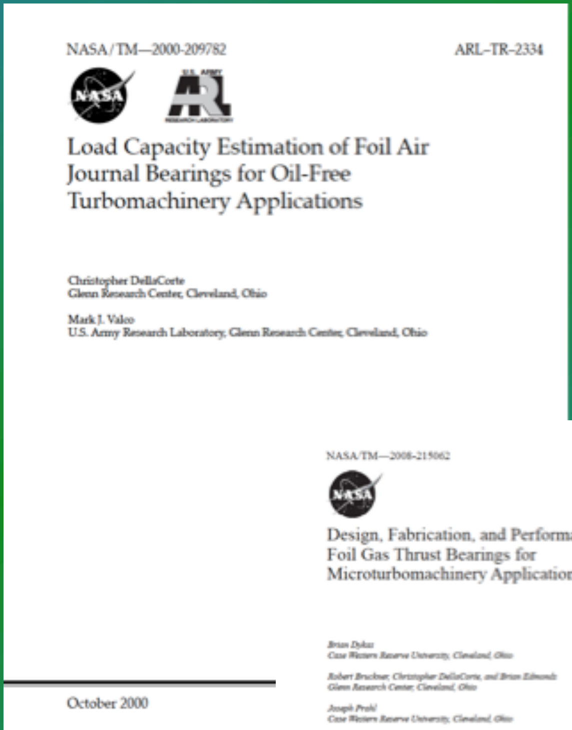
Load = D_j (L×D)×D×N

Data Source	L (in)	D (in)	N (Krpm)	D_j (lb*min/in^3)	Load (lb)
GRC	1.0	1.4	50	1.0	98
MiTi	3.0	4.0	22	1.1	1,140



- **Journal bearings sized for low speed (idle) load capacity and shaft rigidity.**
- **Thrust bearings sized for maximum axial load condition.**

- Foil bearing load capacity ROT (2000) paper
- Enabled simple method for sizing
- Extended to thrust bearings (2008)
- Verified by experiment and production experience



NASA/TM—2000-209782 ARL-TR-2334

Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications

Christopher DellaCorte
Glenn Research Center, Cleveland, Ohio

Mark J. Valco
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

October 2000

NASA/TM—2008-215062 GT2008-50377

Design, Fabrication, and Performance of Foil Gas Thrust Bearings for Microturbomachinery Applications

Brian Dykas
Case Western Reserve University, Cleveland, Ohio

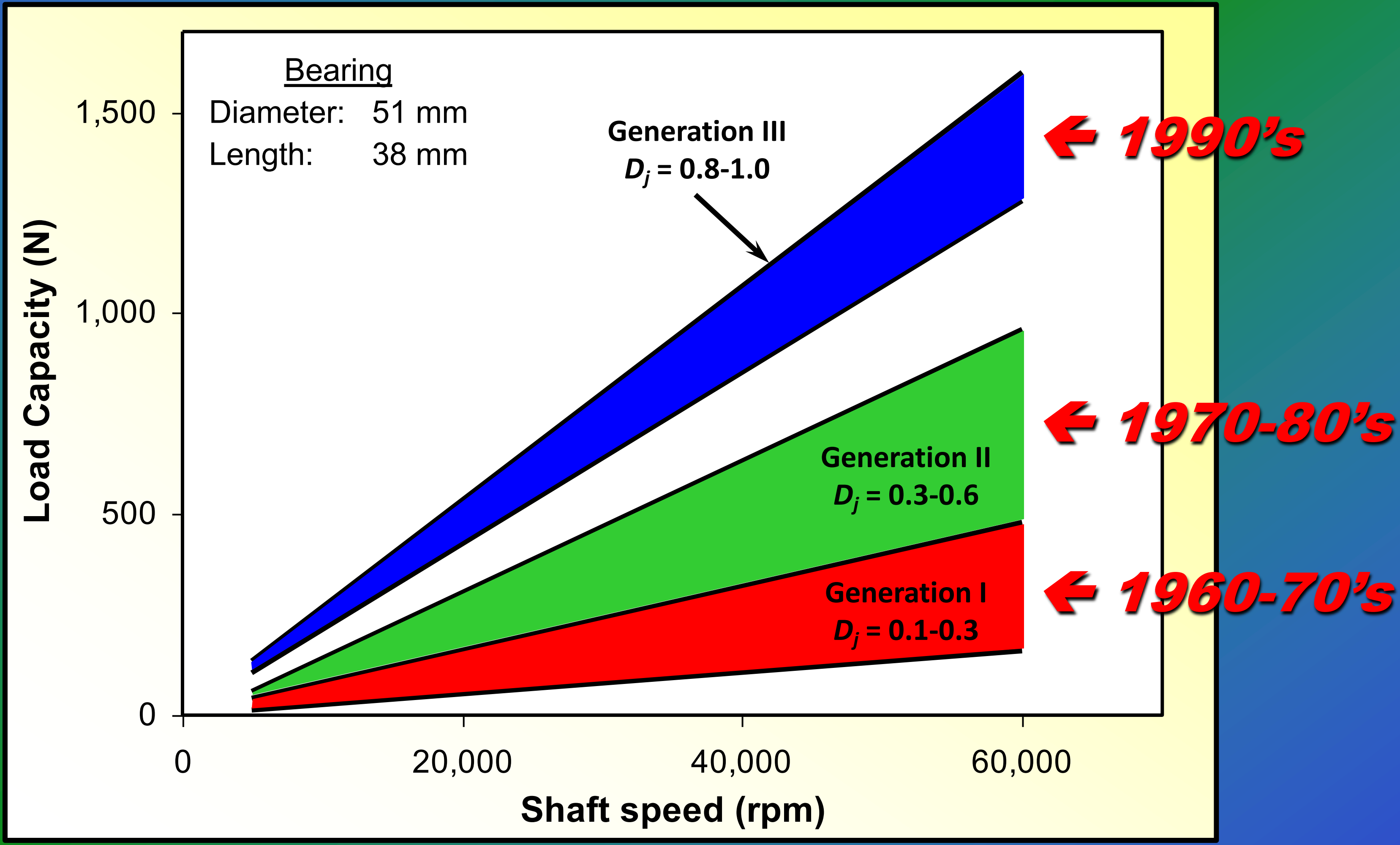
Robert Bruckner, Christopher DellaCorte, and Brian Edmonds
Glenn Research Center, Cleveland, Ohio

Joseph Prahl
Case Western Reserve University, Cleveland, Ohio

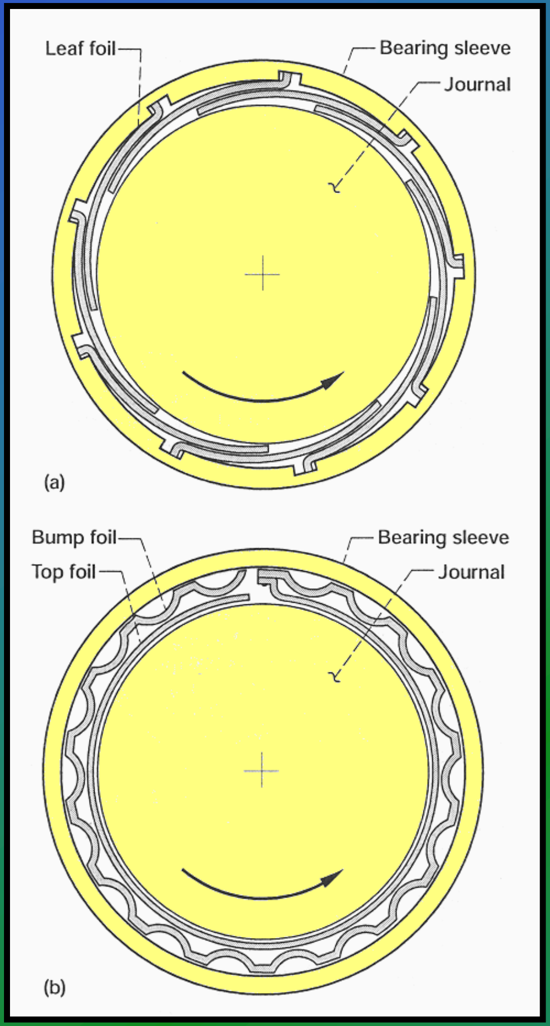
January 2008

These publications give insight into foil bearing load capacity considerations

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



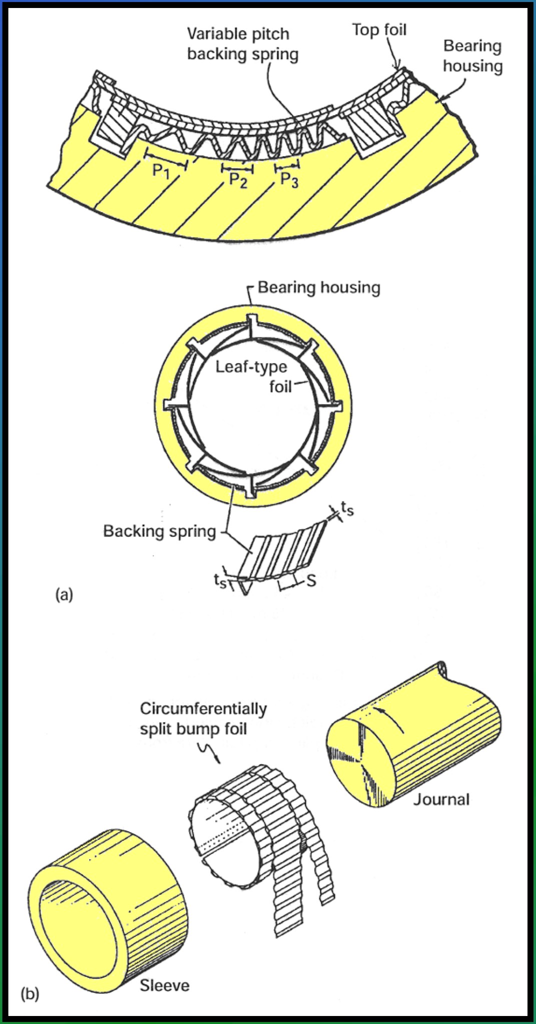
Generation I Foil Bearings *(1960's – 1970's)*



- **Load capacity coefficient, D_j's, 0.1 - 0.3**
- **Foil geometry essentially uniform in both the axial and circumferential directions** *(including uniformly periodic circumferential geometry)*
- **Stiffness characteristics of the foil structure are more or less uniform**
- **Foil surface deforms due to the fluid film pressure without support structure specifically accounting for localized effects such as edge leakage, thermal gradients, heat generation and other hydrodynamic phenomena**

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

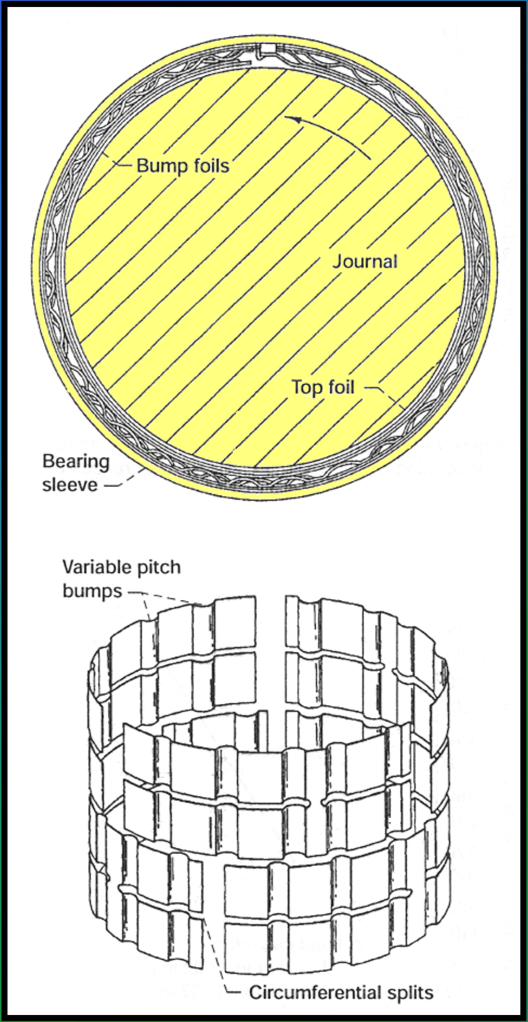
<u>Generation II Foil Bearings</u> *(1970's – 1980's)*



- **Load capacity coefficient, D_j's, 0.3 – 0.6**
- **Stiffness of the foil support structure varies axially along the bearing length or in the circumferential direction, but not both**
- **By controlling stiffness in one dimension** *(axial or circumferential)* **the bearing better accommodates phenomena like edge leakage and, hence, yields improved performance**
- **In leaf foil bearings, use of a "stepped" backing spring**
- **In bump type foil bearings, bump layers are split circumferentially for axial compliance control or the bump pitch is varied for circumferential compliance control**

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

Generation III Foil Bearings *(1990's)*



- **Load capacity coefficient, D_j's, 0.8 – 1.0**

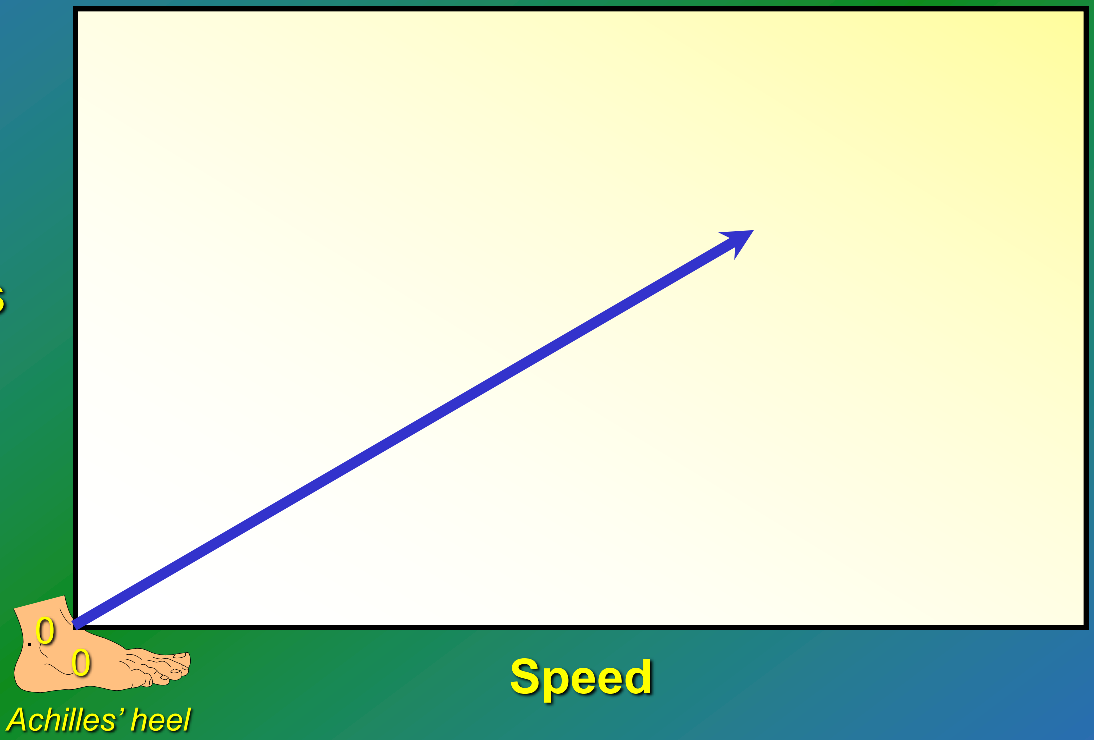
- **Tailoring the foil support structure stiffness in**
  - **Axial** (L)
  - **Circumferential** (π)
  - **Radial** (r) *(i.e., displacement sensitive)*

  directions to enhance bearing performance

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

Bearing Characteristics -- Foil Air Bearings

- Foil Air Bearings Load Capacity



Foil Bearings

- Load capacity very low at low speeds
- Load capacity increases linearly with speed
- Foil bearings have no practical speed limitations (DN)
- Require no external systems (pressurization)

PS304 and PS400 High-Temperature Solid Lubricant Coatings

- Provide start/stop wear protection for foil bearings
- Operate from cold start to 1500°F
- No vaporization or emissions

NASA PS304 *US Patent No. 5,866,518*

60% NiCr	Binder
20% Cr_2O_3	Hardener
10% BaF_2/CaF_2	Hi-Temp Lube
+ 10% Ag	Low-Temp Lube

= Wide temperature spectrum solid lubricant coating

NASA PS400 *US Patent No. 8,753,417*

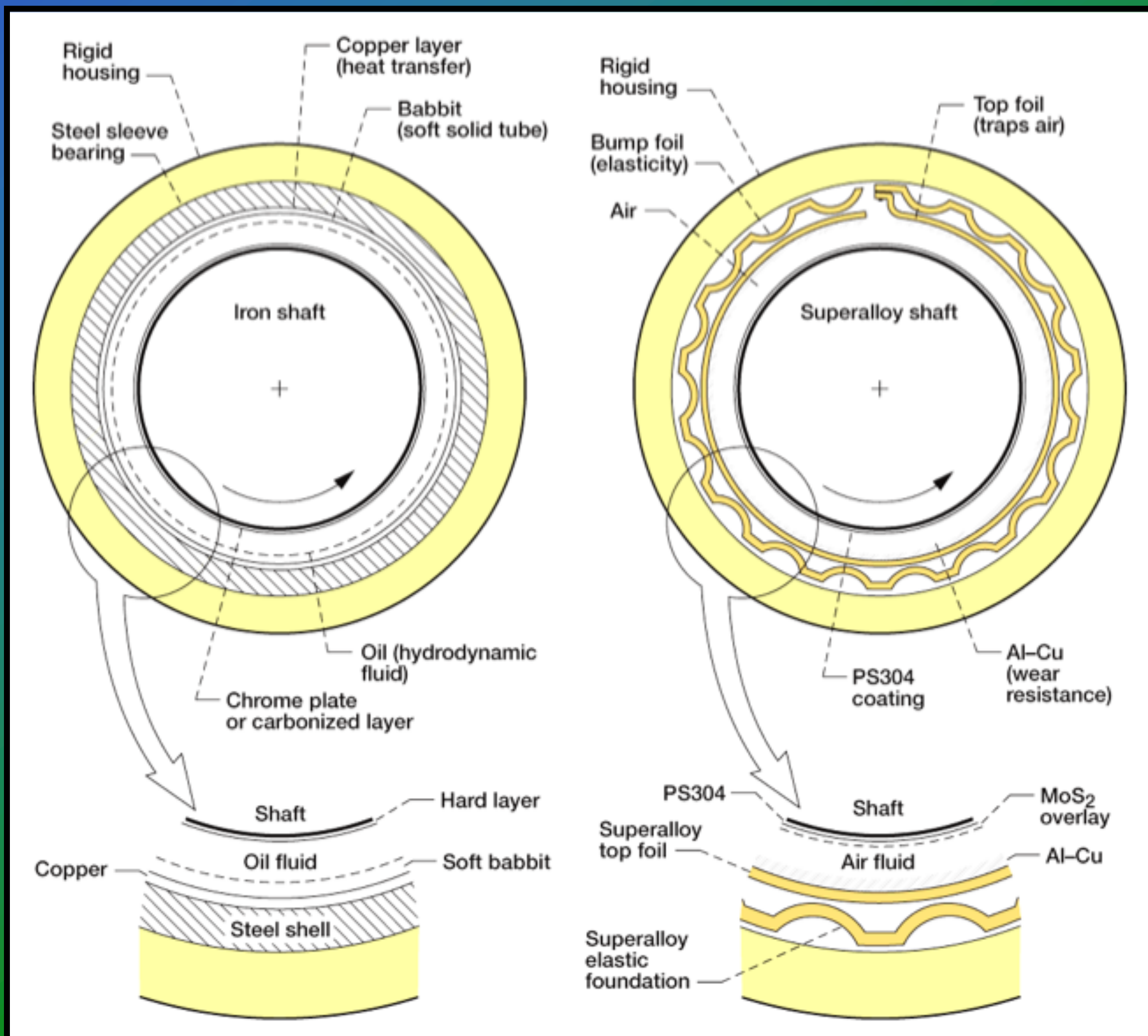
70% NiMoAl	Binder
20% Cr_2O_3	Hardener
5% BaF_2/CaF_2	Hi-Temp Lube
+ 5% Ag	Low-Temp Lube

= Wide temperature spectrum solid lubricant coating

. . . PS400, next generation coating has enhanced dimensional stability and creep strength, no need for heat treatment and improved surface finish.

System Lubrication

Analogy to Conventional Oil Sleeve Bearing

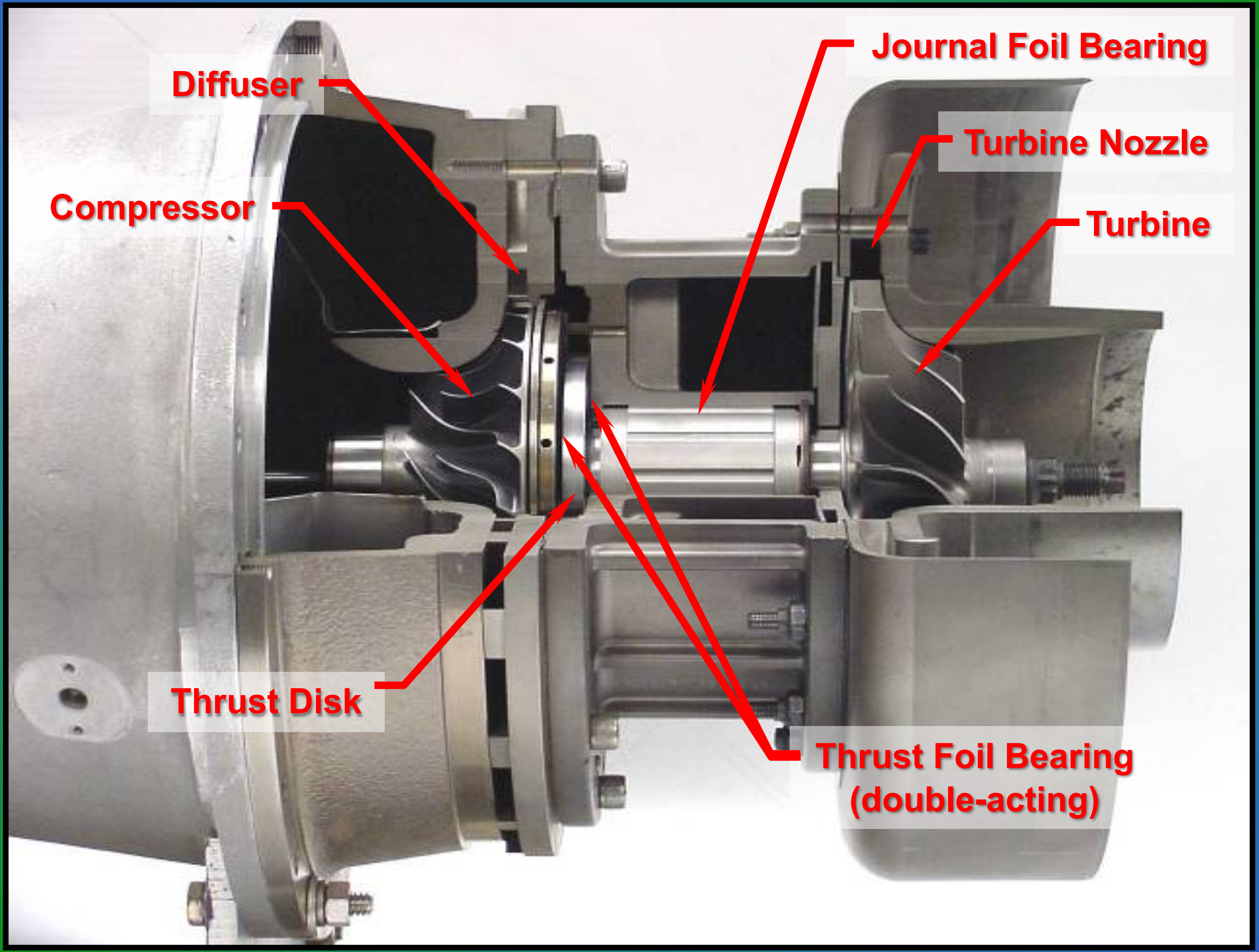


- Clear analogy between modern oil-lubricated bearing and multi-surface lubricated air foil bearing

- Foil bearing coatings have been in development since 1993
- Screening of baselines showed need for dedicated coating
- PS300 series enabled high temperature life
- PS400 longer lasting, simpler to produce
- System lubrication paper explains this complex tribological problem

These publications give insight into foil bearing coatings

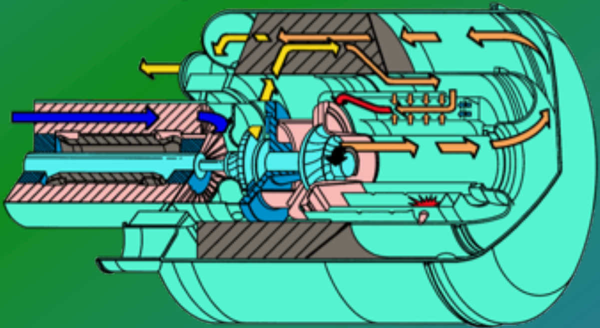
Capstone 30kW MicroTurbine



Capstone turbines are turbochargers + combustor connected to a motor-generator with a quill shaft.

NASA GRC Operating Capstone MicroTurbine

- 30 kW unit installed
- NASA PS400 coating on foil air bearing journal
- Ran ~2000 hrs to first inspection, no changes to coating observed
- Current time ~14,000 hrs.



- Engine tests confirm performance. Basic research now following.

- Foil bearing coatings have been maturing in Capstone turbines since 1998
- Failures have occurred for various reasons. Improvements have resulted.
- Technological “teething pains” must be expected as the corporate knowledge develops.
- Pertinent reference: Lubell et. Al, ASME 2006 IGTI paper GT2006-90572.

Continuing Oil-Free engine testing is key to refining technology.

Basic Bearing Characteristics

- Load Capacity
  - W_{lc}
  - $W_{lc}=f$(D, L, speed, temperature, design)
- Stiffness
  - K_{xx}, K_{yy}, K_{xy}, K_{yx}
  - $K=f$(speed, load, temperature, bearing size)
- Damping Coefficients
  - C_{xx}, C_{yy}, C_{xy}, C_{yx}
  - $C=f$(speed, load, temperature, bearing size)
- These basic bearing characteristics are needed to develop an initial rotor system layout and design and to determine general feasibility.

Conventional Bearings

- Load Capacity
  - Hydrodynamic bearings: 100-1000 psi, temperature range (-30 to 150 C)
  - Rolling Element Bearings: 500-3000 psi, speed to 2+MDN, (solid and oil lubricated)
- Stiffness
  - ~250,000 lb/in., significant cross coupling (hyd. brgs)
  - Deep empirical databases and accepted models
- Damping Coefficients
  - Hydrodynamic bearings: 100’s lb-sec/inch
  - REB’s: squeeze film dampers.
- The basic bearing characteristics are readily available to develop an initial rotor system layout and design and to determine general feasibility.

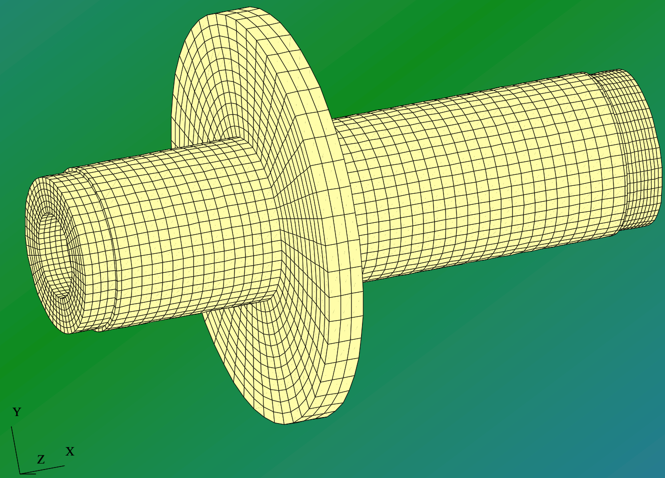
Foil Bearing Rules-Of-Thumb

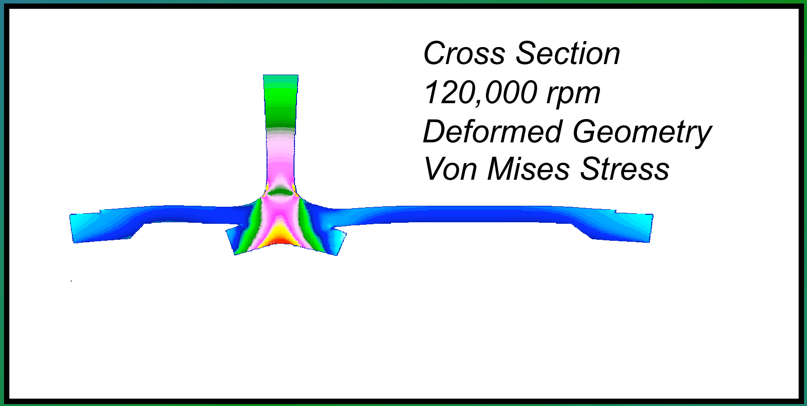
- Load Capacity Coefficient (Load = D_j (L×D)×D×N)
  - D_j =1 lb/[in^2-in-krpm] (~0.3 N/[cm^2-cm-krpm])
- Stiffness
  - K_{xx}=K_{yy}: 5000lb/[in-in^2] (6MN/[m-cm^2]) +/-50%
  - K_{xy}=K_{yx}: typically very low (1/10th or less)
- Damping Coefficients
  - C_{xx}=C_{yy}: 1 lb.-sec./[in-in^2] (200 N-s/[m-cm^2]) range: 100-1800
  - C_{xy}=C_{yx}: typically very low (1/10th or less)
- These rules can be used to conduct rotordynamic feasibility and layout trade studies.

Enabling Technology: Analytical & Rotordynamic Modeling

Advances in . . .

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



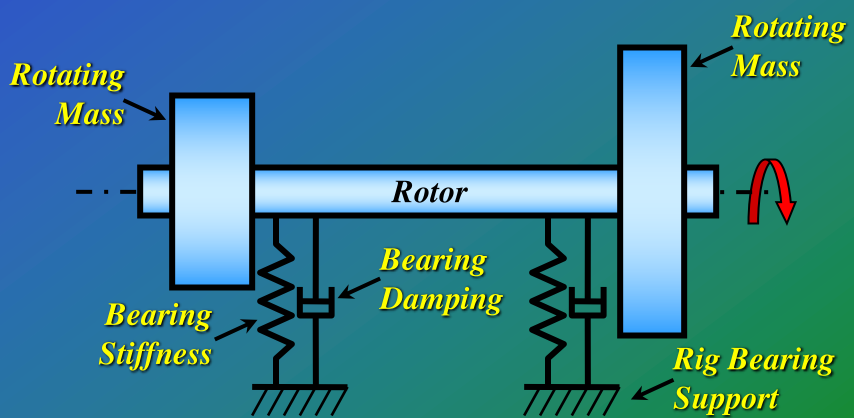


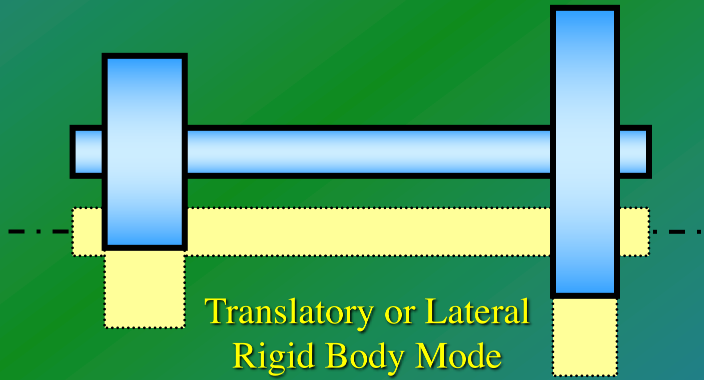
Allow prediction of . . .

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

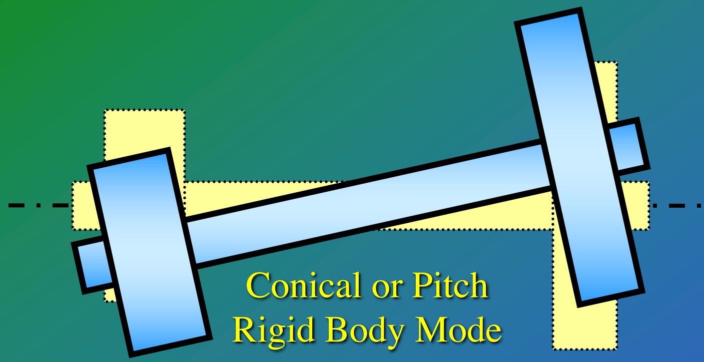
. . . Concurrent analytical methods provide the opportunity to "test" new designs without a risky "make & break" hardware approach

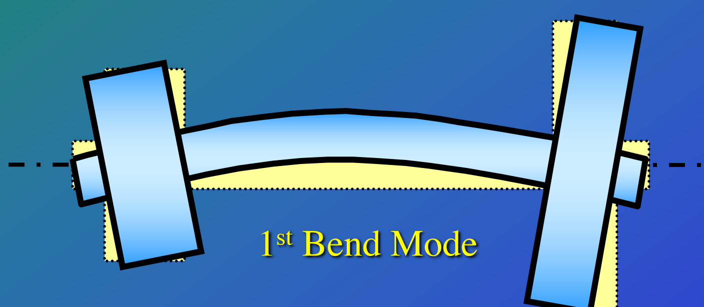
Rotordynamic Analysis



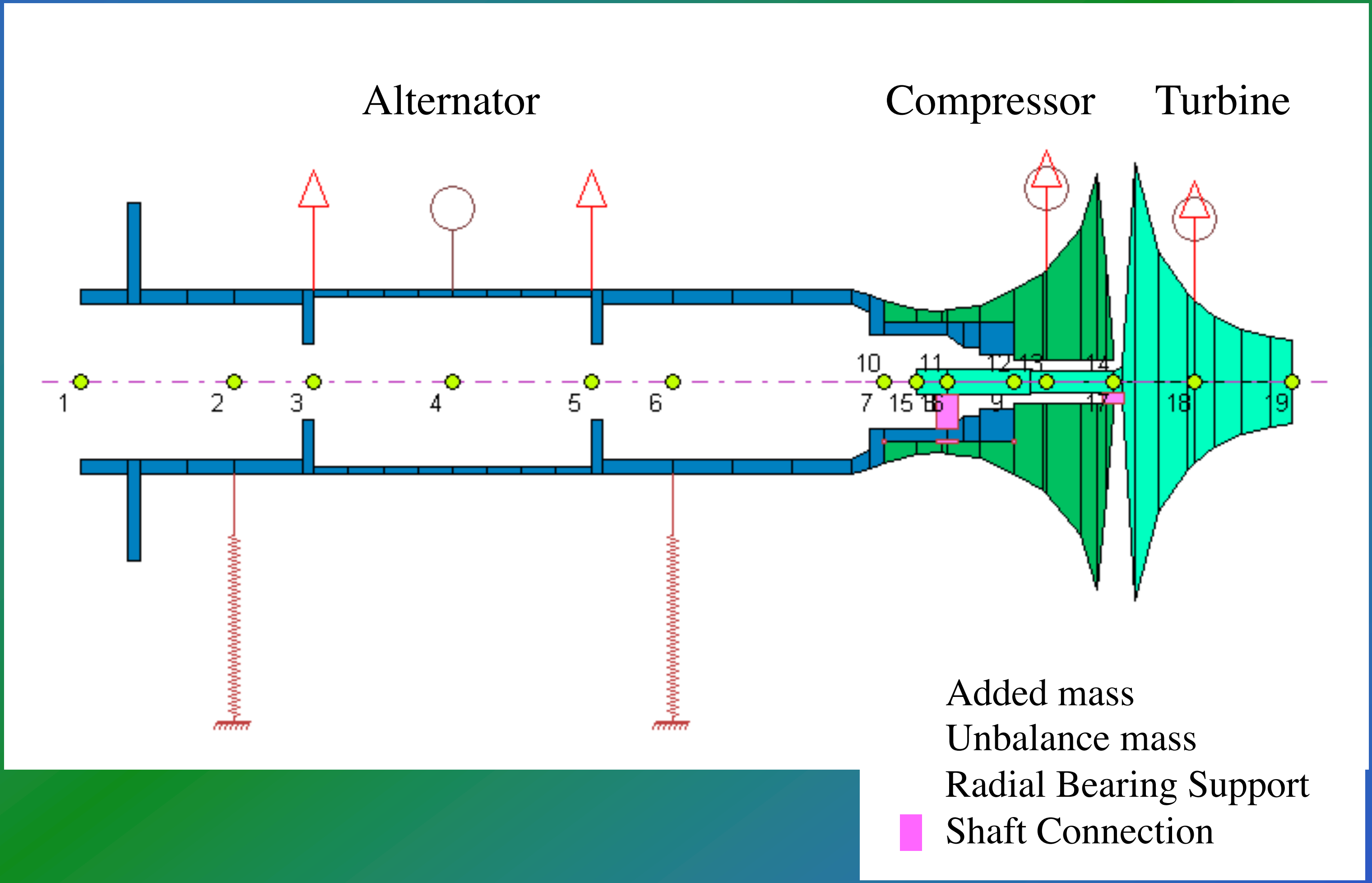


- **Rotor system critical speeds and natural frequencies** *(modes)* **are controlled by:**
  - **Shaft/disk masses and locations**
  - **Shaft geometry and material** *(stiffness)*
  - **Bearing stiffness** *(including rig structural stiffness)*
  - **Bearing damping**
  - **Operating speed**
- **Goal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

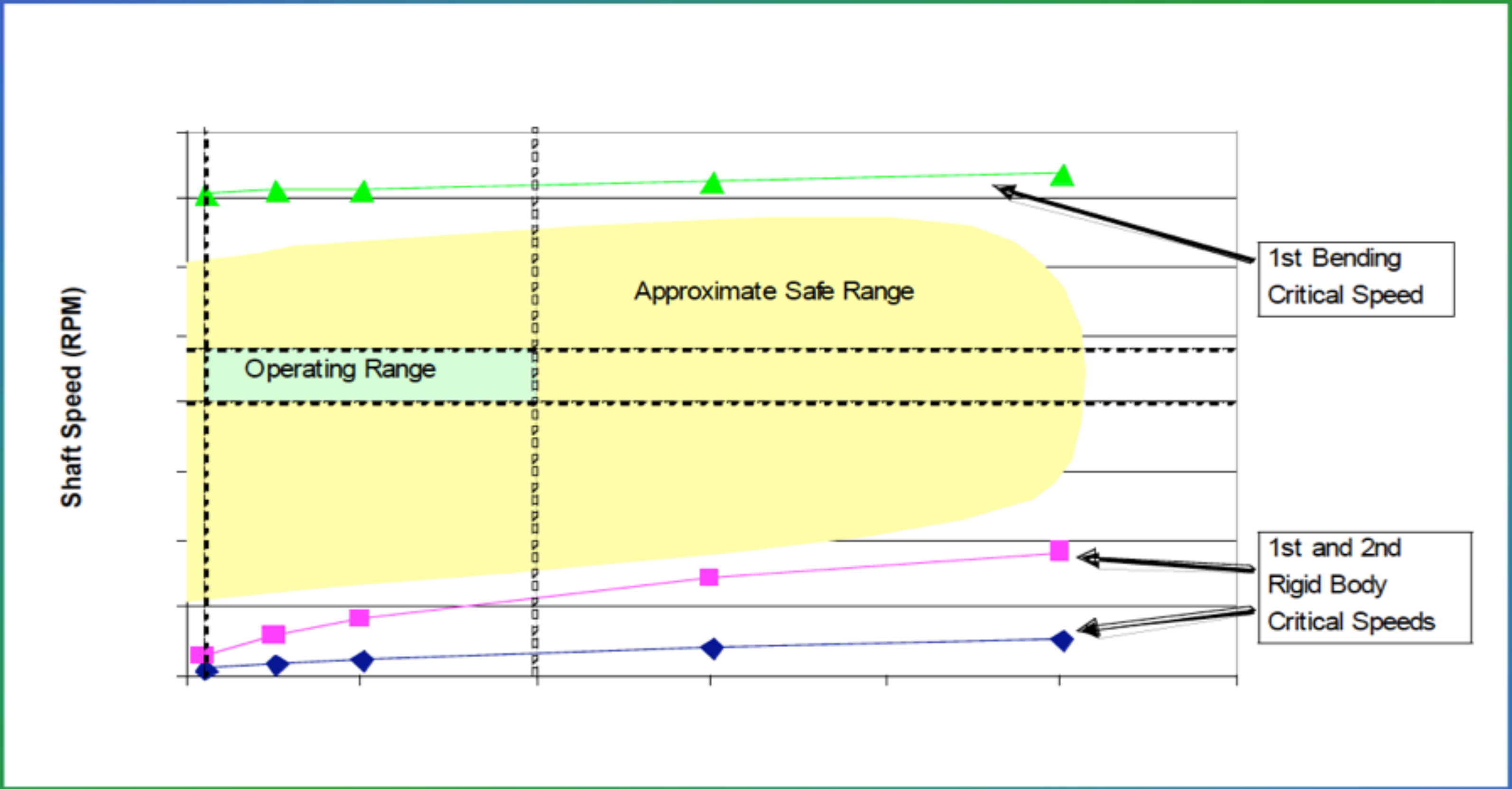




Rotor Model


Alternator
Compressor
Turbine
1
2
3
4
5
6
7
10
11
15
18
19
Added mass
Unbalance mass
Radial Bearing Support
Shaft Connection

Critical Speed Map

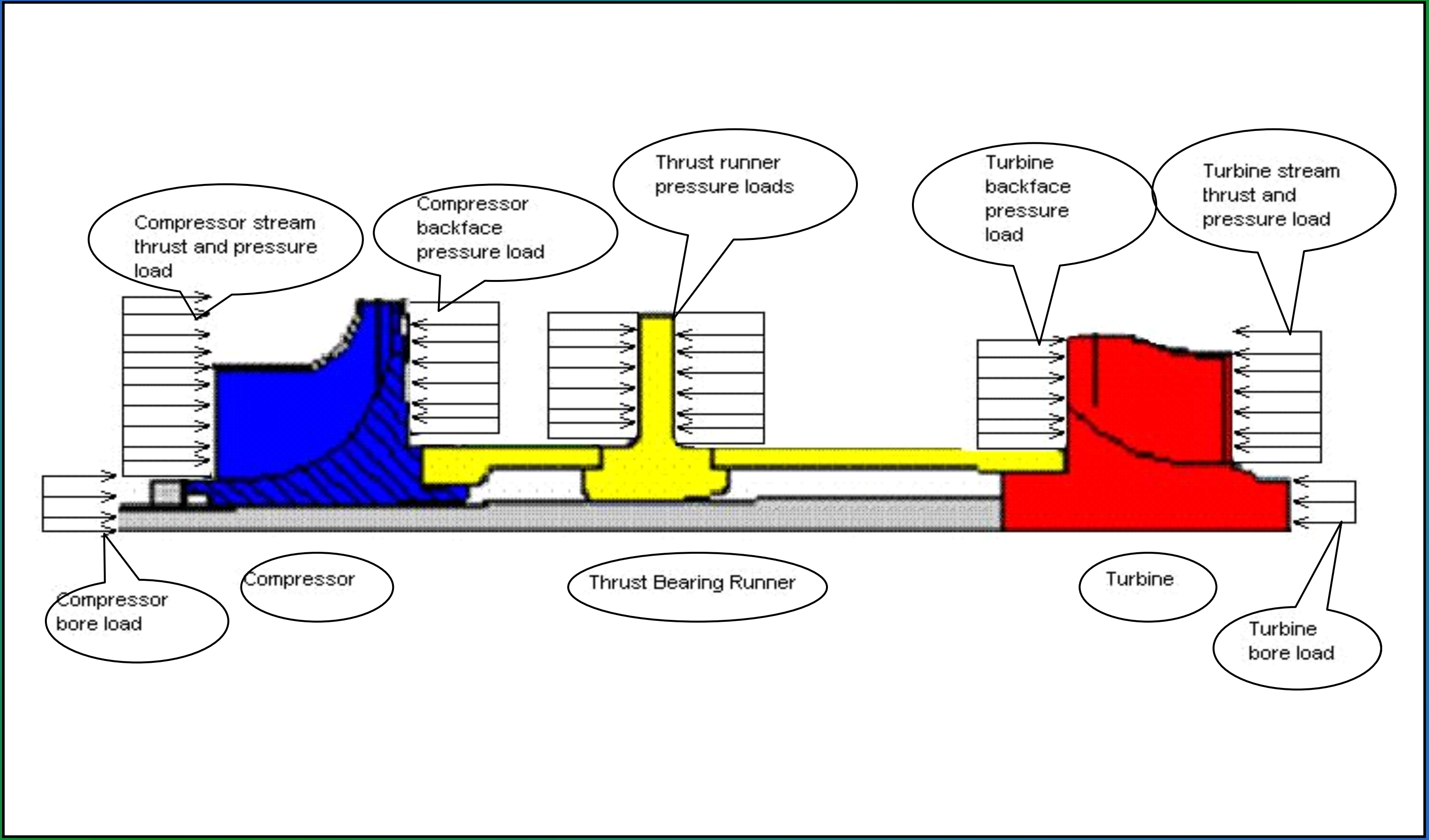


- Wide margins for critical speeds
- Opportunity may exist for system optimization

System Thrust Load Management

- Aerodynamic forces on various rotating components combine with gas pressures to create axial thrust loads on rotor
- Resulting thrust loads must be carried by foil thrust bearings
- Bearing load capacity must not be exceeded
- Thrust bearing loads result in frictional losses
- System is needed to estimate thrust loads and manage them

System Thrust Load Management



- Use algebraic sum of forces to monitor thrust bearing loads and ensure adequate load capacity margins

Foil Bearing Operating Map

(Physical Limits to operating space)

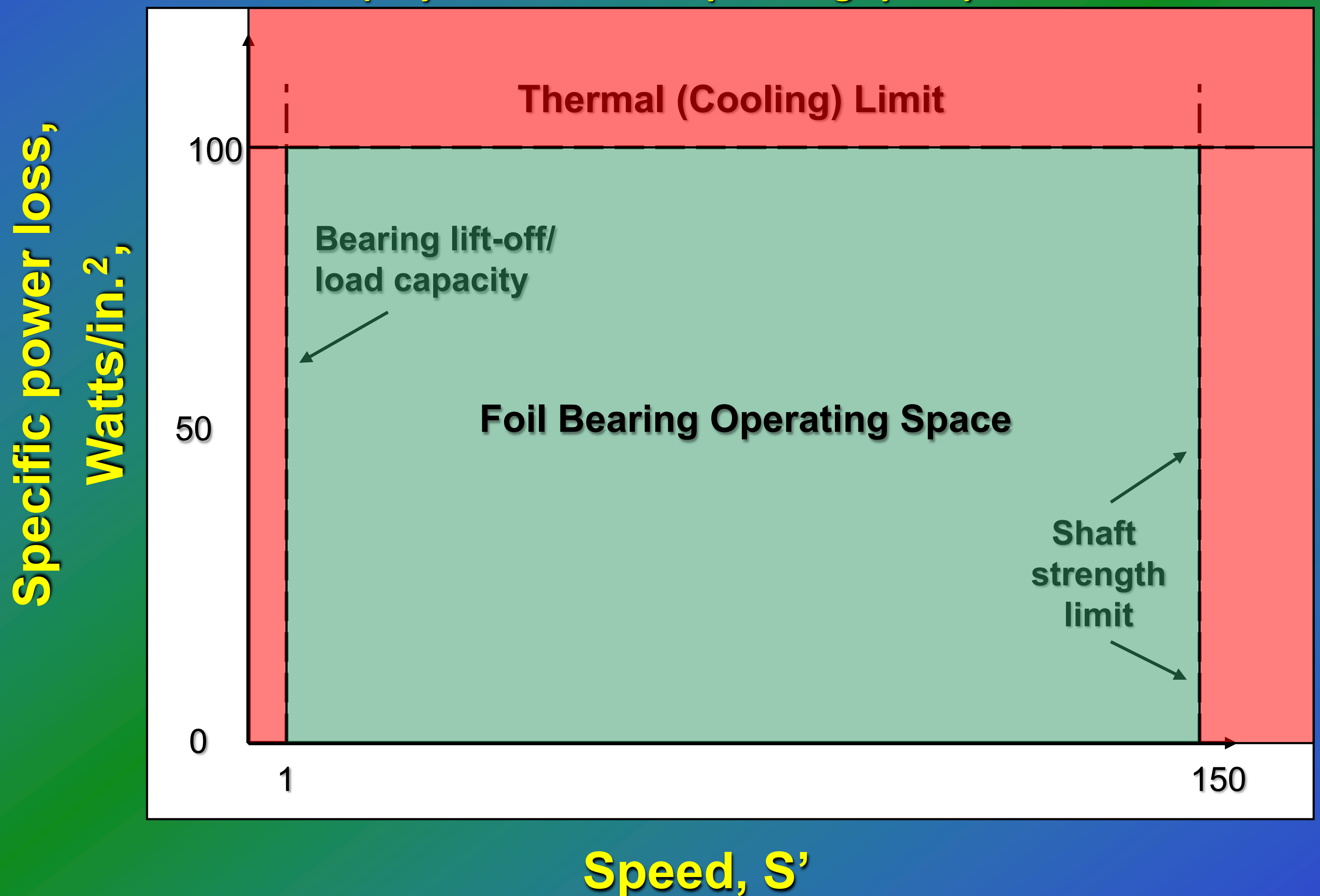


Fig 3

Foil Bearing Operating Map

(Physical Limits to operating space)

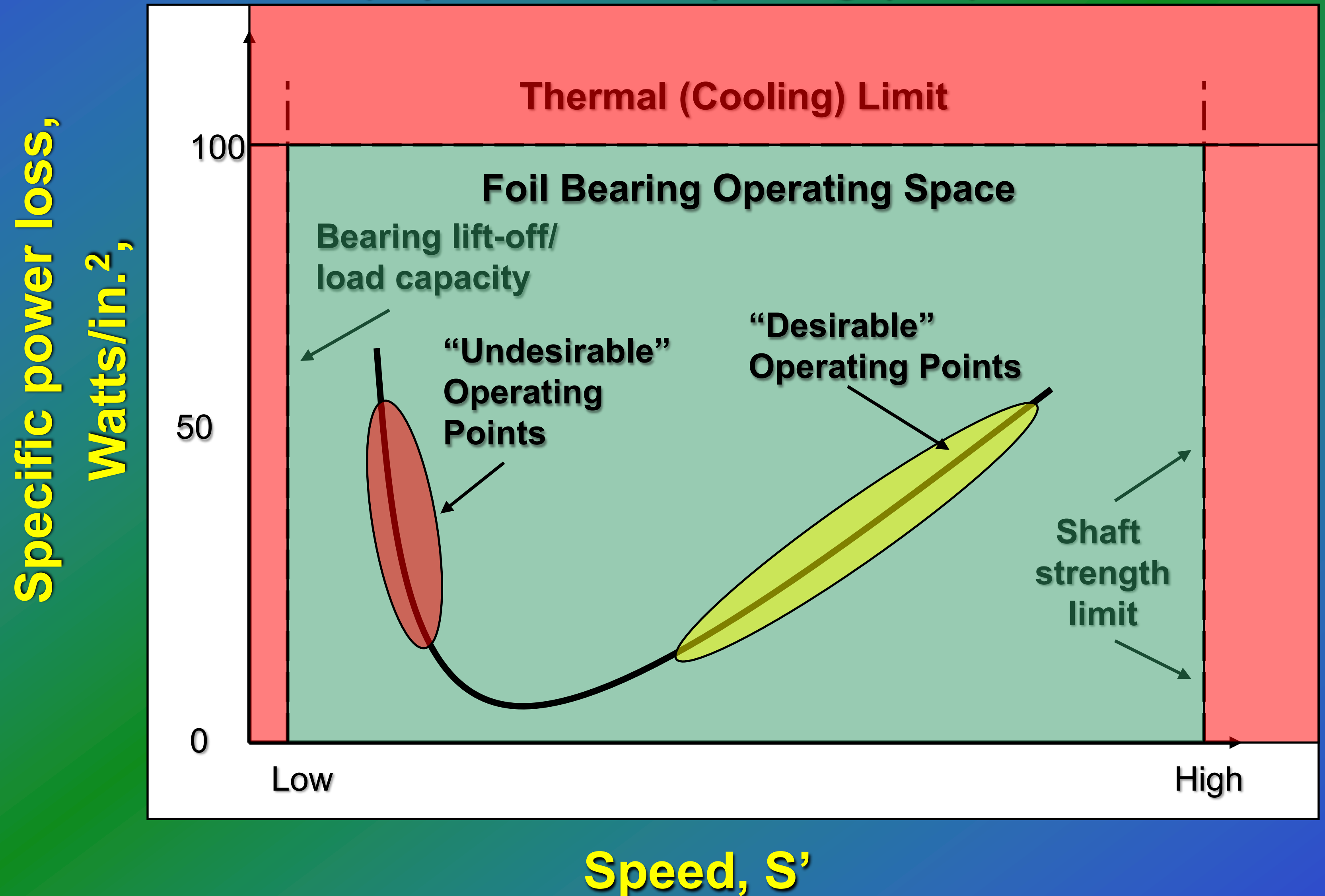
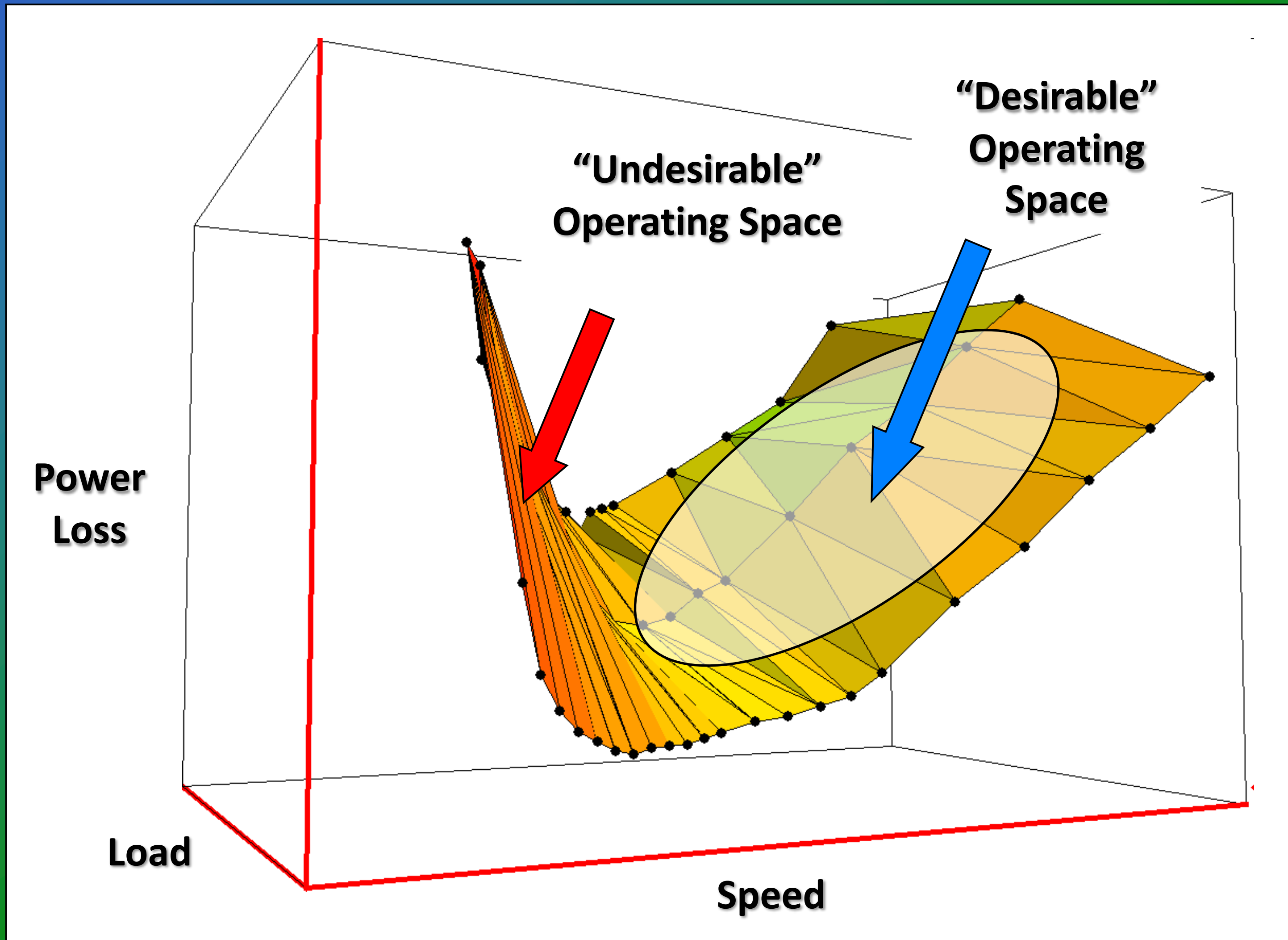


Fig 3

3-D Performance Map

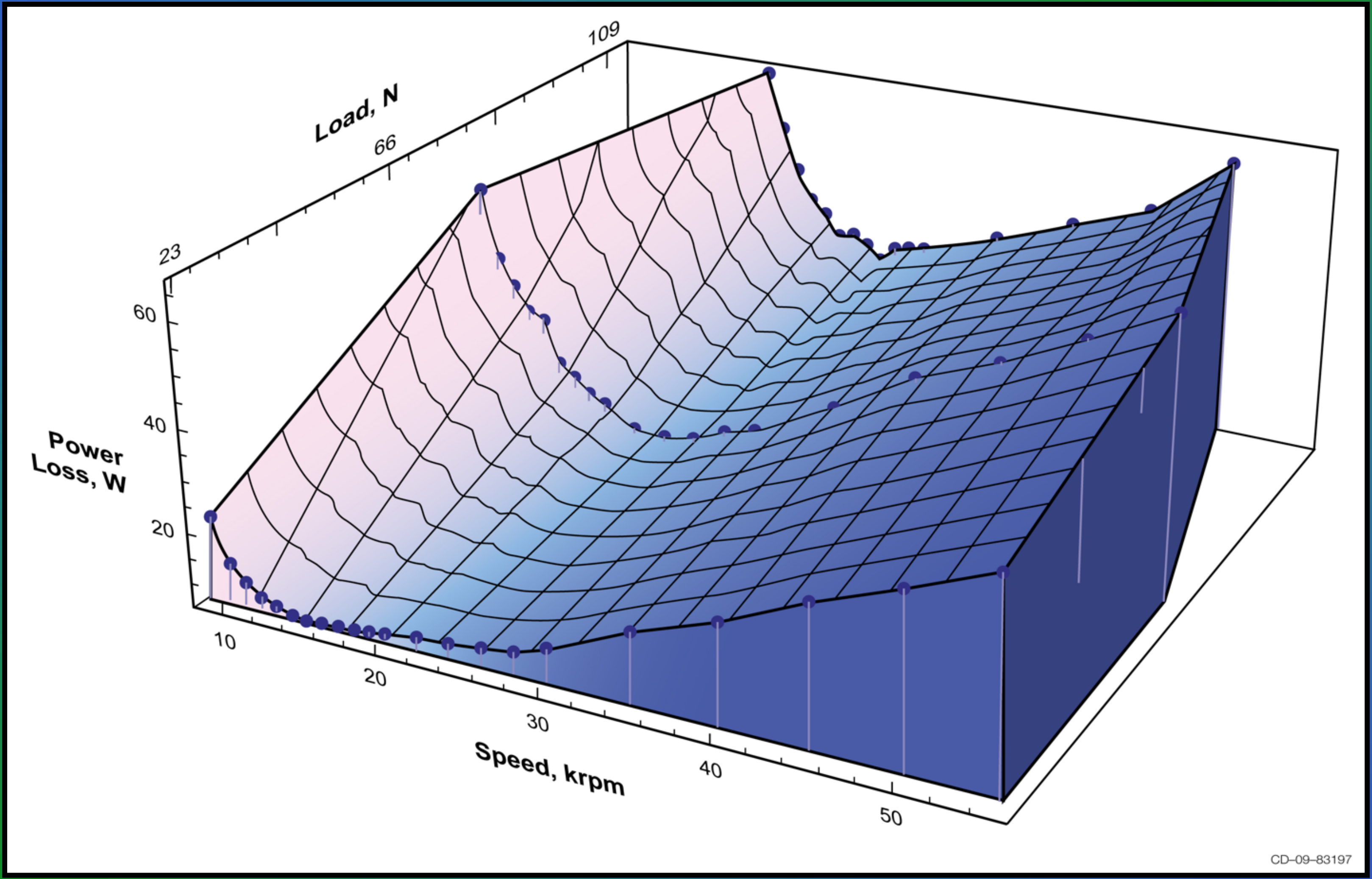
Power Loss



Load

Speed

(Oil-Free Turbo Journal Bearing)



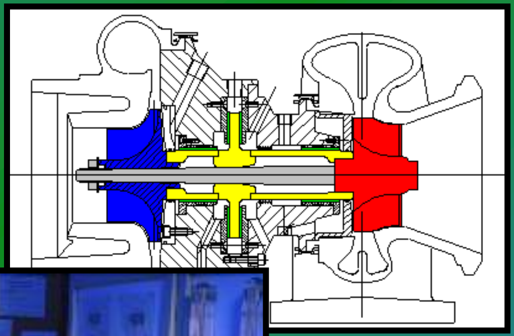
- **Foil bearing failures are typically due to poor thermal management, not some mysterious dynamic issue or durability.**
- **Tools and understanding are available to avoid problems.**
- **NASA TM-2006-214343.**

Oil-Free technology appears very simple and it is. But it must be conscientiously applied or problems will arise.

System Integration

(four steps to success)

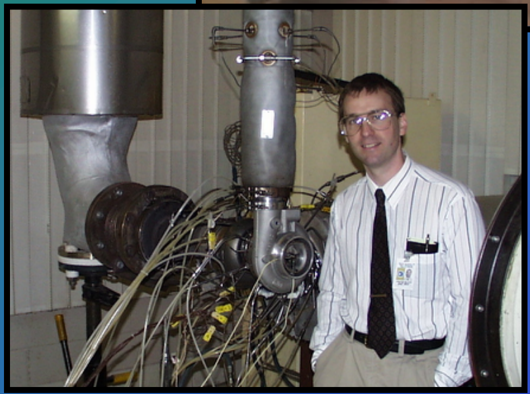
Oil-Free Technology Integration Approach



1) Rotor System Conceptual Design & Feasibility Study

2) Bearing Integration & Testing

3) Rotordynamic System Simulation

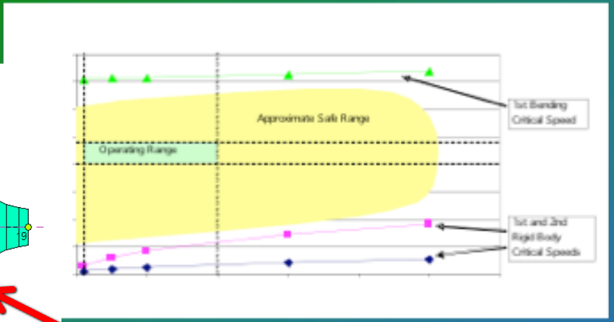


4) Oil-Free Technology Demonstration

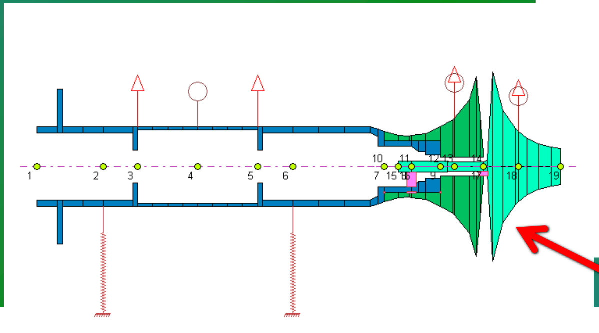
High-Speed Turbomachinery Development Approach

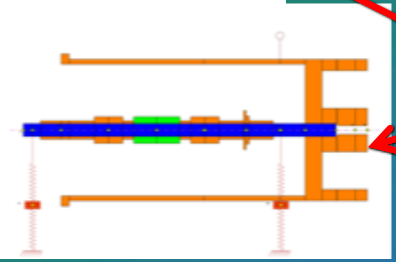
1) Rotor System Conceptual Design & Feasibility Study

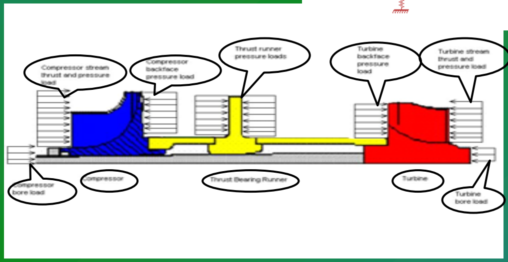
- Identify major loads, bearing sizes, shaft geometry and layout
- System level rotordynamic trade studies to identify sensitivities to design changes (bearing locations, shaft diameter vs. deflection)
- Parametric studies to determine necessary stiffness and damping
- Identify potential technical hurdles (excessive thrust loads, starting torque)



Critical Speed Maps







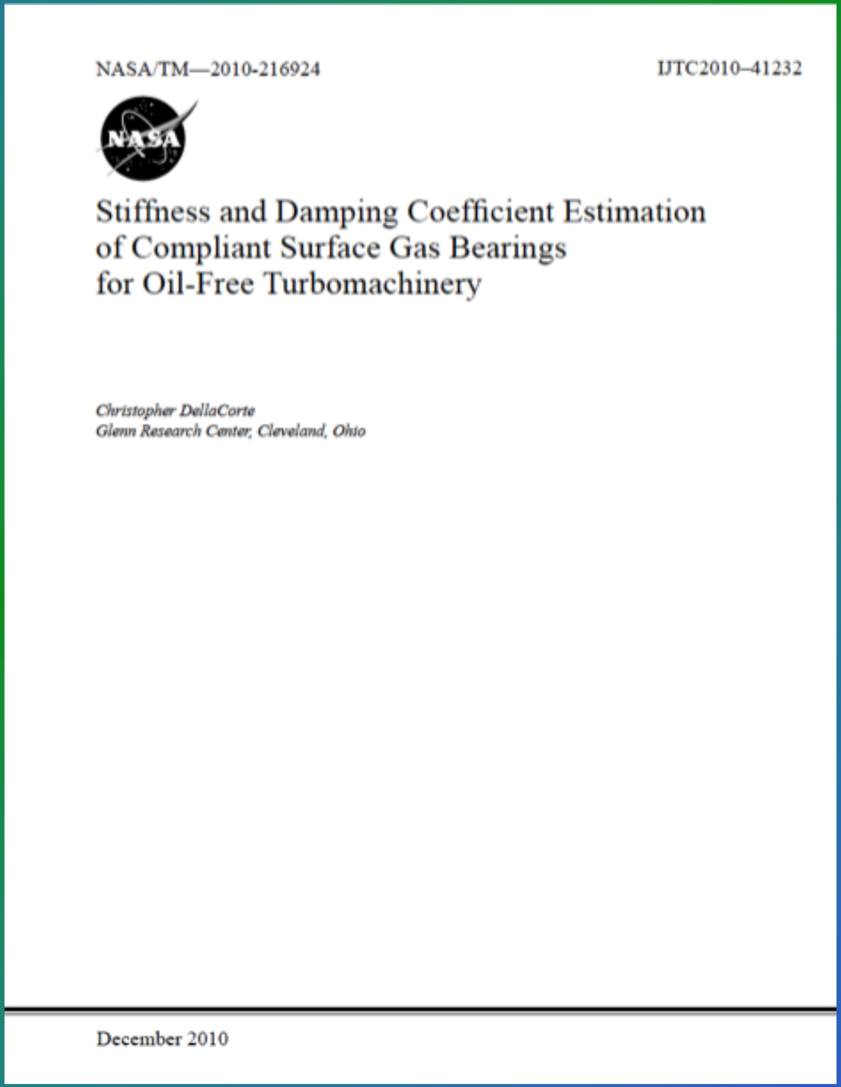
Rotordynamics layout models

Cavity pressure thrust balance model

Foil Bearing Rules-Of-Thumb

- Load Capacity Coefficient (Load = D_j (L×D)×D×N)
  - D_j =1 lb/[in^2-in-krpm] (~0.3 N/[cm^2-cm-krpm])
- Stiffness
  - K_{xx}=K_{yy}: 5000lb/[in-in^2] (6MN/[m-cm^2]) +/-50%
  - K_{xy}=K_{yx}: typically very low (1/10th or less)
- Damping Coefficients
  - C_{xx}=C_{yy}: 1 lb.-sec./[in-in^2] (200 N-s/[m-cm^2]) range: 100-1800
  - C_{xy}=C_{yx}: typically very low (1/10th or less)
- These rules can be used to conduct “Step 1” rotordynamic feasibility and layout trade studies.

- Step one rotordynamics trades study requires an understanding of bearing load capacity, stiffness and damping capability.
- Design trades must be done as a function of layout, speed and load in order to size bearings, shafts etc.
- Recent simplified ROT paper makes this step possible.
- Alternative approach is to reverse engineer existing hardware.


NASA/TM—2010-216924 IJTC2010–41232

Stiffness and Damping Coefficient Estimation of Compliant Surface Gas Bearings for Oil-Free Turbomachinery

Christopher DellaCorte
Glenn Research Center, Cleveland, Ohio

December 2010

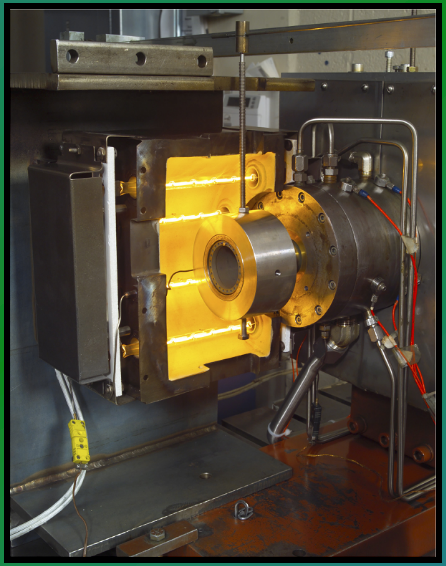
System integration is the most expensive, time consuming and currently the key area for investment.

High-Speed Turbomachinery Development Approach

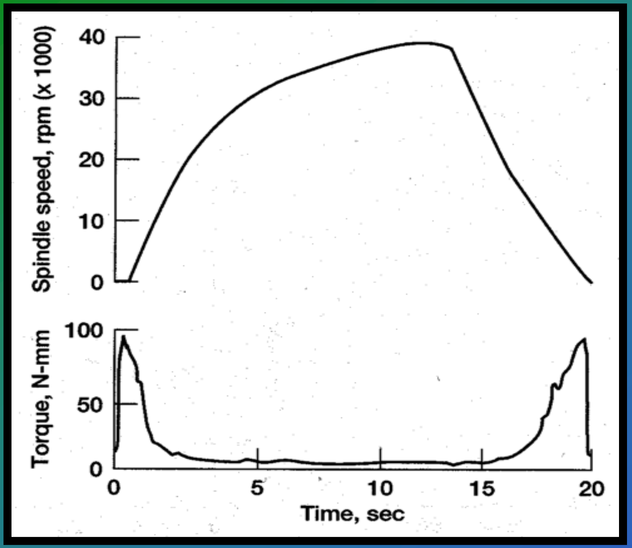
2) Bearing integration & Testing

- Design bearings to meet requirements. Fabricate bearings.
- Test bearings to verify load capacity, static stiffness, start torque, cooling flow required.
- Compare bearing performance to estimates used in Step 1.

Design and build test bearings



Bearing Test rigs



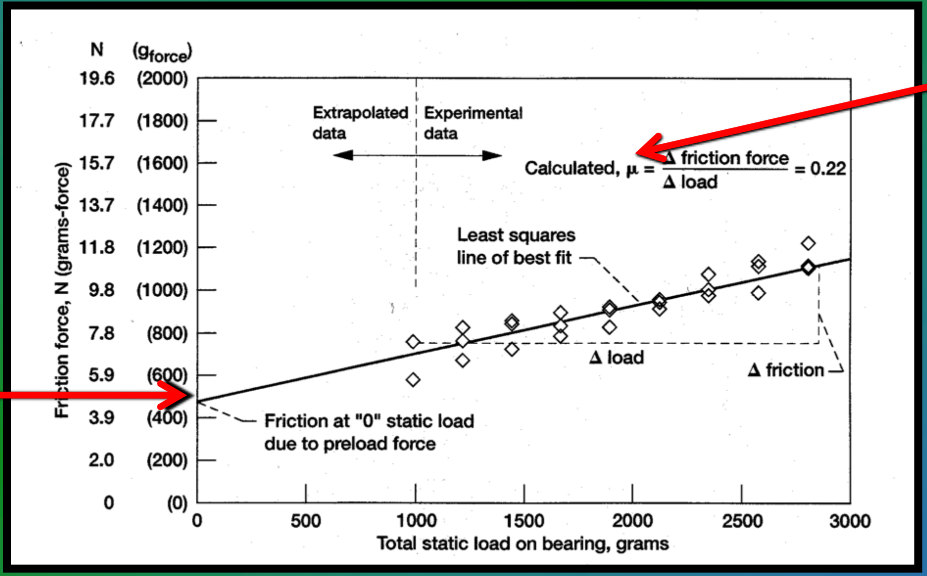
Start-Stop Cyclic testing: torque, wear and load capacity

High-Speed Turbomachinery Development Approach

2) Bearing integration & Testing

- Characterize bearing spring preload and sliding friction
  - Foil bearings are spring preloaded against shaft (no clearance, interference fit).
  - Preload must be small to minimize starting torque friction.

Friction due to spring preload



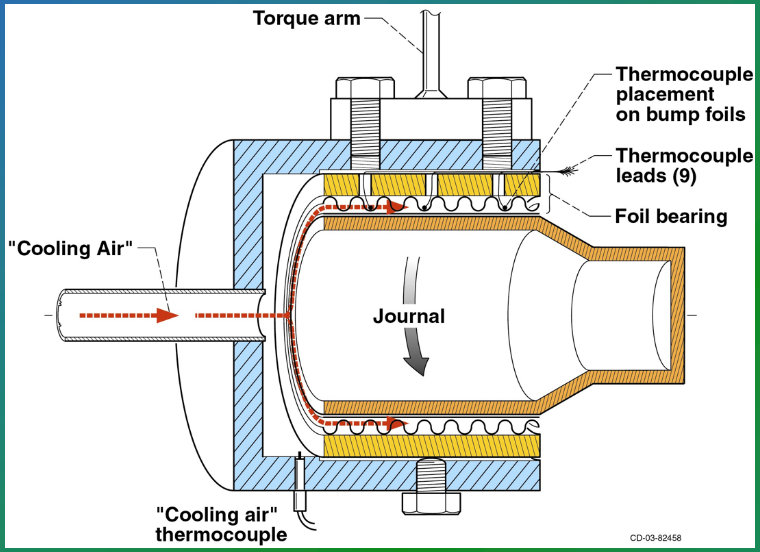
Sliding friction coefficient

Sliding Friction vs. load at start-up shows preload pressure (interference fit or negative pressure)

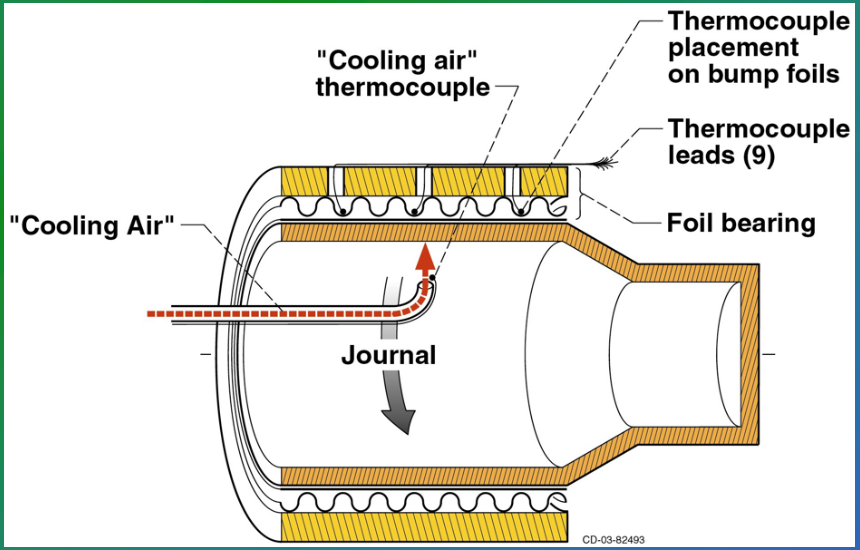
High-Speed Turbomachinery Development Approach

2) Bearing integration & Testing

- Determine cooling flow requirements.
- How much cooling, where to blow air?



Cooling passes through foils



Cooling passes through shaft

Re-check step 1 results with new data obtained in step 2

Sourcing foil bearings?

- Until recently the choices were very limited.
- Few sources, heavily controlled by IP, existed to support development.
- The most capable sources were not business friendly.
- The most willing sources were not very technically advanced.

NASA recognized this problem and spent three years developing open source bearing technology and disseminating manufacturing know-how to enable new players into the field.

- Design and manufacturing know-how have been obscurely available in the literature since the 1970's.
- Two recent papers clearly detail the manufacturing process.
- A NASA funded grant developed a design tool at Texas A&M that can be purchased.
- New suppliers of bearings have been brought online.
- NASA TM 2008-215062 and TM2007-214691.

While working with an experienced supplier is advantageous, no OEM can be held hostage by a foil bearing supplier any longer.

Current Foil bearing Users and Suppliers

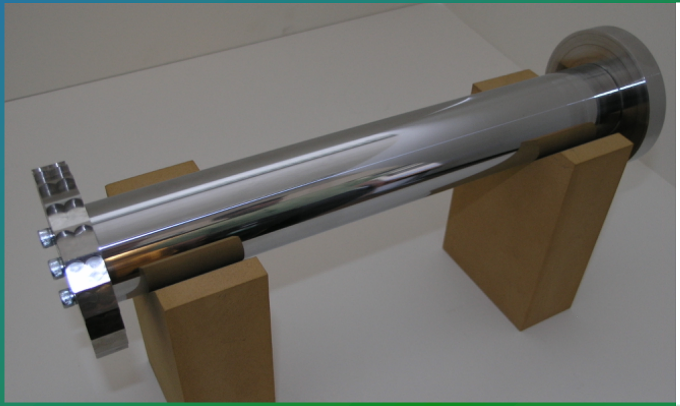
- Kturbo
- GE
- Samsung Techwin
- NRC of Canada
- Honeywell
- Hamilton Sundstrand
- Air Products
- ACD-Snecma
- Liebherr Aerospace
- Honda
- Toyota
- IHI
- Daido*
- R&D Dynamics*
- Mohawk (*not known)
- Capstone Turbines*
- Barber-Nichols*
- Dyna-Tech*
- ATI (Hampton, VA)*
- Mechanical Solutions Inc (MTI)*
- Neuros*
- Vortech Engineering*
- KIST*
- Universities*

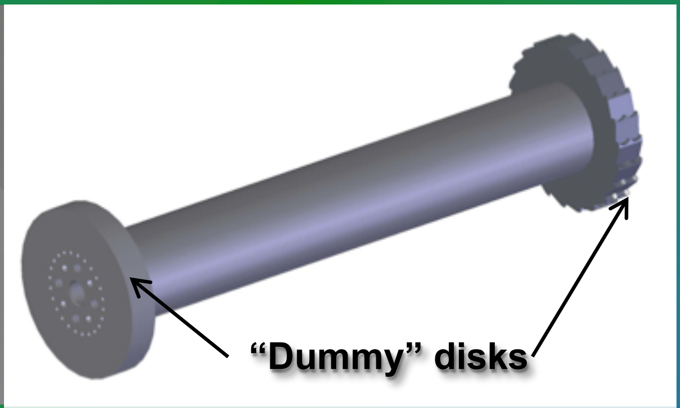
** Denotes suppliers who willingly sell their bearings into third party machinery applications. There are other users who prefer not to be disclosed.*

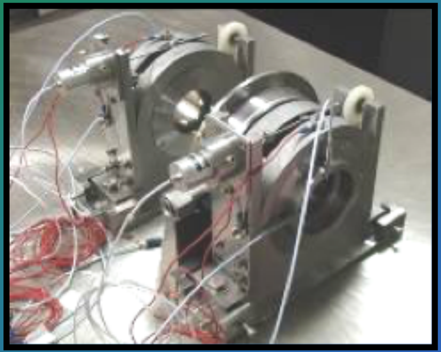
High-Speed Turbomachinery Development Approach

3) Rotordynamic System Simulation

- Experimental test of rotor with multiple bearings, no blades, mass and inertia equal to real machine.
- Characterize system behavior, imbalance response, rotordynamic stability, lift-off and shut down speeds
- Measure rotor orbit to compare to machine clearances







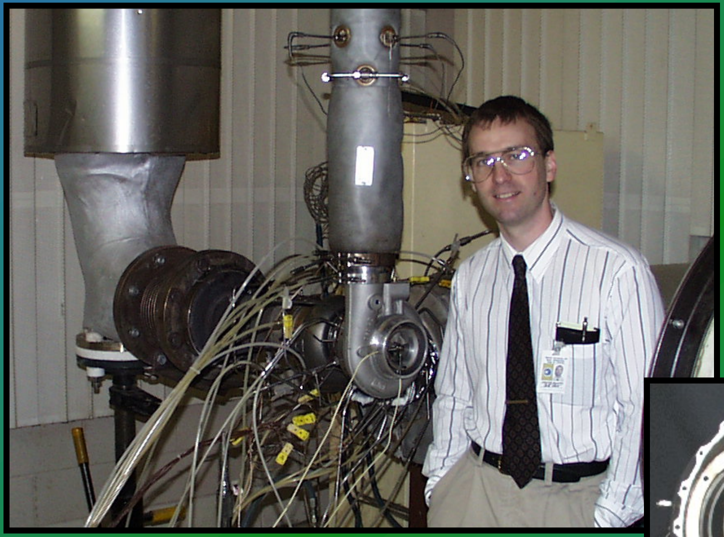
Shaft rotordynamic simulator test facility

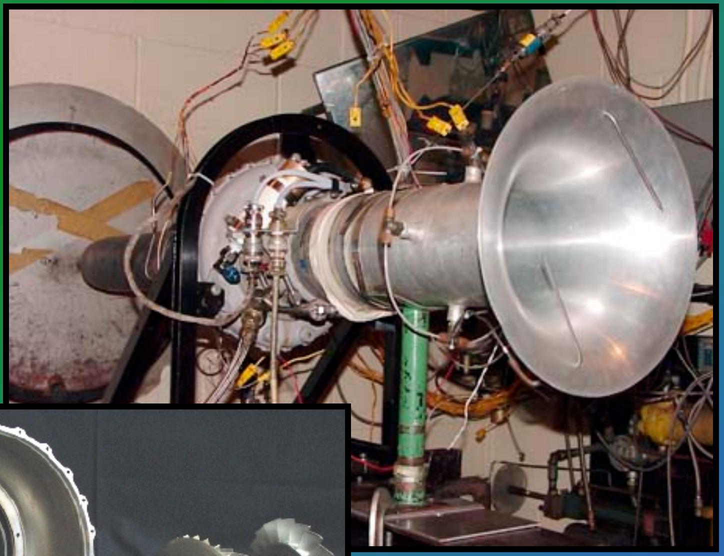
Re-check step 1 and 2 results with new data obtained in step 3

High-Speed Turbomachinery Development Approach

4) Fully Functional System Level Demonstration

- Well instrumented hardware test of engine, turbine, compressor
- Verify thermal and dynamic stability of final design
- Life testing



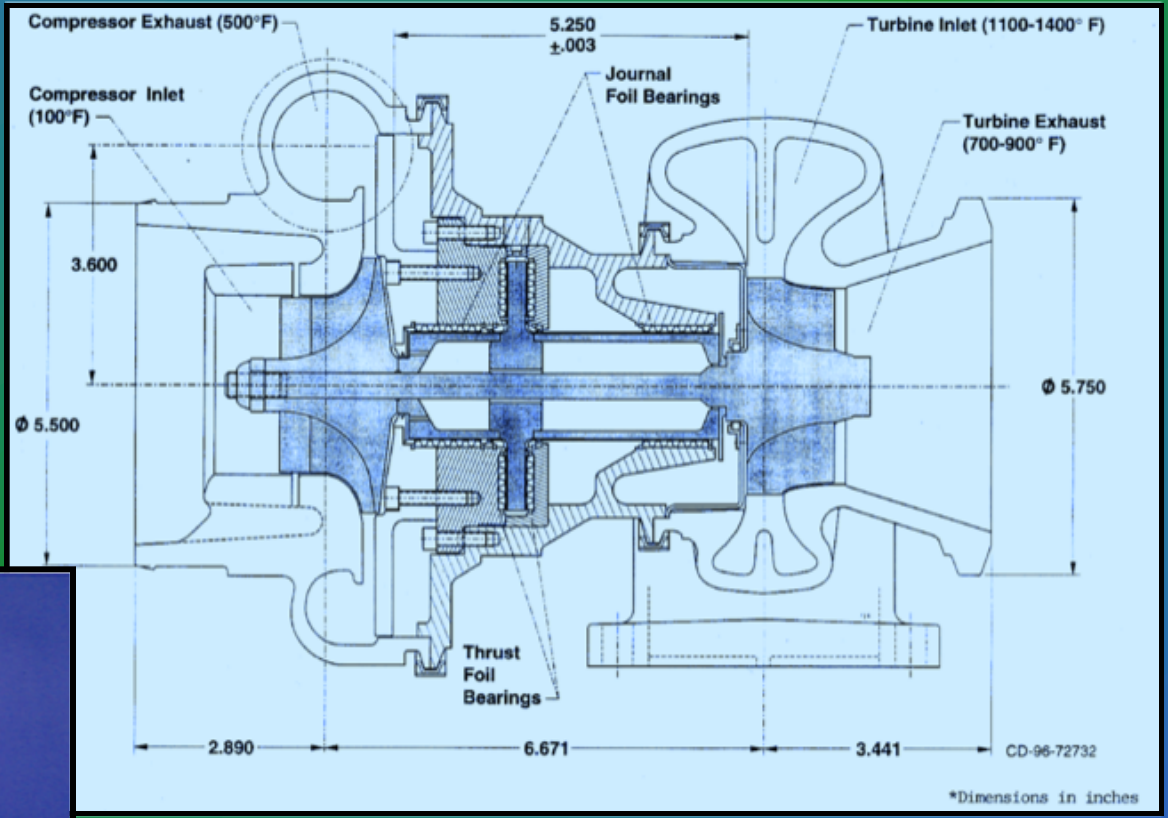


- System integration and the four step process have been the subject of many papers..
- All successfully fielded Oil-Free machines have followed the four-step process.
- Few users do so their first time out and learn the hard way not to take short-cuts.
- Often times, the shortest route between two points is not a straight line.
- ARL report ARL-TR-4873.

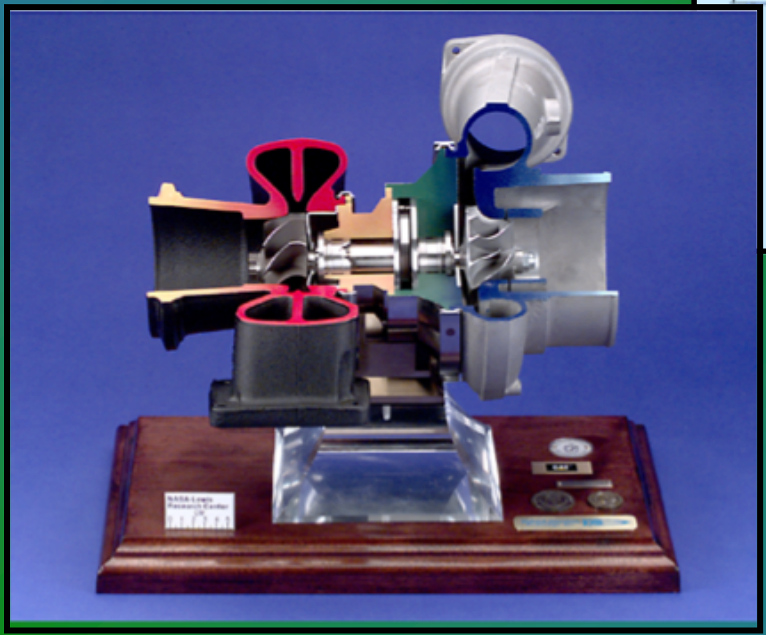
System integration is the most expensive, time consuming and currently the key area for investment.

Oil-Free Turbocharger

- 2 Journal Foil Bearings
- 2 Thrust Foil Bearings
- NASA PS304 Coating
- Rigid Rotor



Schwitzer S410FG



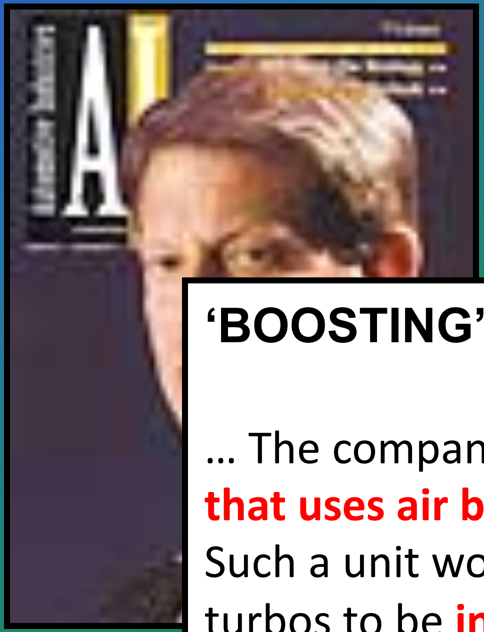
- World's First Oil-Free Turbo demo-March 17, 1999.
- Publicized widely
- Not immediately acted upon for a variety of reasons (IP issues, higher priority emissions issues, lack of clear supply chain)
- ASME IGTI 2000, paper 2000-GT-620.
- ASME WTC2005-63724.

Despite apparent lack of industry response, this demonstration ignited several key R&D initiatives in the US and abroad.

1999 Climate for Oil-Free turbos

- Schwitzer was exploring its future (looking for a buyer)
- NASA funds for further turbo work were not available.
- Foil Bearing manufacturing limited to just a few sources, none of which were willing to transfer the bearing technologies
- We still didn’t have performance and emissions data for the Oil-Free turbo with which to make an investment decision.
- Diesel industry was investing heavily in emissions compliance for 2004.
- Turbo was dropped by Schwitzer.

AlliedSignal Turbocharging Systems



‘BOOSTING’ BUSINESS AT ALLIEDSIGNAL

… The company [AlliedSignal] is also investigating a **“dry” turbo that uses air bearings borrowed from its aerospace division**. Such a unit would **eliminate oil** and bearing failure and allow turbos to be **installed in any orientation**.

Garrett-brand turbochargers enjoy a 51% share of the world market, ...

- **Often times, the first demonstration breeds competition**

Source: *Automotive Industries*, Cahners Publishing, January 1999, p. 50

- Pre-production patent protection.
- Explicit detail showing how barrier problems were solved.
- New bearings designed for high volume and low cost.
- Patent applied for in 2004
- Funded entirely by industry with limited NASA consultation.

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

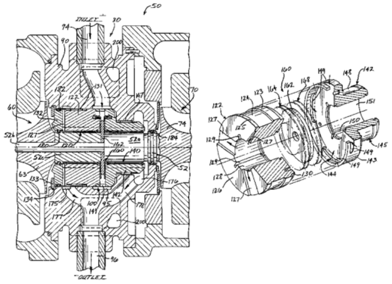
Copy of International Search Report & Written Opinion for PCT Application No. PCT/2005/010145; Filed Mar. 28, 2005; Date of Completion Jun. 27, 2005; Date of Mailing Sep. 21, 2005.

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

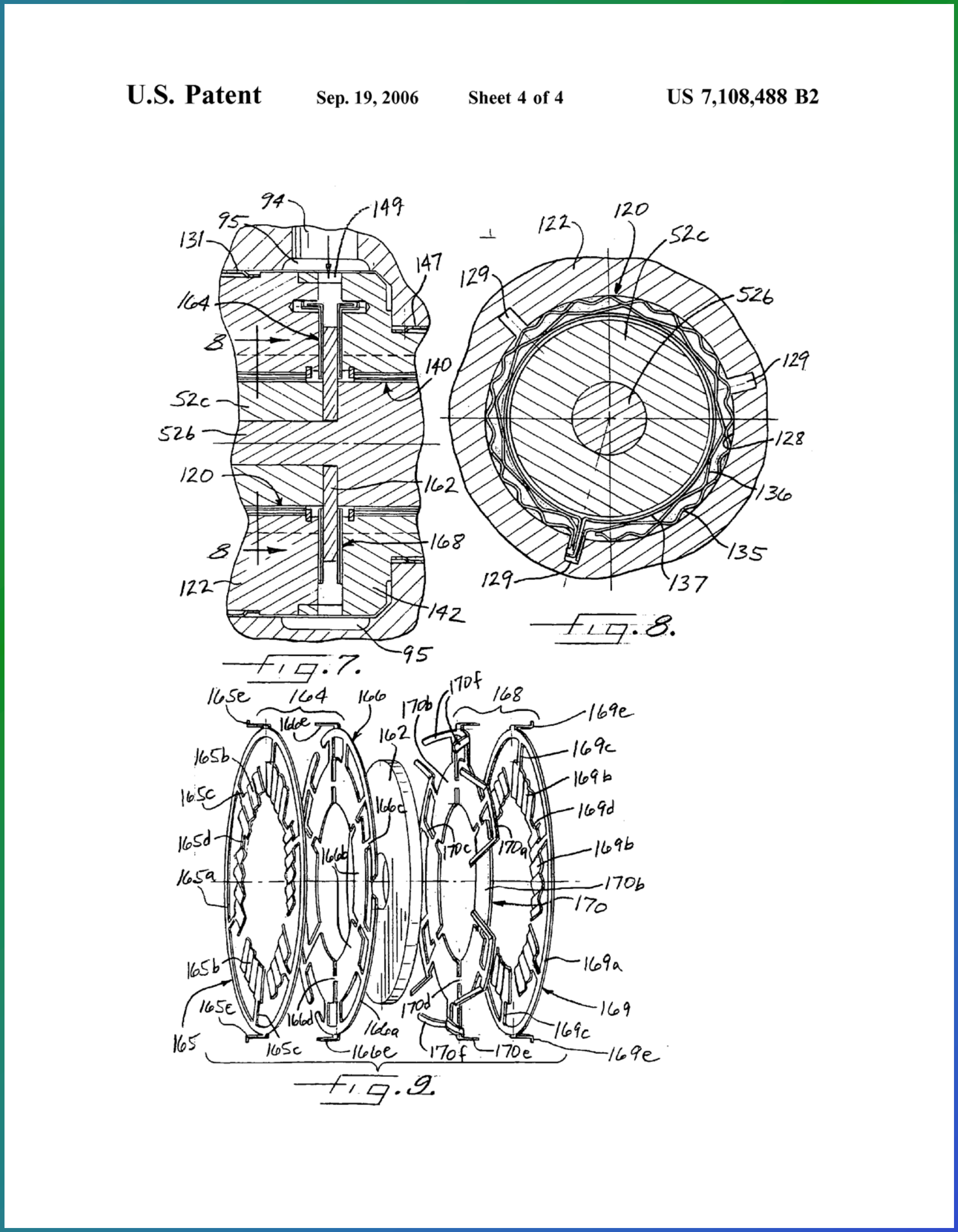
(57) **ABSTRACT**

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



- Gen II journal bearing is self-preloaded
- Thrust bearing is very simple
- Layout mimics NASA turbo
- Patent names NASA PS304 as viable shaft coating
- Background names reduced oil viscosity as driver for going Oil-Free
- Likely to be first high-volume Oil-Free application.
- Very detailed patents



- KIST Oil-Free Turbocharger
- Hyundai Santa Fe engine
- Verified our experience (reduced friction etc.)

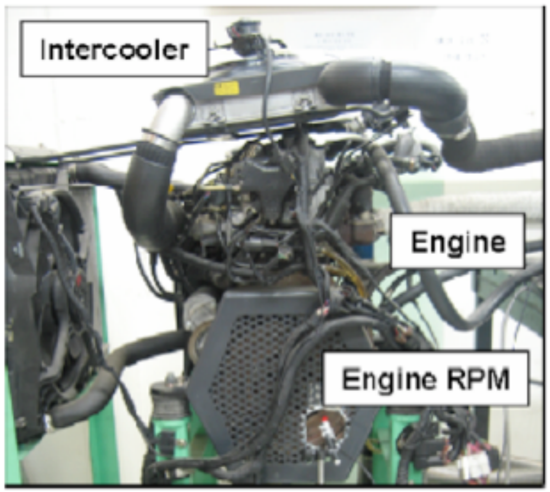
2008 SAE International Powertrains, Fuels and Lubricants Congress, Shanghai, China

Stability and Efficiency of Oil-Free Turbocharger With Foil Bearings for SUV (08SFI-0083)

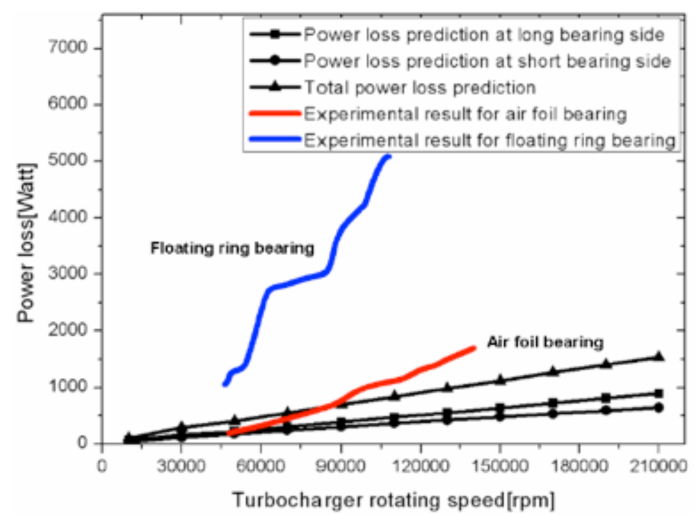
2008. 6.24.

Yong-Bok Lee, Dong-Jin Park, Chang-Ho Kim
Energy Mechanics Research Center
Korea Institute of Science and Technology

◇ SUV Engine & Turbocharger



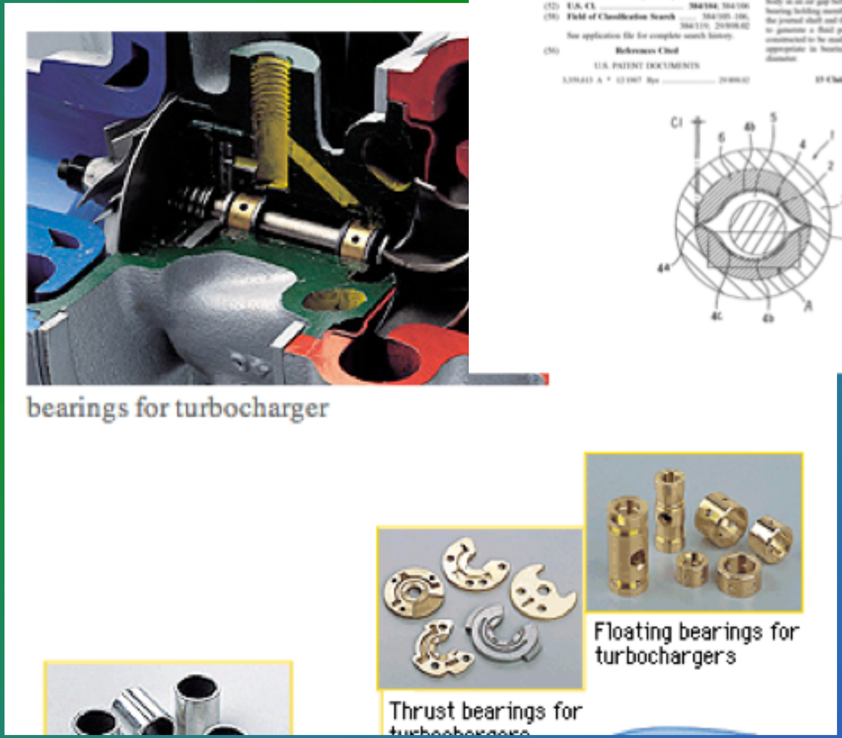
- *CI Diesel Engine – Hyundai D4EA engine, 2.0 TCI for SANTA FE*
- *Tachometer- Engine rotating speed*

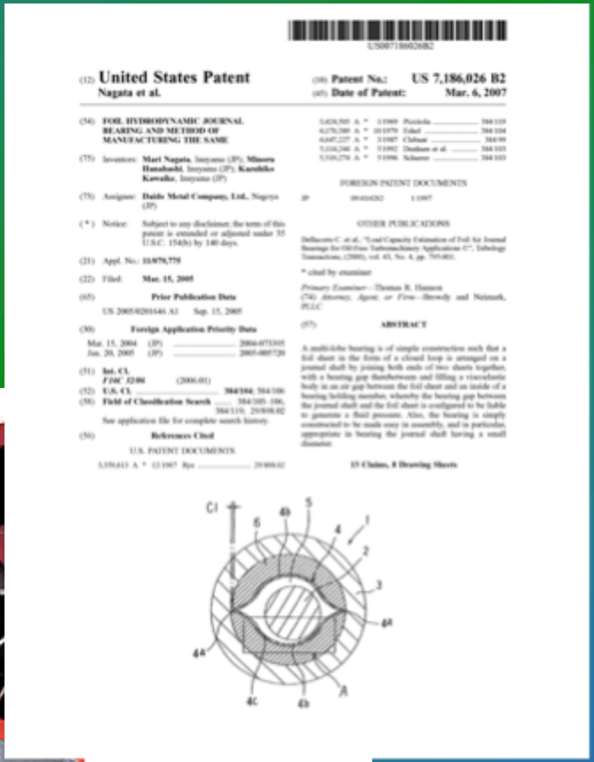


KIST group has designed, built and tested three different sized Oil-Free turbos for their automotive industry.

Automotive OEM's are going Oil-Free

- Daido Metal bearing company (Nagoya)
- Low temperature design
- Very low cost (intended for HD Drive spindles)
- Good for mass production
- Excellent damping
- Oil-Free consumer applications (vacuum cleaners, fans, fuel cell blowers, etc.).





United States Patent
Nagata et al.

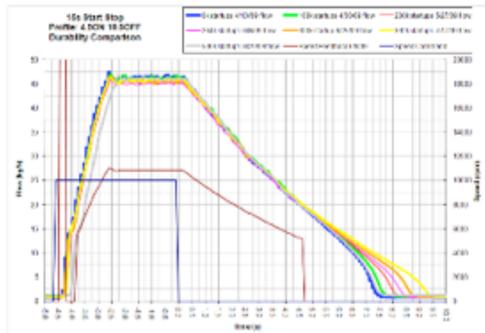
Patent No.: US 7,186,026 B2
Date of Patent: Mar. 6, 2007

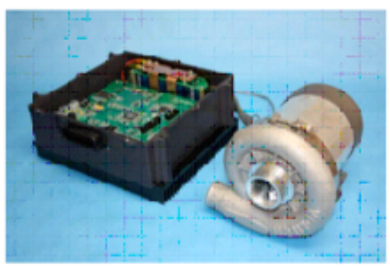
(54) FOIL HYDRODYNAMIC JOURNAL BEARING AND METHOD OF MANUFACTURING THE SAME

Innovative designs will lead to new machines for market

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



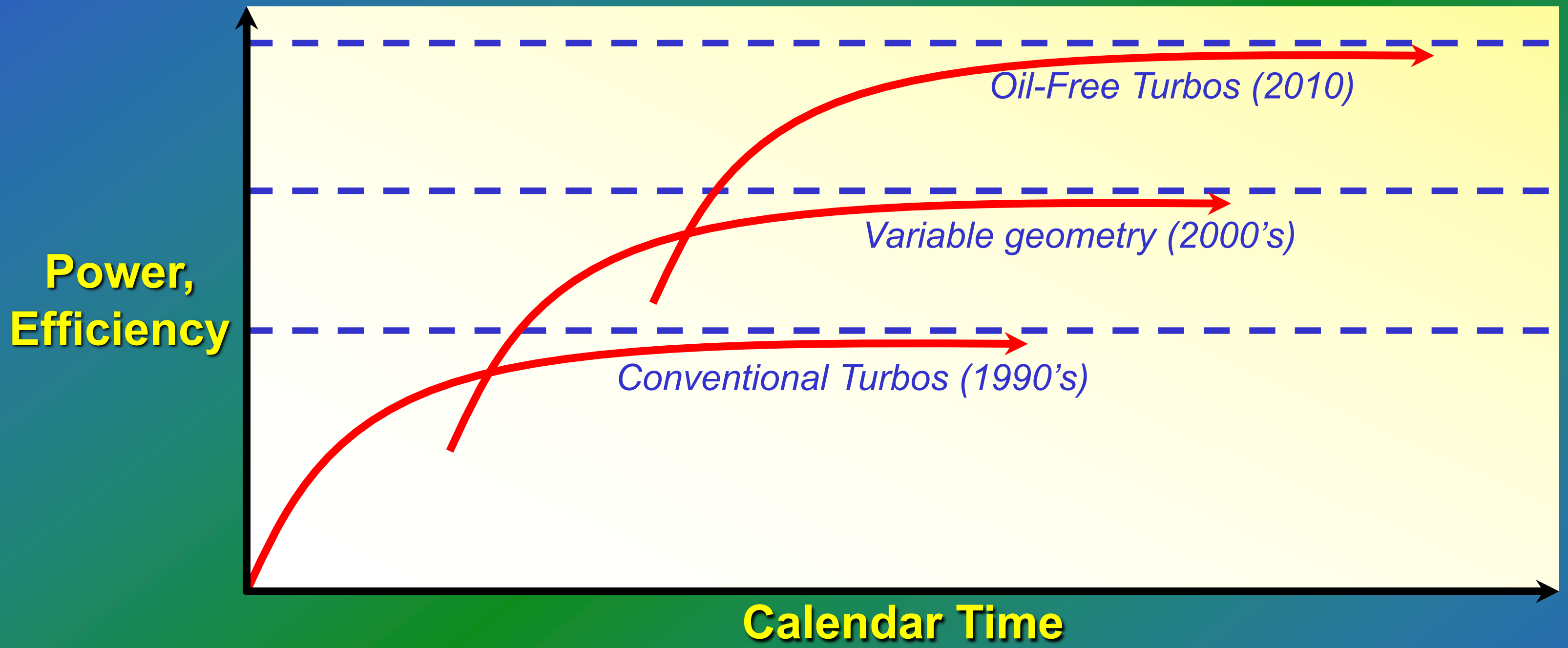


*Neuros Air Foil Bearings Successfully Passed 500,000 cycles of Start/Stop Durability Test

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.

Technology Example

Turbocharger Efficiency



Oil-Free technology is just the initial entry point to dramatically improved systems that include rigid sub-critical rotors, reduced tip clearance, eliminate oil seal leakage emissions, increased DN, no soak back issues, flexible orientation, etc.

Short Summary

- **Oil-Free Turbocharger at a transition point**
  - **Technology commercialized in microturbines, blowers and larger turbocompressors.**
  - **High volume application yet to be done but no “deal breakers” are apparent.**
  - **Turbocharger manufacturer will carry the technology forward.**

Summary

- Growing acceptance that turbomachinery design and performance, and emissions is limited by current (oil) conventional bearing.
- Bearing research has resulted in a firm understanding of load capacity, dynamic properties, manufacturing and integration.
- Foil bearing commercialization into turbochargers will greatly aid technology maturation and acceptance for aerospace applications.
- It is time to transition the Oil-Free technologies into industry so that profits can adequately fund further development.
- Collaborative relationships provide mutually beneficial opportunities for technology development.

Oil-Free Enabling Technology:

Gas Foil Bearings

by

Dr. Christopher DellaCorte (NASA)

Glenn Research Center at Lewis Field

Cleveland, Ohio

January 25th, 2018

Schaeffler, A.G.

Schweinfurt, Germany