Gas Bearings for Microturbomachinery

Rotordynamic Performance & Stability

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Justification

Current advancements in vehicle turbochargers and midsize gas turbines need of proven gas bearing technology to procure compact units with improved efficiency in an oil-free environment.

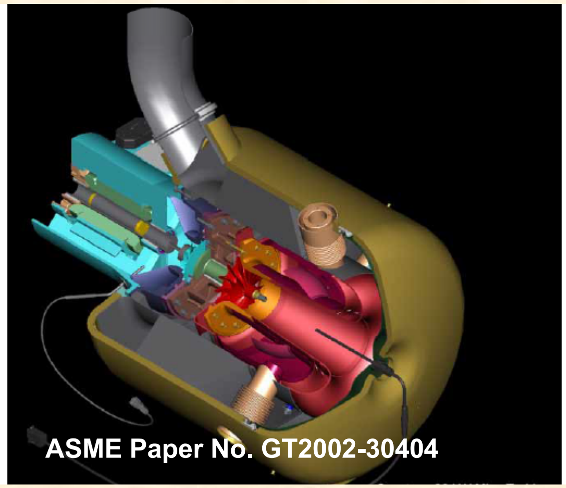
DOE, DARPA, NASA interests range from applications as portable fuel cells (< 60 kW) in microengines to midsize gas turbines (< 250 kW) for distributed power and hybrid vehicles.

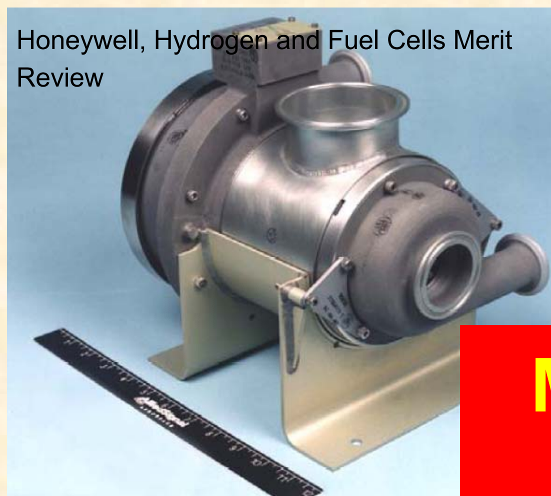
Gas Bearings allow

- **weight reduction, energy and complexity savings**
- **higher temperatures, without needs for cooling air**
- **improved overall engine efficiency**

Microturbomachinery as per IGTI

Drivers:
deregulation in distributed power, environmental needs, increased reliability & efficiency


ASME Paper No. GT2002-30404


Honeywell, Hydrogen and Fuel Cells Merit Review

Distributed power (Hybrid Gas turbine & Fuel Cell), Hybrid vehicles

Automotive turbochargers, turbo expanders, compressors,

Max. Power ~ 250 kWatt

Micro Gas Turbines

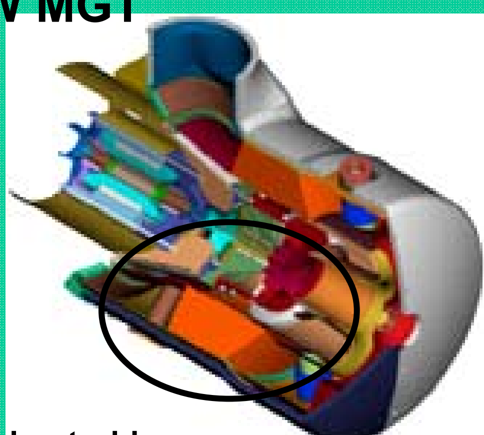
Microturbine Power Conversion Technology Review, ORNL/TM-2003/74.

Cogeneration systems with high efficiency

- Multiple fuels (best if free)
- 99.99X% Reliability
- Low emissions
- Reduced maintenance
- Lower lifecycle cost

MANUFACTURER	OUTPUT POWER (kW)
Bowman	25, 80
Capstone	30, 60, 200
Elliott Energy Systems	35, 60, 80, 150
General Electric	175
Ingersoll Rand	70, 250
Turbec, ABB & Volvo	100

60kW MGT



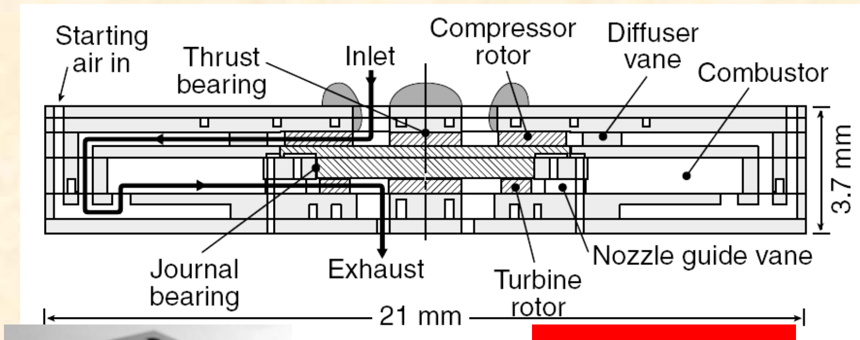
www.microturbine.com

Hybrid System : MGT with Fuel Cell can reach efficiency > 60%

Ideal to replace reciprocating engines. Low footprint desirable

Ultra Microturbomachinery

MEMS MTM

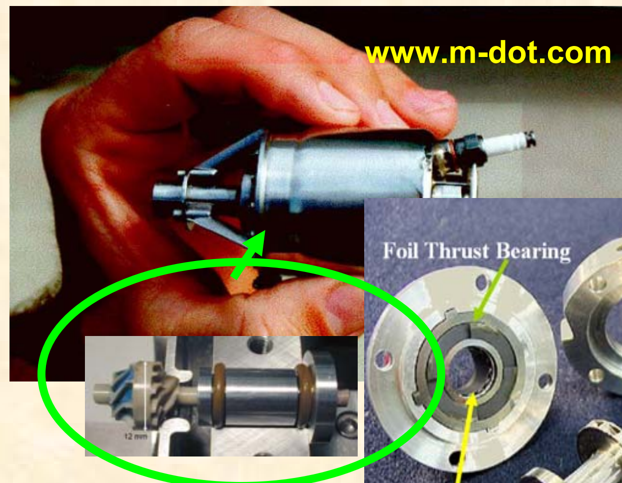


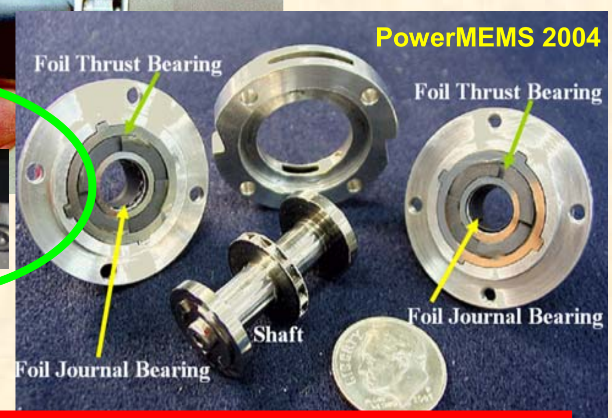
GT-2003-38866

- Silicon wafer
- 1.2 Million rpm
- Thrust 0.1 N
- Spiral groove and hydrostatic gas bearings

Meso-scale MTM

- Palm-size power source
- Brayton cycle
- Gas foil bearings





100 Watt & less

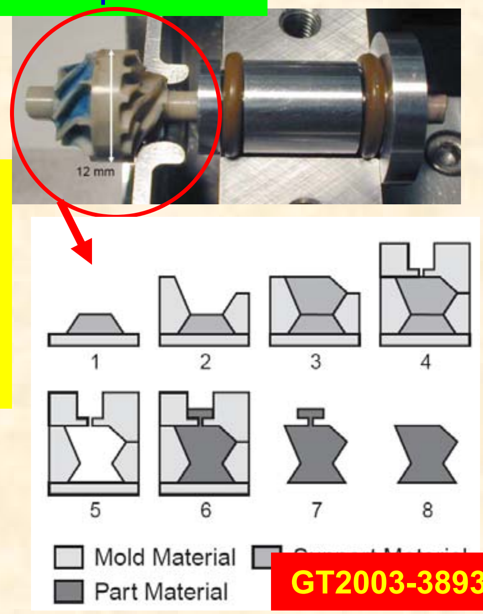
Small unmanned vehicles and to replace batteries in portable electronic devices

MTM materials & fabrication

Fabrication

- Mold SDM
- Precision 3D Milling
- MEMS

Mold SDM process



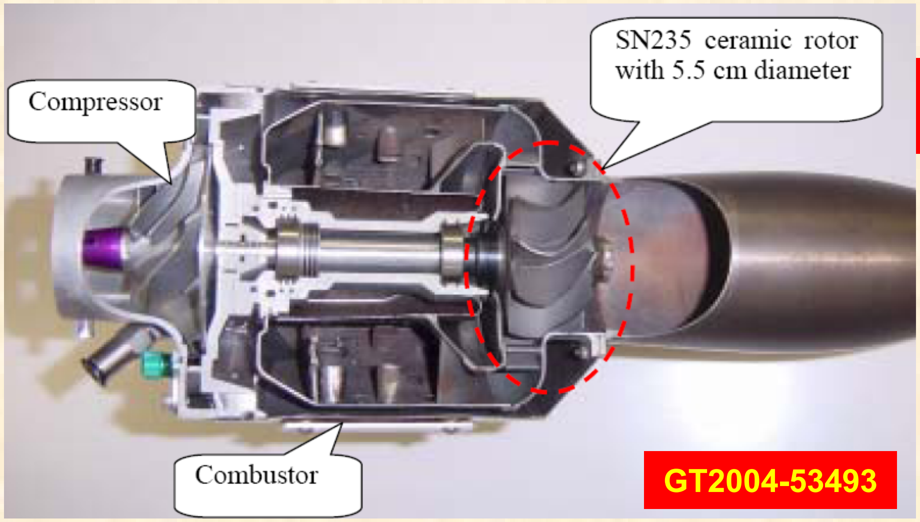
GT2003-38933

3D Milling

GT2003- 38151

DRIE process

GT2003-38866



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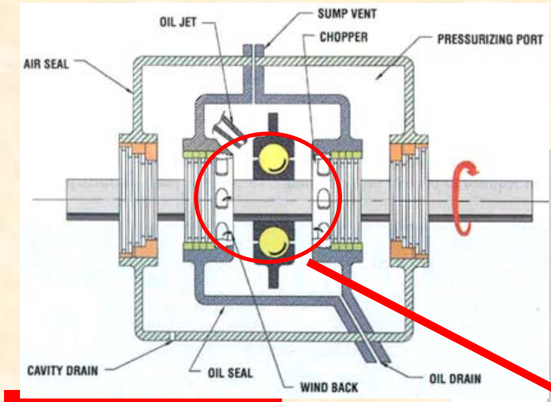
Materials & Reliability

- High temperature durability
- Light weight

Available Bearing Technologies

Rolling element bearings

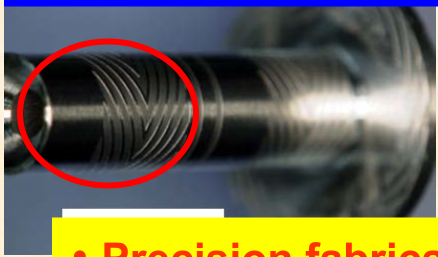
- Low temperatures
- Low DN limit (< 2 M)
- Need lubrication system



AIAA 2004-4189

PowerMEMS 2003

Herringbone grooved bearing



NICH Center, Tohoku University

- Precision fabrication process
- Low load capacity and stiffness and little damping

GAS BEARINGS

- Oil-Free
- NO DN limit
- Low friction and power loss
- Thermal management

Gas Foil Bearing

AIAA-2004-5720-984

Flexure Pivot Bearing

GT 2004-53621

MTM – Needs, Hurdles & Issues

Largest power to weight ratio,
Compact & low # of parts

High energy density

Reliability and efficiency,
Low maintenance

Extreme temperature and pressure

Environmentally safe (low emissions)

Lower lifecycle cost ($ kW)

High speed

Rotordynamics &
(Oil-free) Bearings & Sealing

Materials

Coatings: surface conditioning for low friction and wear
Ceramic rotors and components

Manufacturing

Automated agile processes
Cost & number

Processes & Cycles

Low-NOx combustors for liquid & gas fuels
TH scaling (low Reynolds #)

Fuels

Best if free (bio-fuels)

Gas Bearings for Oil-Free MTM

Advantages of gas bearings over oil-lubricated bearings

- Process gas is cleaner and eliminates contamination by buffer lubricants
- Gases are more stable at extreme temperatures and speeds (no lubricant vaporization, cavitation, solidification, or decomposition)
- Gas bearing systems are lower in cost: less power usage and small friction, enabling savings in weight and piping

Gas Bearings Must Be Simple!

Ideal gas bearings for MTM

Load Tolerant – capable of handling both normal and extreme bearing loads without compromising the integrity of the rotor system.

Simple – low cost, small geometry, low part count, constructed from common materials, manufactured with elementary methods.

High Rotor Speeds – no specific speed limit (such as DN) restricting shaft sizes. Small Power losses.

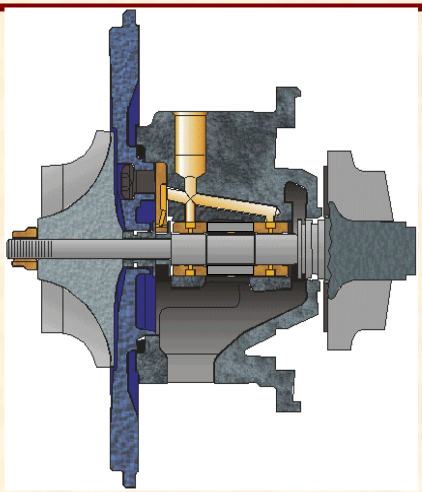
Good Dynamic Properties – predictable and repeatable stiffness and damping over a wide temperature range.

Reliable – capable of operation without significant wear or required maintenance, able to tolerate extended storage and handling without performance degradation.

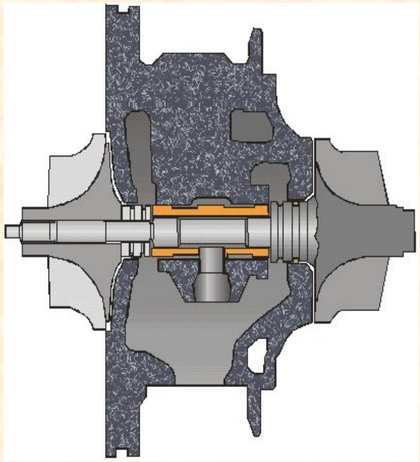
+++ Modeling/Analysis (anchored to test data) available

Example: Turbochargers

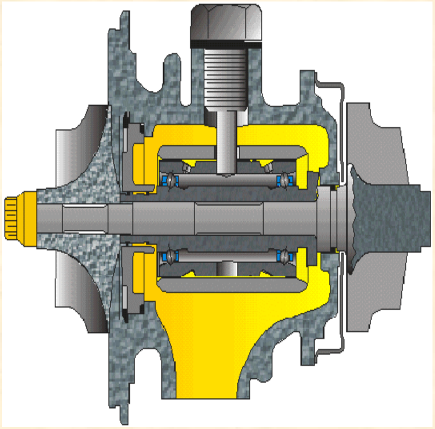
RBS: **R**otor **B**earing **S**ystem



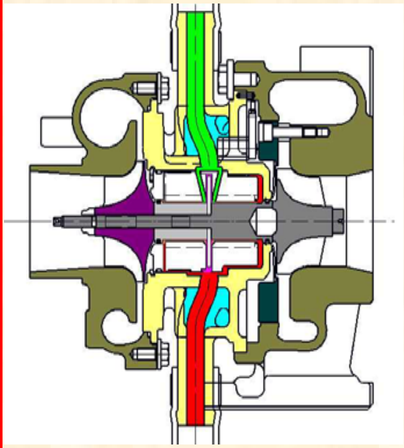
RBS
With Fully Floating Bearing



RBS
With Semi Floating Bearing



RBS
With Ball Bearing



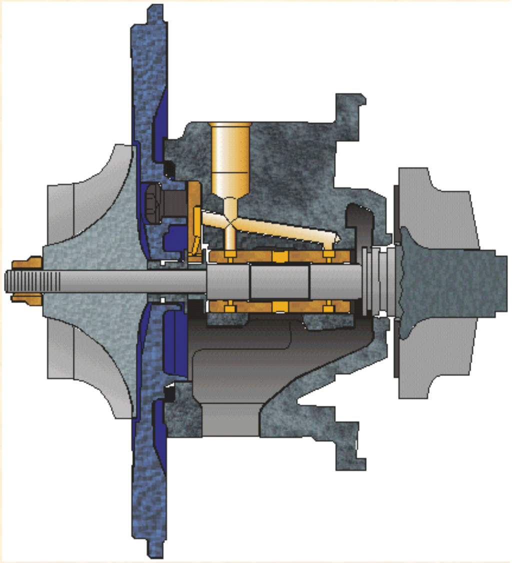
Oil Less Bearing System (2007)

Increased engine efficiency and performance relies on a robust rotor-bearing system

DETC2007-34136

Technical requirements for turbochargers

	PV turbo	CV turbo
Compressor wheel diameter (mm)	41 to 60	71 to 183
Rotor weight (gram)	68 to 182	459 to 6690
Max speed (krpm)	169 to 247	61 to 157
DN (rpm-mm)	3.7 M	5.75 M
Tip speed (m/s)	800	752
P V (psi ft/s)	6 M	8.77 M



Bearing technologies

- Preformed bushings
- Ceramic rolling element bearings
- Rigid geometry gas bearings
- Flexure tilting pad gas bearings
- Foil gas bearings
- Solid lubricant films (coatings)
- Active and passive magnetic bearings

Preformed Bushings

Self-lubricating material, typically a thermoplastic or a graphite derivative. The bushings may have a rigid support backing (steel or bronze).

Vespel, Torlon, Peek
Graphalloy

Limits:
PV 300,000 psi ft/min
Low Temperature

Advantages:

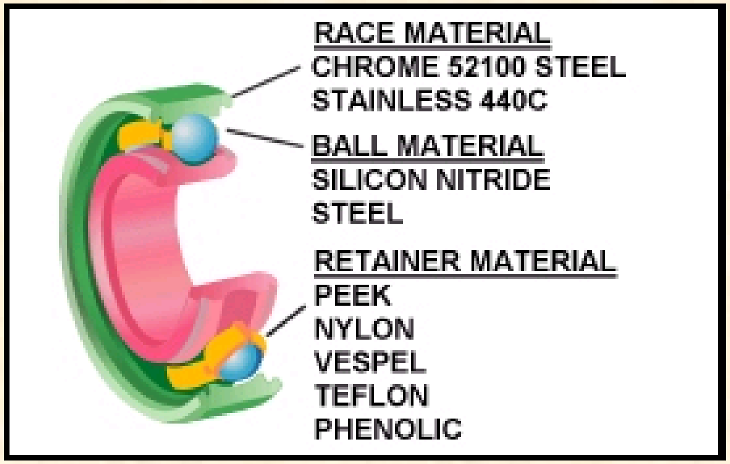
- No lubrication required
- Simple design and construction
- Moderate friction and wear
- Inexpensive
- Off the shelf items
- Low conductivity – electrical and thermal insulation.

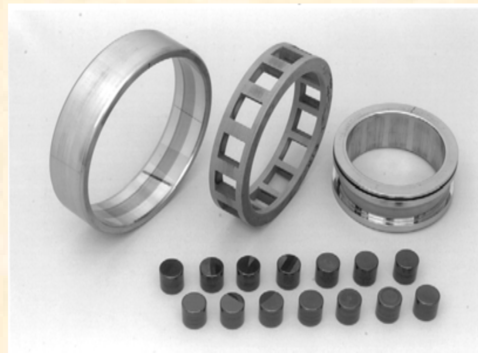
Disadvantages:

- Dynamic behavior unknown
- Restricted to low P-V numbers.
- Relatively Low temperature limit (Graphalloy bushings to 1000 F).
- Simple cylindrical configurations molded
- Not suitable for high speeds
- Unknown hydrodynamic performance

Ceramic Rolling Element Bearings

silicon nitride (Si_3N_4) balls and hardened steel outer and inner raceways. Cage retainer made of thermoplastics (PTFE with bronze impregnated, Vespel™, Thorlon™, Peek™, Nylon)





Dry friction μ= 0.17
(compare to 0.42 steel/steel)
Need lubrication to last, Expensive

Advantages:

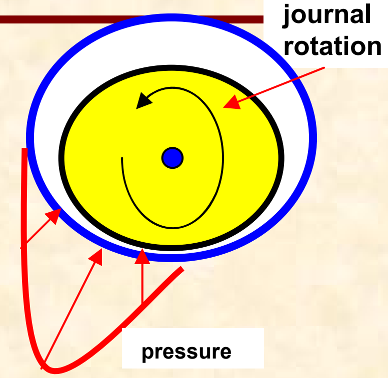
- High speed and acceleration - up to 3 million DN
- Increased stiffness
- Less friction, less heat
- Low thermal expansion, higher accuracy
- Non-conductive
- Extended operating life
- Ability to support thrust (axial) loads.

Disadvantages:

- Requires some form of lubricant for extended usage.
- Higher cost for parts and lubricant
- Operating temperature limited by lubricant
- Dissimilar heat expansion of materials can cause seizure.
- Too stiff, little damping.

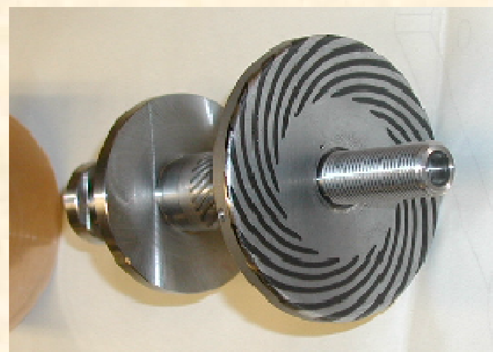
Rigid Geometry Gas Bearings

Gas film bearings (hydrostatic/hybrid) give low friction and support load (< 1 bar)



Plain journal bearing

Cheap!



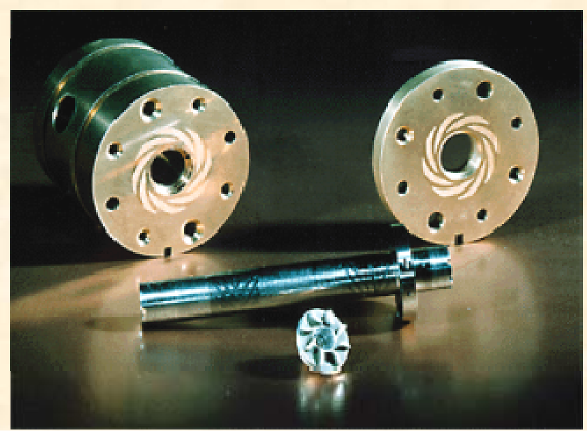
Major issues:

Little damping,

Wear at start & stop,

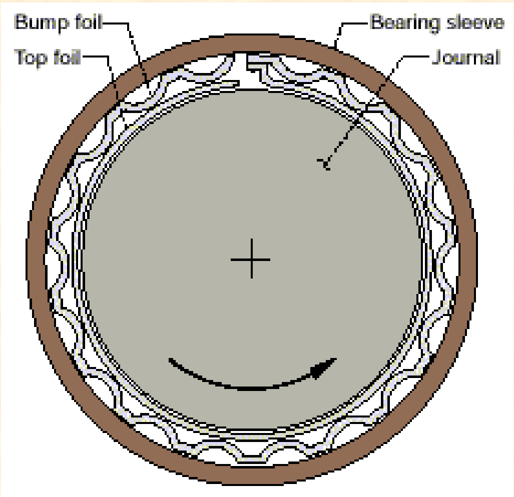
Instability (whirl & hammer)

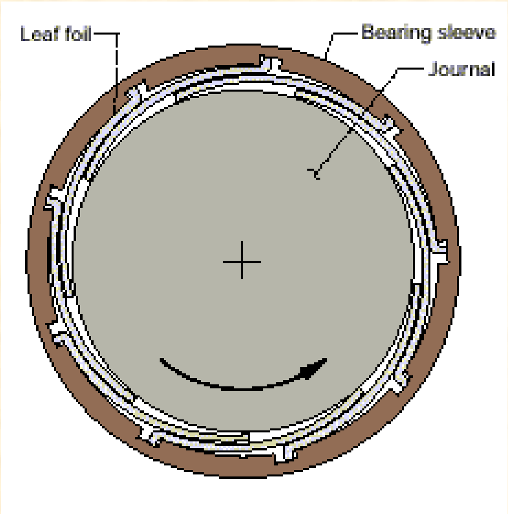
Herringbone grooved journal bearings and spiral groove thrust bearings for gas turbo expanders



Gas Foil Bearings

Foil bearings integrate a gas film in series with an elastic substructure. **Bump foil and multi-leaf foil** bearings are used. **Foils must be coated to avoid wear and seizure, and to reduce drag friction during frequent start and stops.**





Currently used in micro power (<100 kW) systems and secondary cryogenic turbopumps

Issues:

Excessive cost / Protected technology
Extensive testing for coatings
Rotordynamic instability or forced nonlinearity
Thermal management Issues
Complicated analysis tools

Expensive!

Source: NASA Oil Free MTM program

Coatings (Solid Lubricant Films)

Solid lubricant films ensure low friction and reduced surface wear rates while promoting early rotor lift off.

Applied with plasma spray, ion beam deposition, sputtering, and chemical vapor deposition.
PS304, Near Frictionless Carbon Coating (NFC™) , UltraC Diamond™, Casidiam™ , Fluoropolymer (EMRALON™), Molybdenum and Graphite coatings

Low friction coefficients in air are as low as 0.10

Still costly for mass production !

Source: NASA Oil Free MTM program

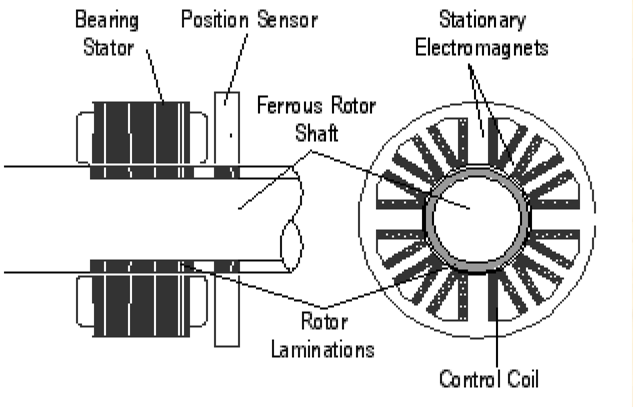
Undercut shaft First plasma spray Second plasma spray Polished

Procedure for depositing PS304 coating on shaft

Vital for MTM!

Active Magnetic Bearings

Attraction type – controlled 5 axes



Limitations

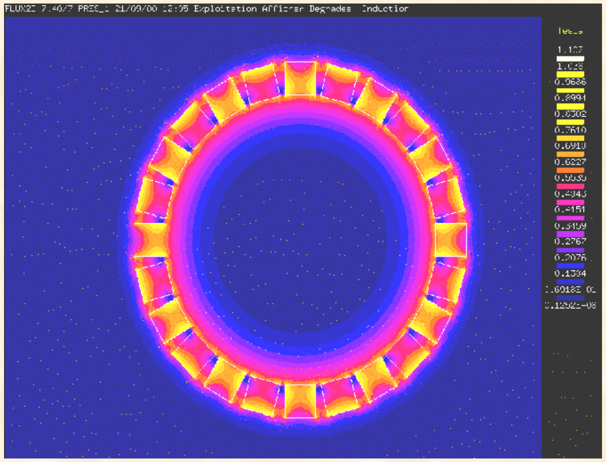
- Cost,

- Low temperature,

- Complexity

Passive Magnetic Bearings

Permanent magnet – reluctance bearings



Expensive!

Rankings for gas bearings

RRD: relative ranking of current state of development.

(1): off the shelf item with proven results over a wide range of applications

(2): readily available technology, engineering analysis or experimentation required

(3): known technology, both engineering and testing required

(4): some applications known, largely empirical development

(5): unknown product, research phase.

RRA: ranking for readiness of application to oil-free TCs

(1): readily available engineered product proven for TC application

(2): technology known, engineering analysis in progress, manufacturing process and performance issues for TC application.

(3): technology available, proven engineer ing analysis, product development needed to extend limits of application.

(4): some applications known, largely empirical development at this time

(5): unknown application to oil-free TC.

	Technology	Details	Cost/unit	RRD	RRA
A	Preformed bushings	Thermoplastics & Graphite derivatives	$30.00 unit	1	4
B	Ceramic rolling element bearings	Ceramic – steel Contained lubricant	$33.00 unit	1	2
C	Rigid geometry gas bearings	Hydrodynamic/ hydrostatic	$2-$4 unit	2	3
D	Tilting pad gas bearings	Hydrodynamic/ hydrostatic	$50 Hypad©	2	3
E	Foil bearings	Hydrodynamic	$ 100 MITI	3	2
G	Active magnetic bearings		$50-100 system (bulk)	3	4
H	Passive magnetic bearings		NA	5	5
F	Solid film lubricants.	Applicable to products C-E			
	Coatings on shaft.	Diamond like coating (DLC).	$0.75 part	2	2
		PS 304	$50 part + grinding	2	3
	Foil coatings	Teflon (Emralon™)	$ 0.50 part (bulk)	1	2

What are the needs?

Make READY technology for industrial application by PUSHING development to

- make of the shelf item with proven results for a wide range of applications;
- engineered product with well known manufacturing process;
- known (verifiable) performance with solid laboratory and field experiences

Gas Bearings for Oil-Free MTM

Thrust:

Investigate **conventional bearings of low cost, easy to manufacture (common materials) and easy to install & align.**

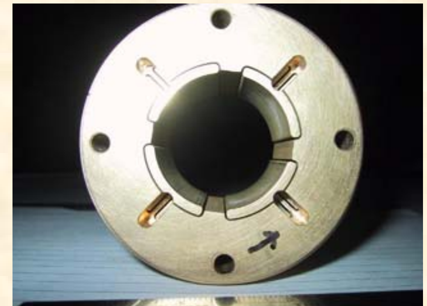
Combine hybrid (hydrostatic/hydrodynamic) bearings with low cost coating to allow for rub-free operation at start up and shut down

Major issues:

Little damping, Wear at start & stop, Instability (whirl & hammer)

Gas Bearing Research at TAMU

2001/2 - Three Lobe Bearings



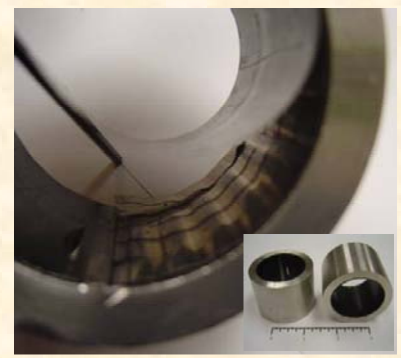
Stability depends on feed pressure.
Stable to 80 krpm with 5 bar pressure

2003/4 - Rayleigh Step Bearings

Worst performance to date with grooved bearings

2002-09 - Flexure Pivot Tilting Pad Bearings

Stable to 93 krpm w/o feed pressure.
Operation to 100 krpm w/o problems. Easy to install and align.



2004-10: Bump-type Foil Bearings

Industry standard. Reliable but costly.
Models anchored to test data.

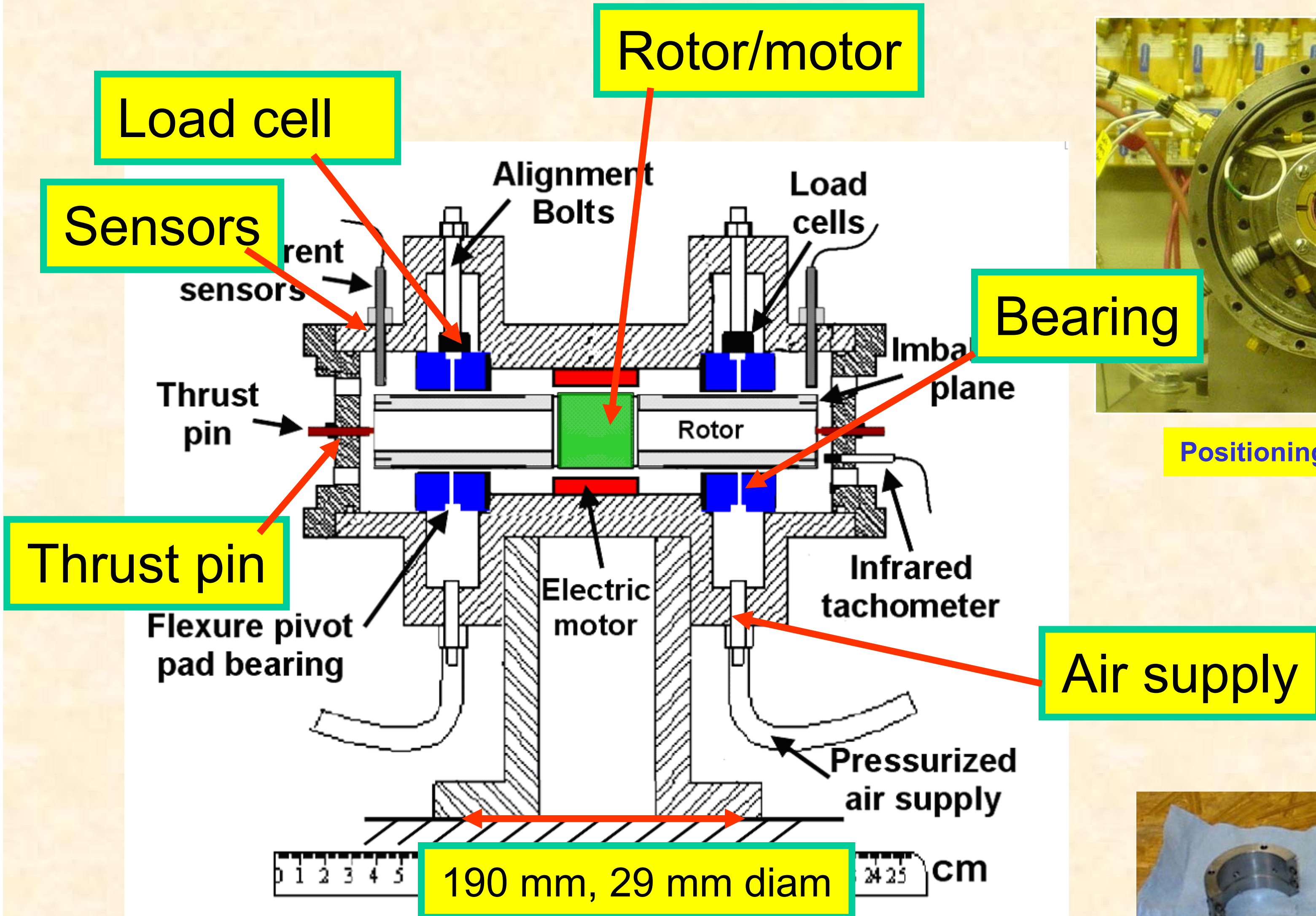
2008-10: Metal Mesh Foil Bearings

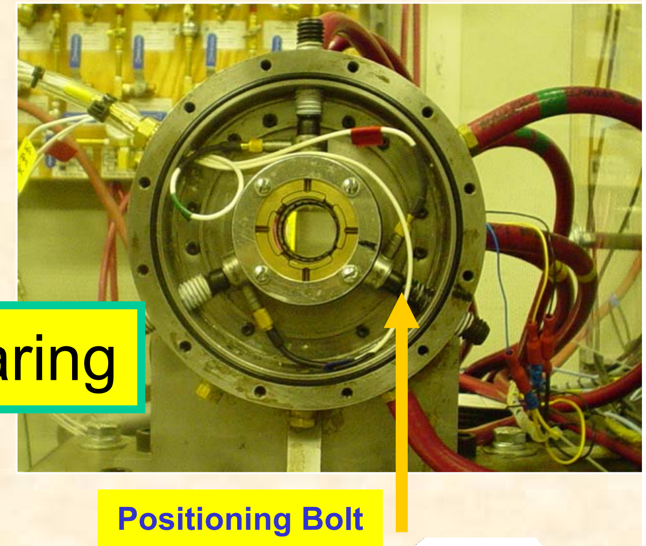
Cheap technology. Still infant. Users needed

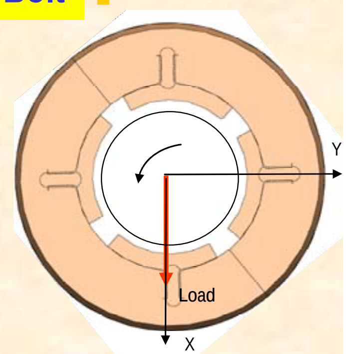
Overview of experience with gas bearings

- Three Lobe Bearings
- Flexure Pivot Tilting Pad Bearings
- Bump-type Foil Bearings
- Metal Mesh Foil Bearings

Hybrid Gas Bearing Test Rig (1)



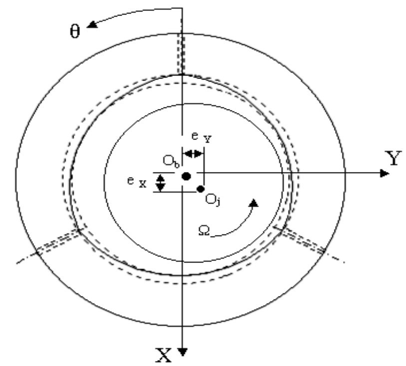




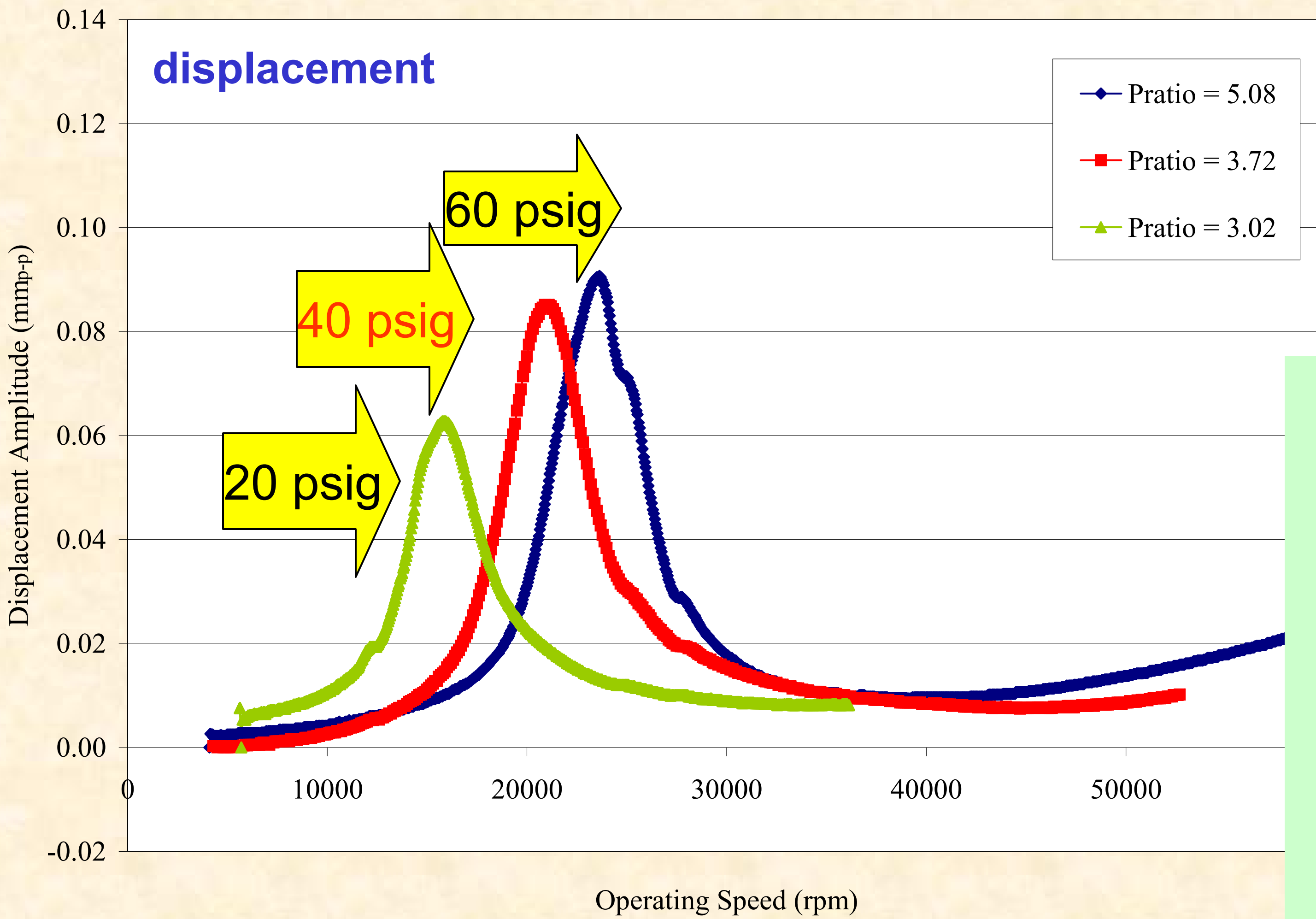
Rotor: 826 grams

Bearings: L= 30 mm, D=29 mm, C < 25 um

Three lobe gas bearings



ASME GT2003-38859



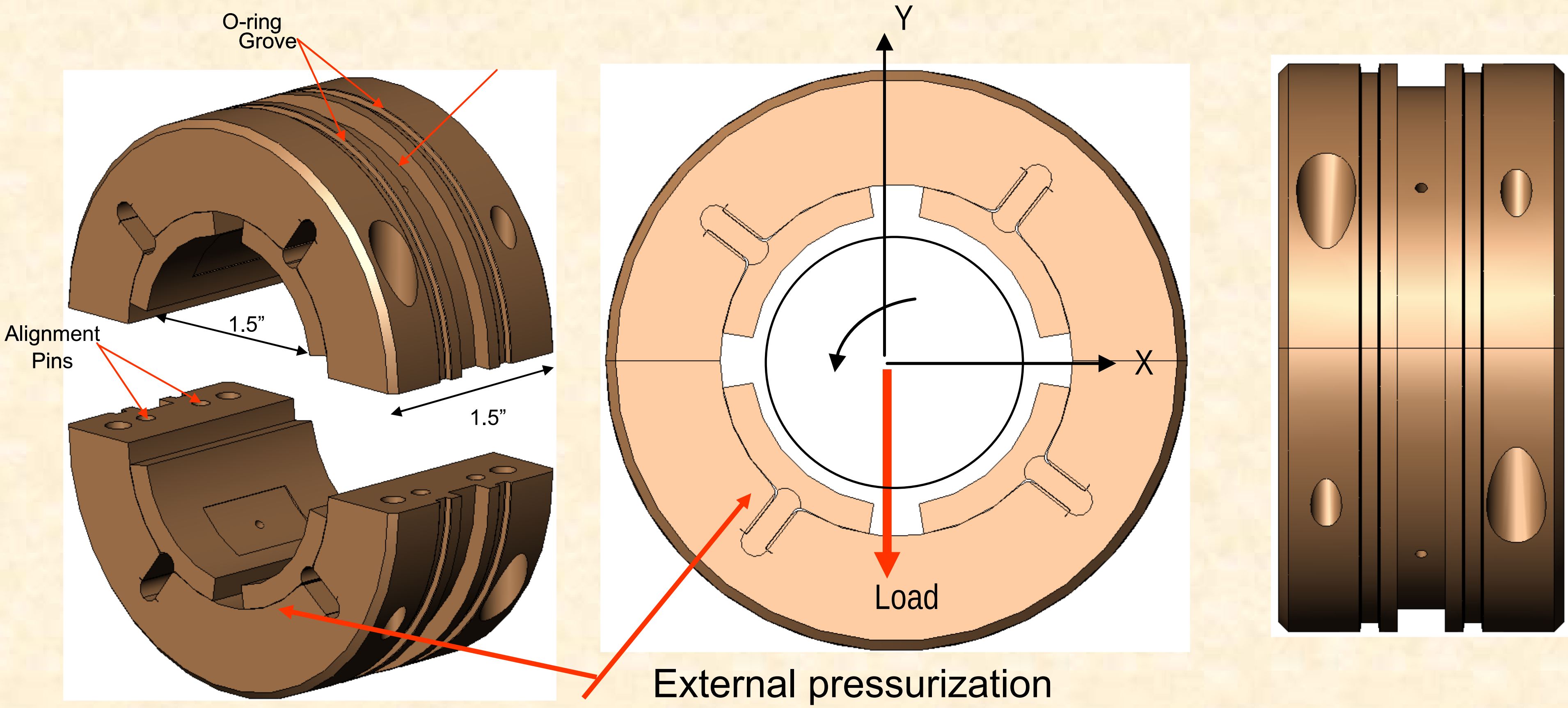
As supply Pressure increases, critical speed rises & damping ratio drops

C=66 um, r:0.32 , do: 1mm

Imbalance response

Flexure Pivot Bearings

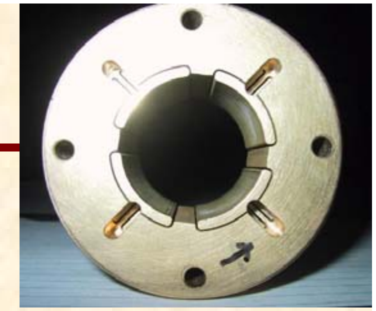
Flexure-Pivot Tilting Pad Bearings



Wire-EDM, low cost, common material, engineered design, no stack-up tolerances,

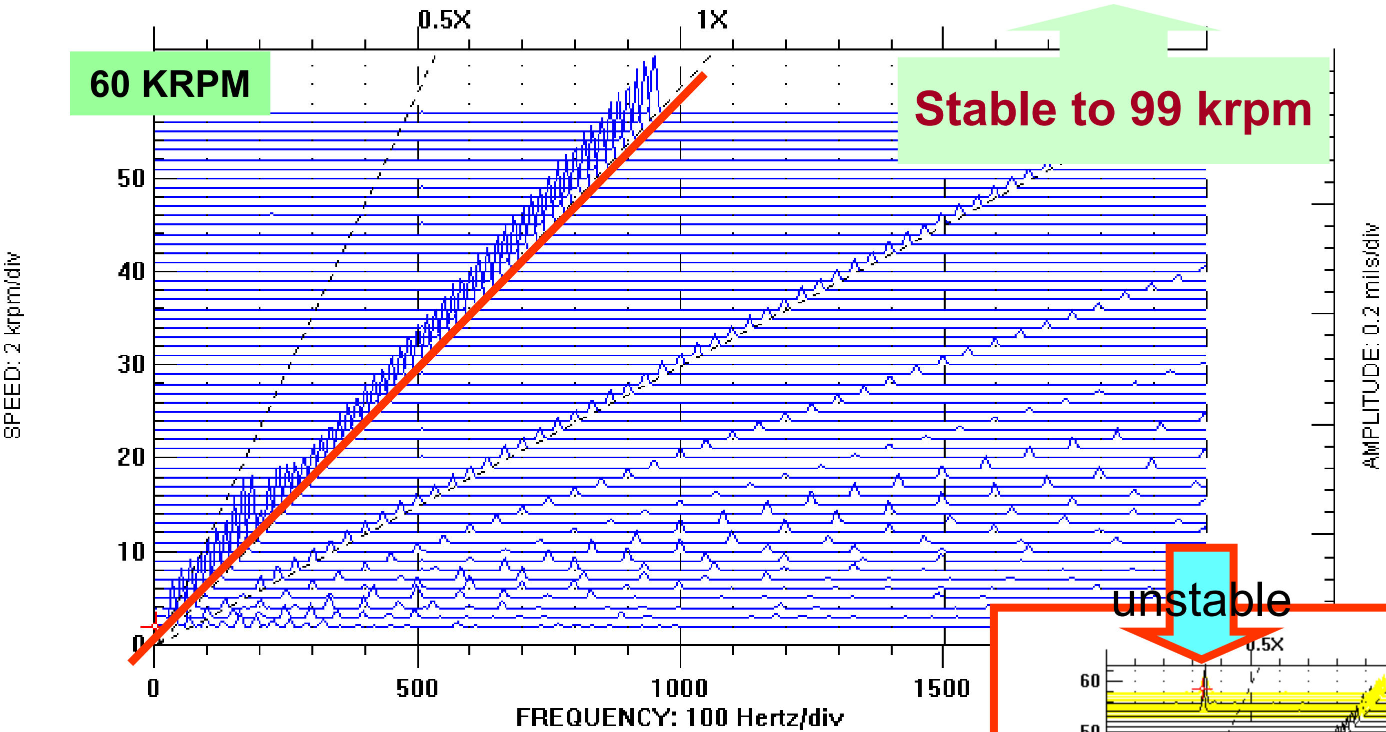
PROVEN record in HP compressors (oil lubricated)

Waterfalls of rotor motion

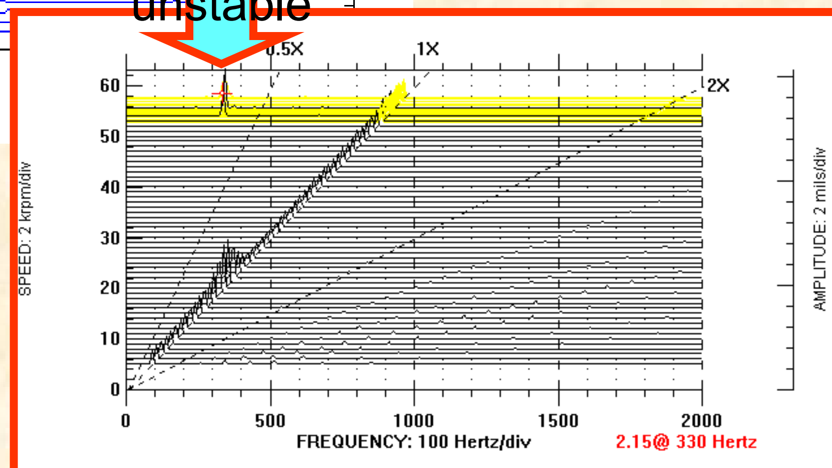


Ps=3.8 bar (40 psig)

GT 2004-53621



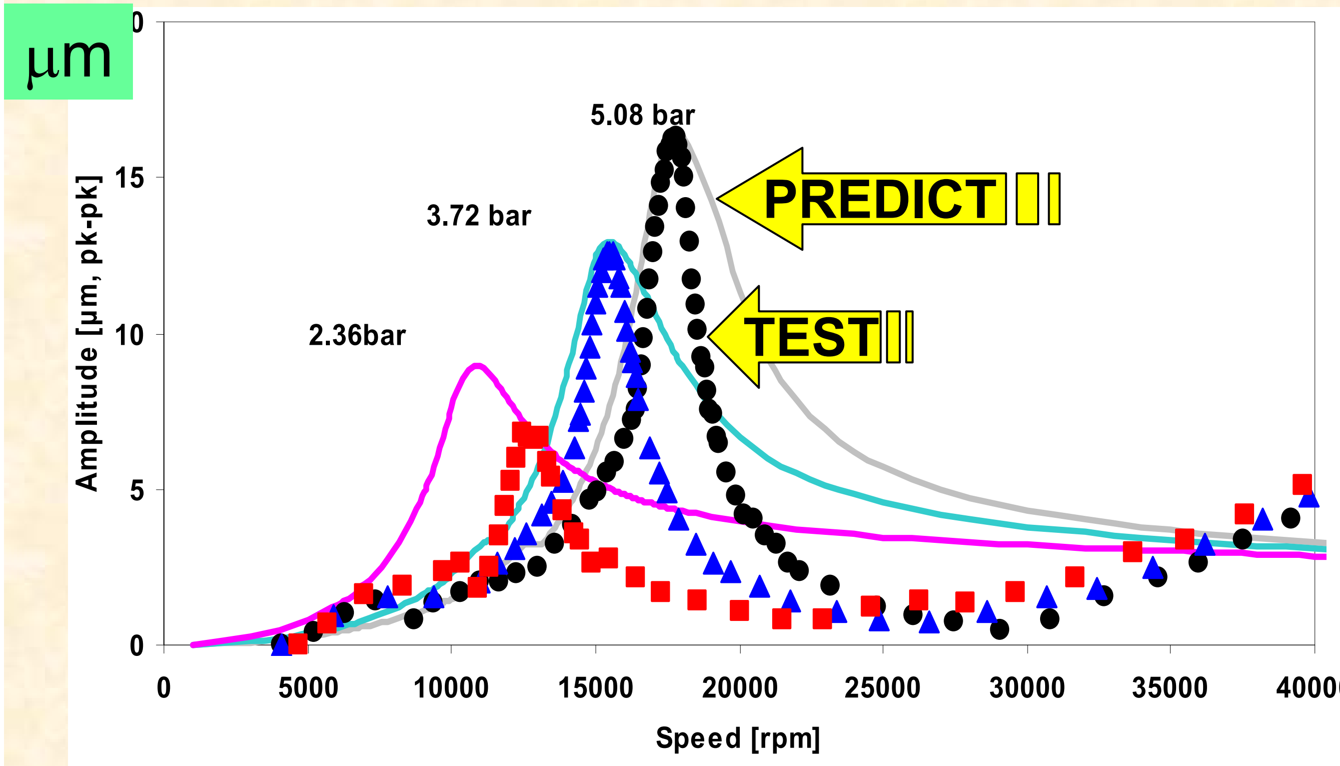
GT 2003-38859

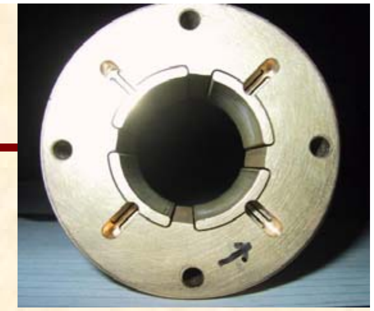


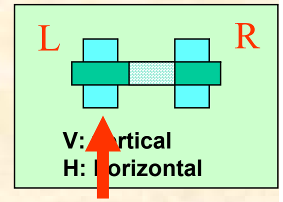
Clean 1X rotor response (no instability – hydrodynamic type)

Three-lobe Bearing (WFR=0.37)

Rotordynamic response







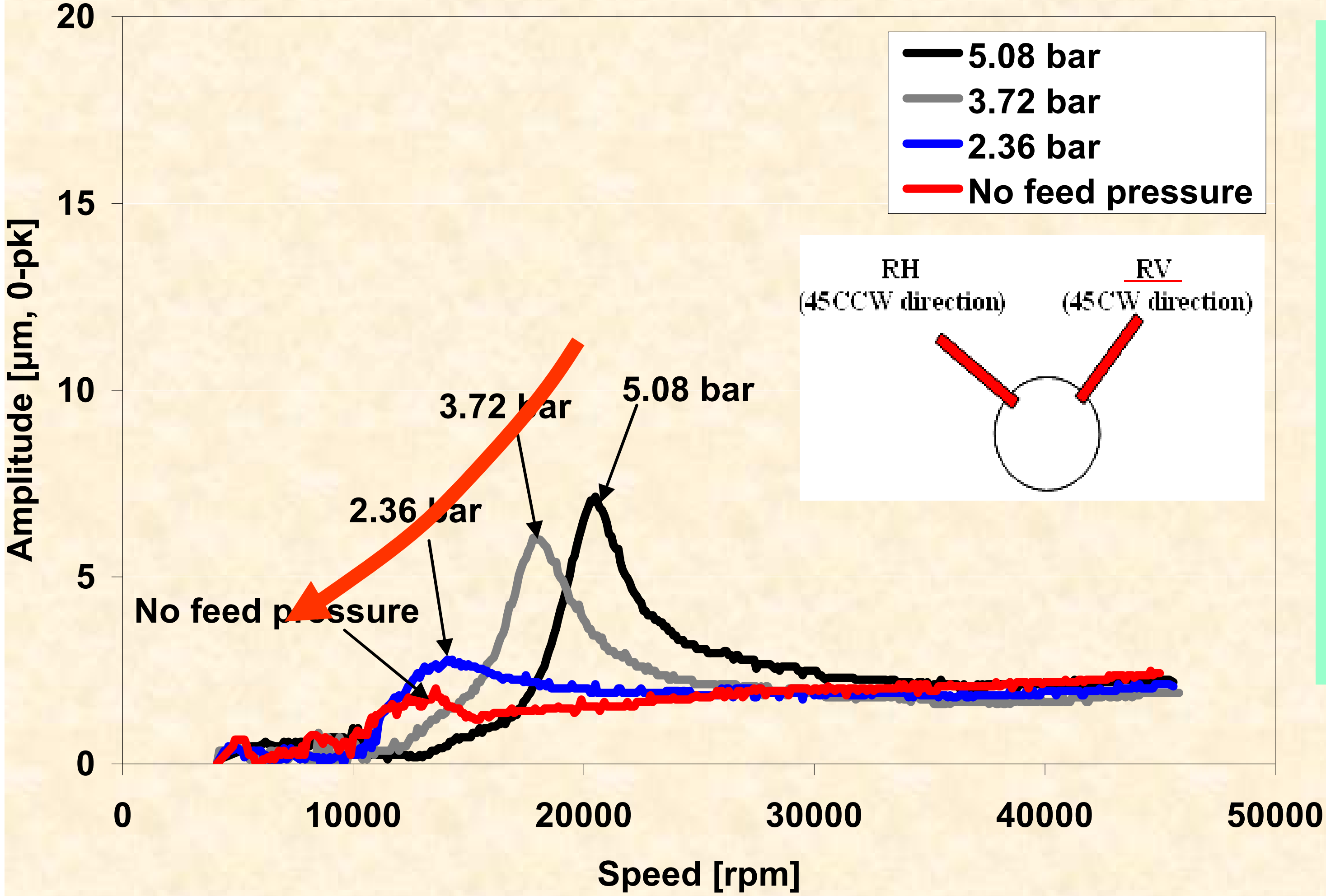
As supply Pressure increases, critical speed raises & damping ratio drops

Predictions vs. test data

Good correlation: tests and rotor-gas bearing model predictions

IJTC 2006-12026
ASME GT2008-50393

A way to control rotordynamics?

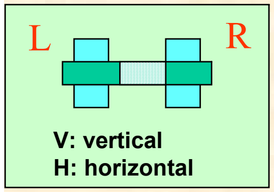


Question:

If shaft speed regulates feed pressure, could large rotor motions be suppressed ?

ASME 2007-27127

Towards suppression of critical speeds



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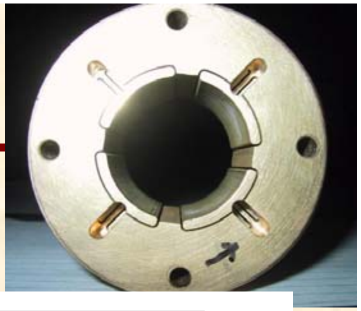
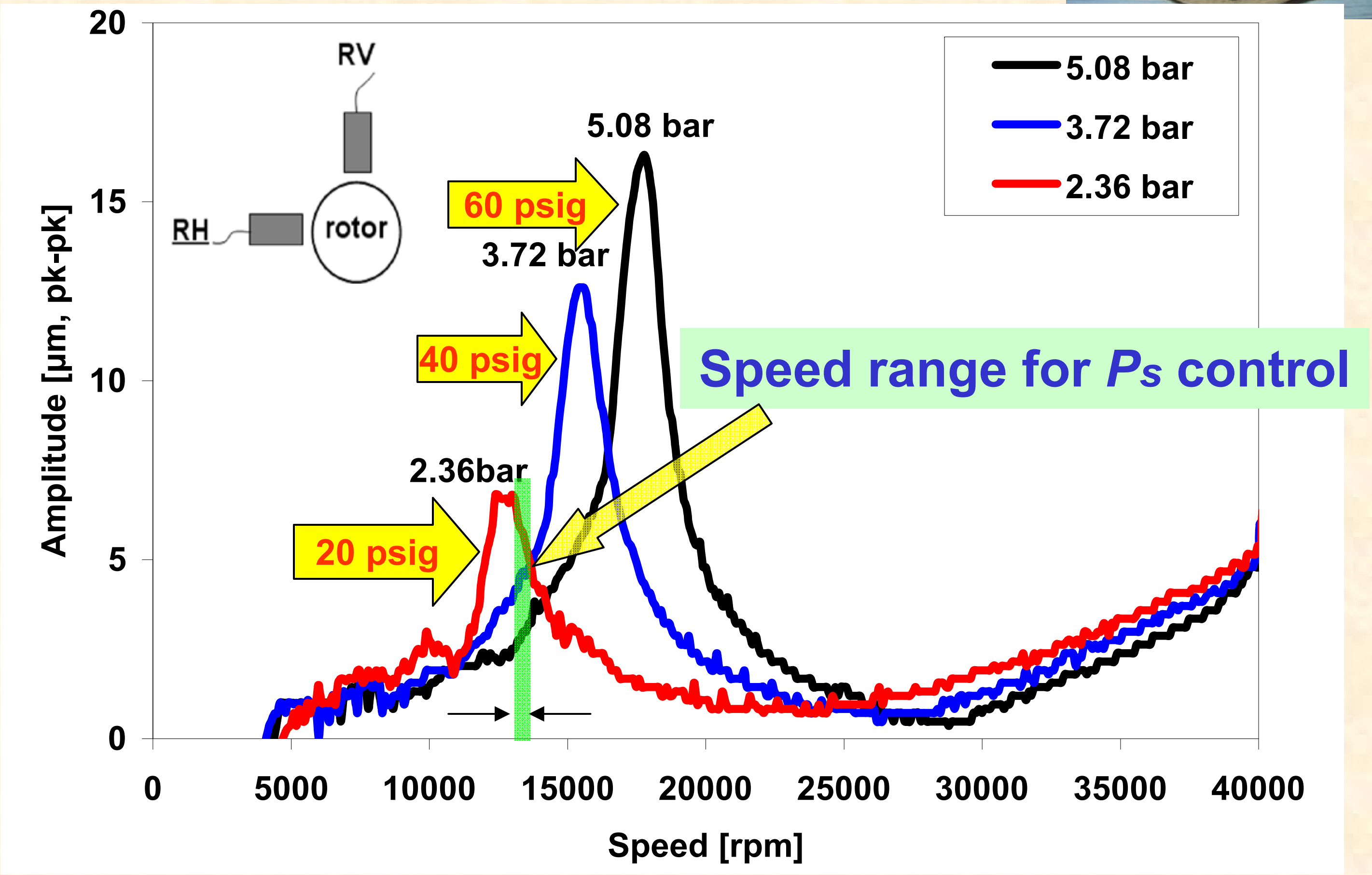
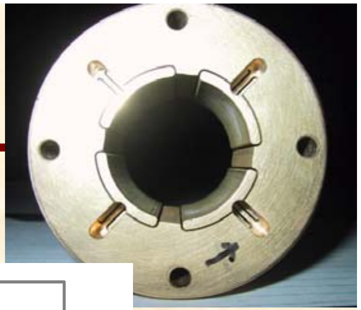




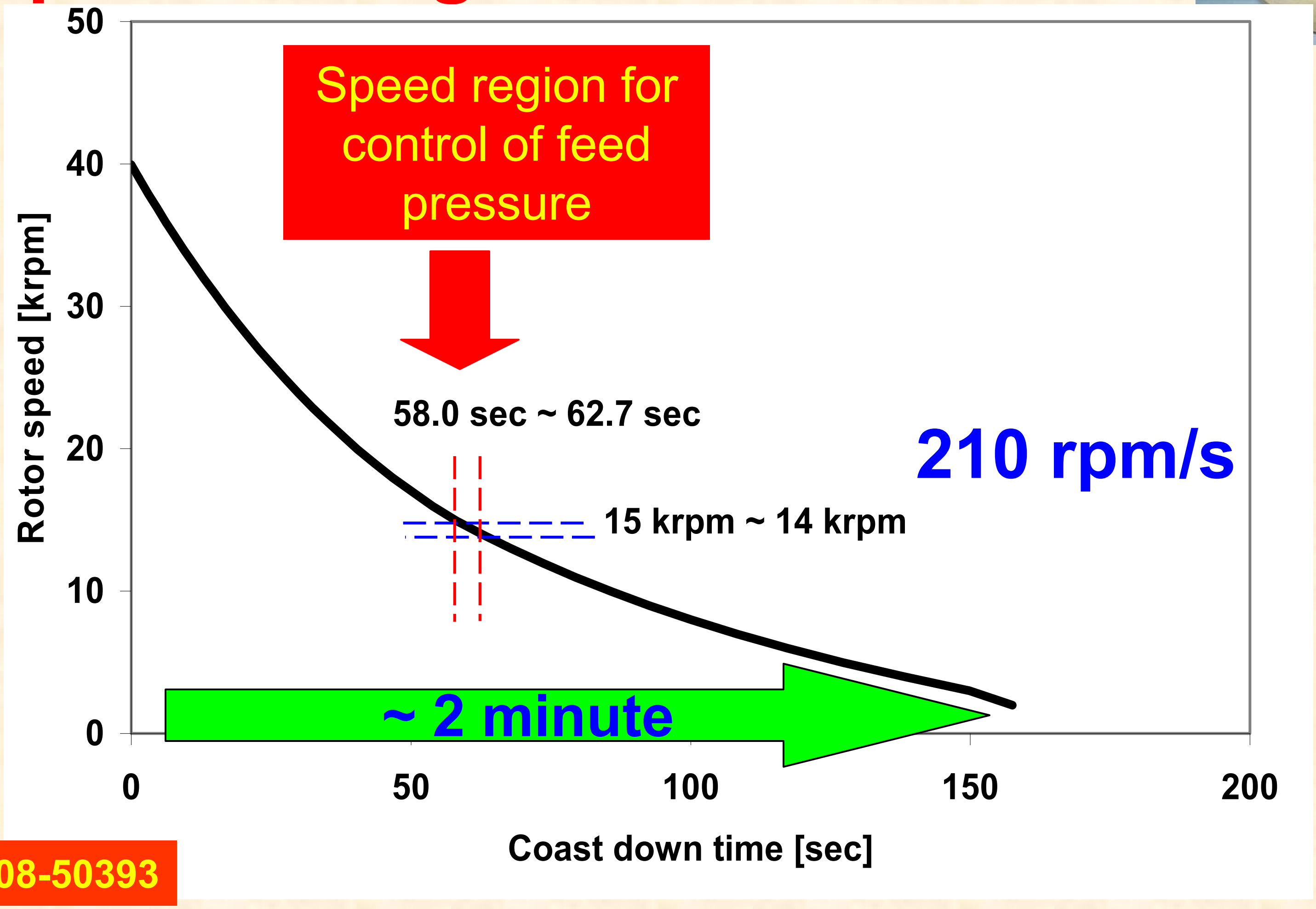
As pressure supply increases, critical speed raises and damping ratio decreases

Towards suppression of critical speeds



Rotor speed during coast down

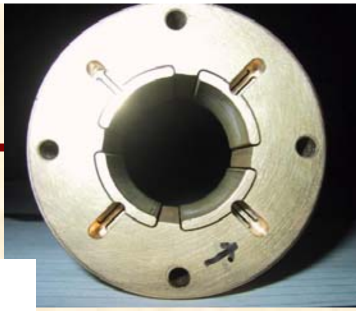
2.36 bar

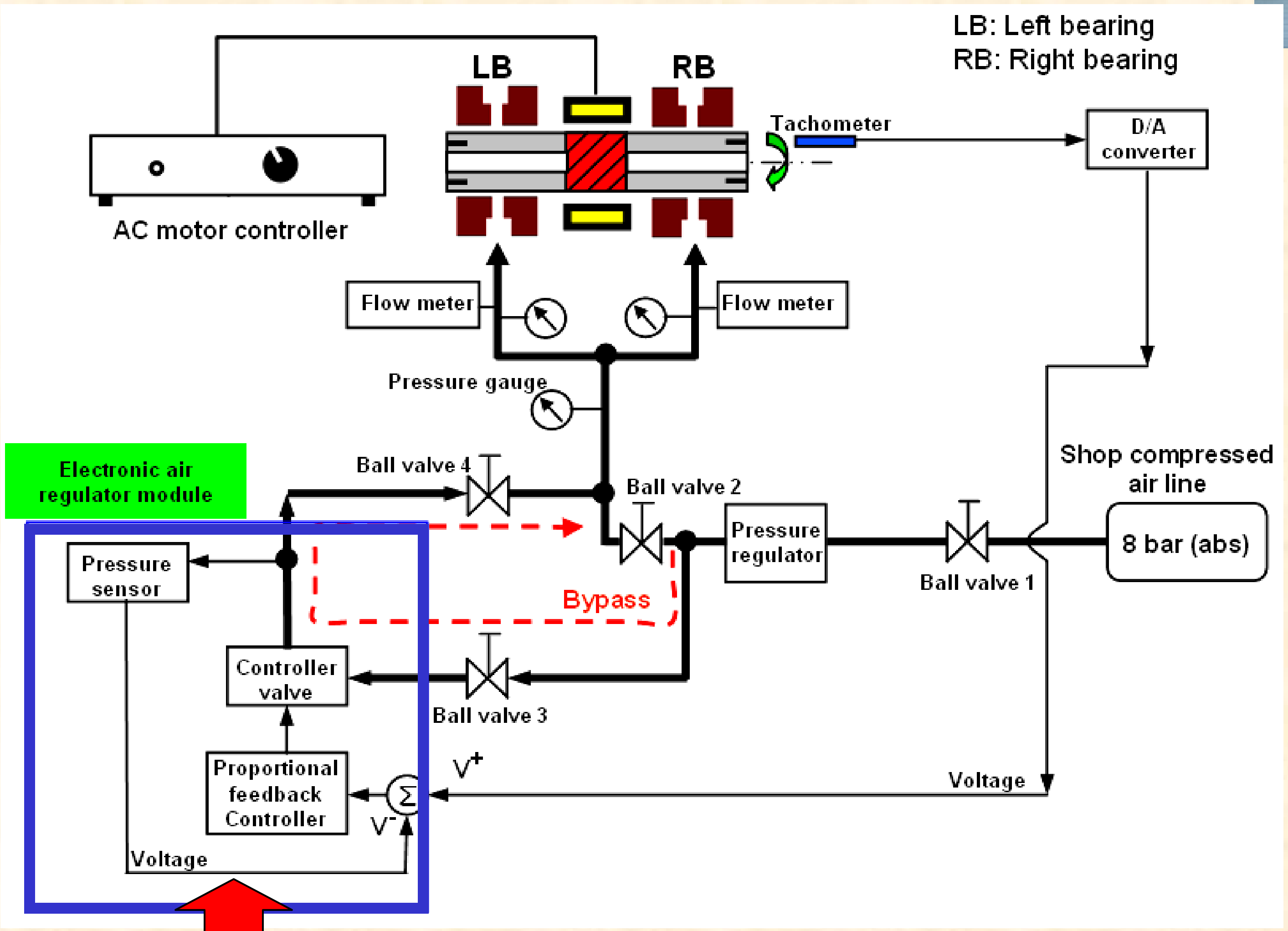


ASME GT2008-50393

Speed decays exponentially with time. Little viscous drag.

Control of feed pressure



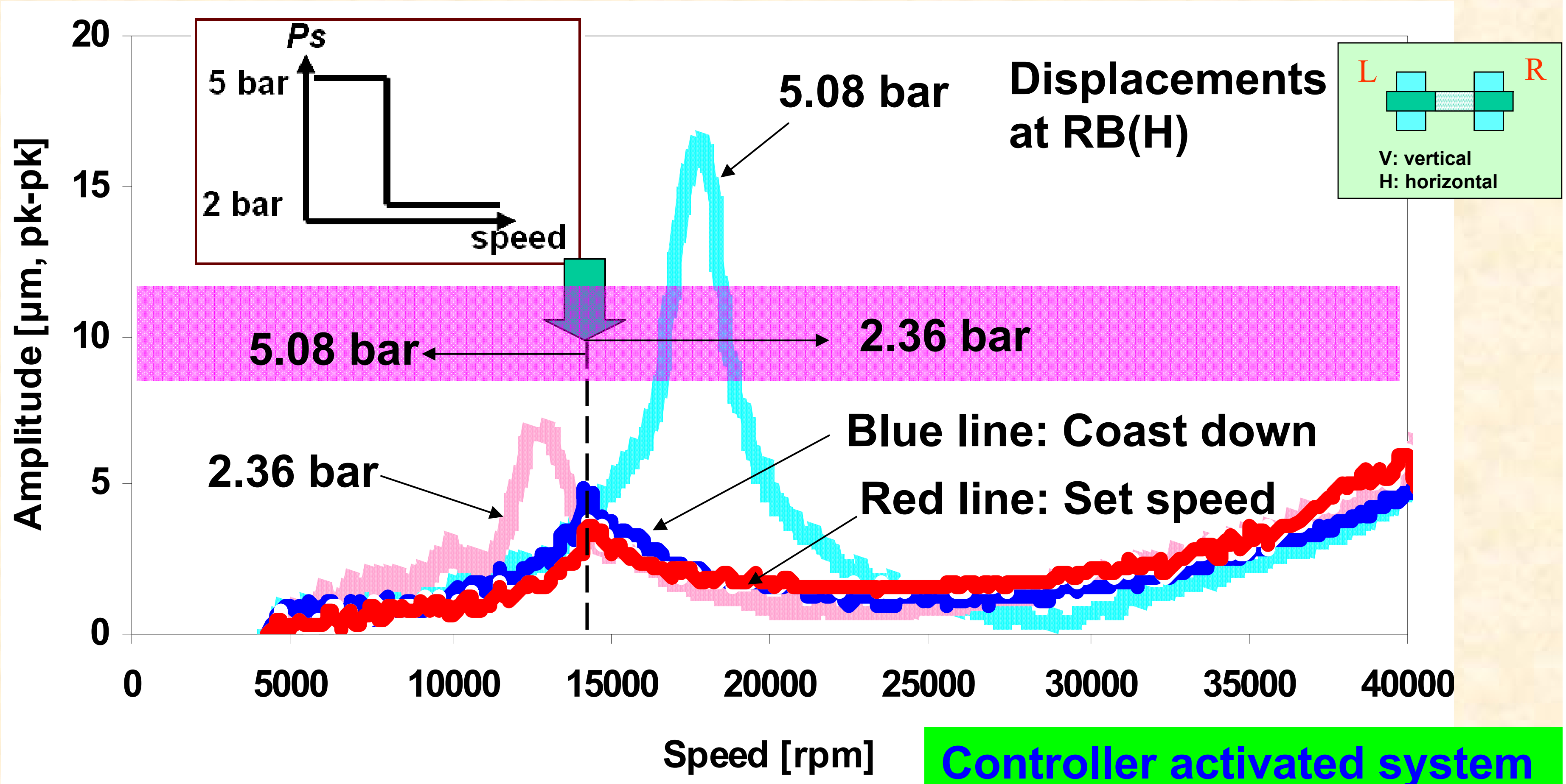


Simple on/off valve

ASME GT2008-50393

Suppression of critical speeds

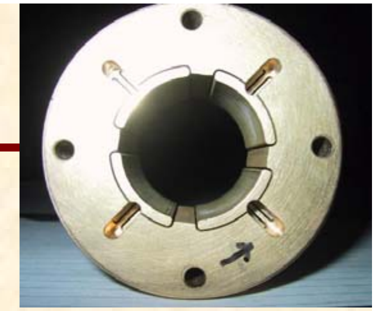
ASME GT2008-50393

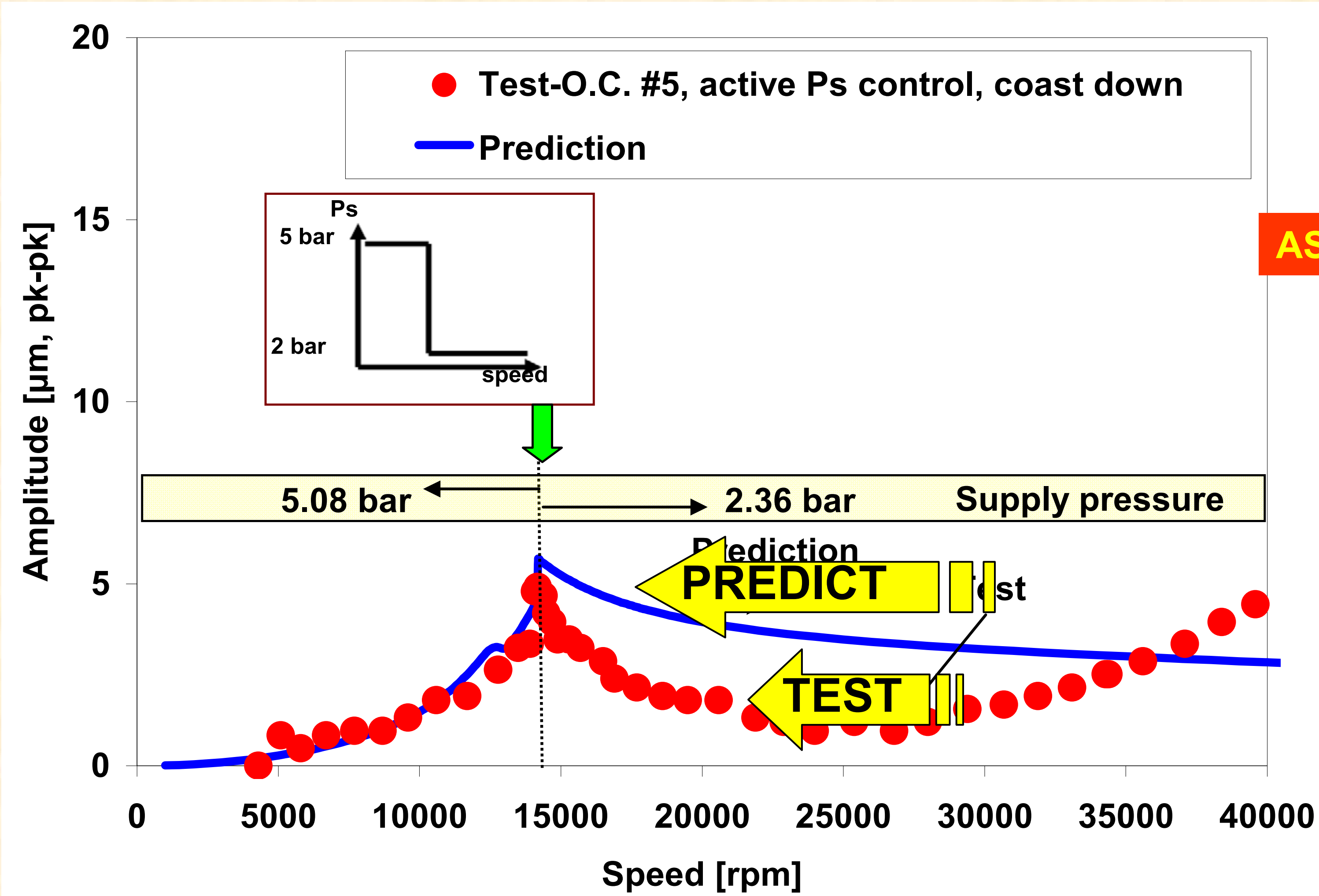


Controller activated system

Rotor peak amplitude eliminated by sudden increase in supply pressure

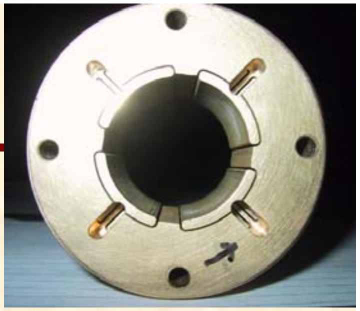
Tests vs predictions





Good agreement! (predictable RBS performance)

Flexure Pivot Gas Bearings

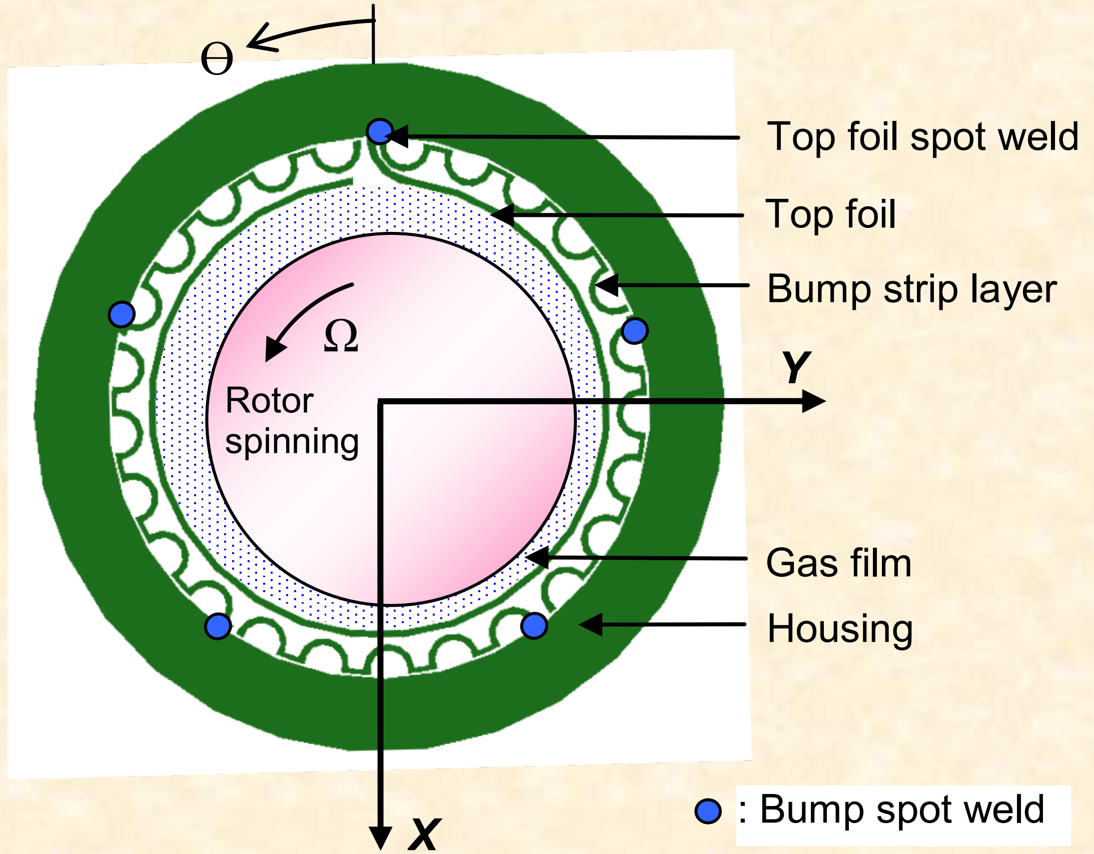


Closure: Stable to 99 krpm!

- External pressurization stiffens bearings and reduces their modal damping, thus raising critical speeds.
- Speed coast down tests with controlled supply pressure show displacement of critical speed and elimination of peak displacements.
- Predictive codes reproduce well test rotor response; even for large rotor motions and controlled supply pressure!
- Hybrid bearings demonstrated reliable rotordynamic performance free of sub sync. whirl.
- OTHER measurements show reliability of gas bearings to external shocks and base periodic motions.

Gas Foil Bearings

Gas Foil Bearings



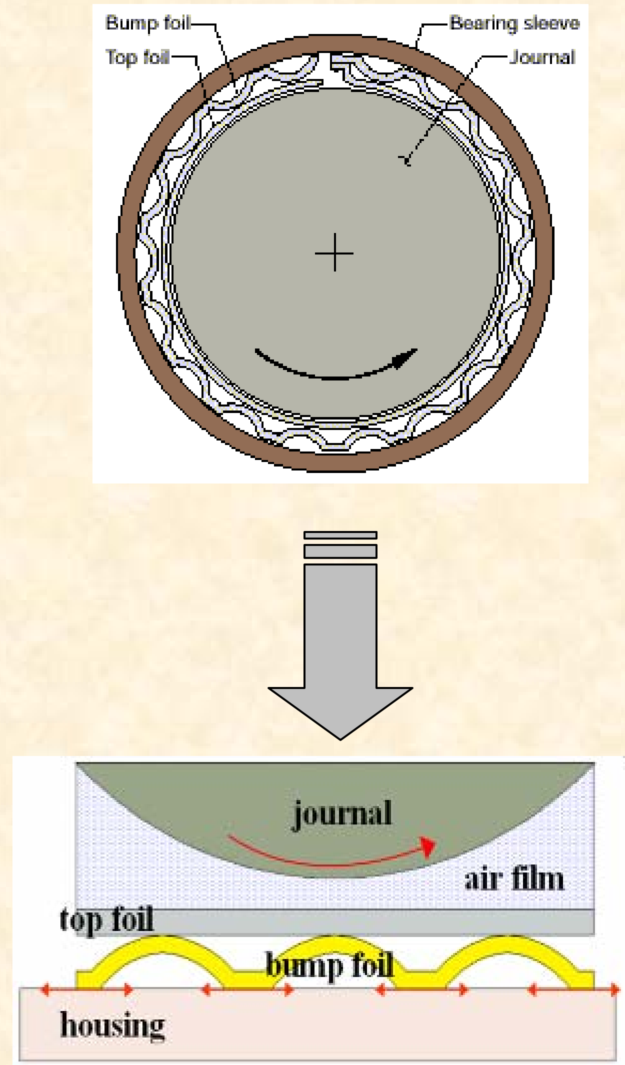
Advertised advantages: high load capacity (>20 psig), rotordynamically stable, tolerance of misalignment and shocks

Gas Foil Bearings – Bump type

- **Series of corrugated foil structures (bumps) assembled within a bearing sleeve.**
- **Integrate a hydrodynamic gas film in series with one or more structural layers.**

Applications: APUs, ACMs, micro gas turbines, turbo expanders

- **Reliable**
- **Tolerant to misalignment and debris, also high temperature**
- **Need coatings to reduce friction at start-up & shutdown**
- **Damping from dry-friction and operation with limit cycles**



Foil Bearings (+/-)

+

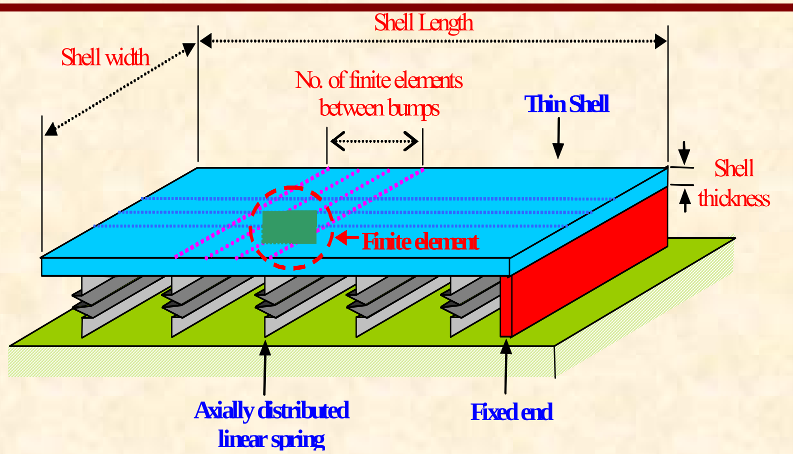
- Increased reliability: load capacity (< 20 psi)
- No lubricant supply system, i.e. reduce weight
- High and low temperature capability (> 1,000 C)
- No scheduled maintenance
- Tolerate high vibration and shock load. Quiet operation

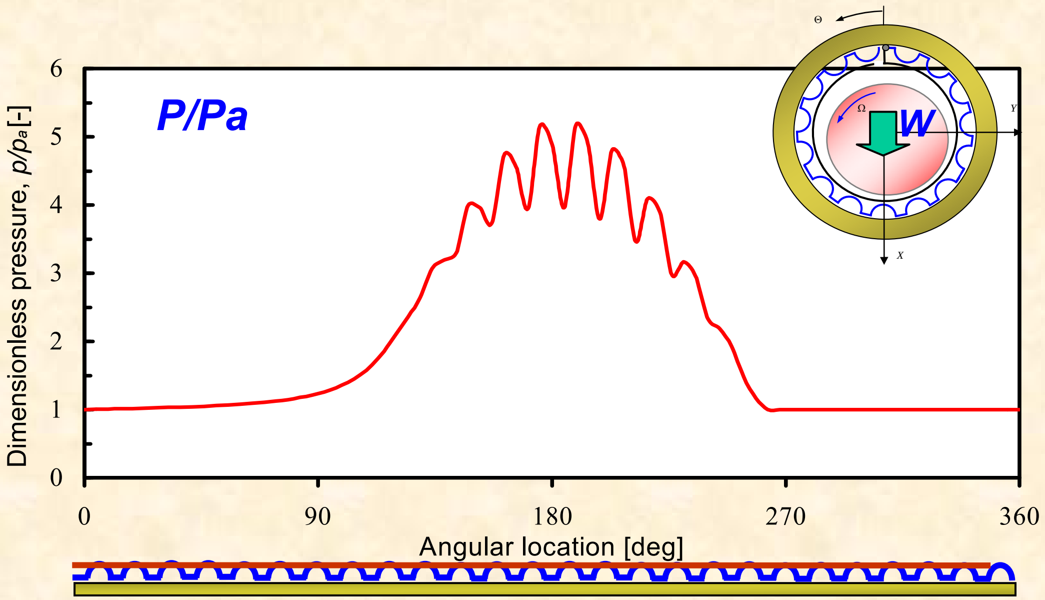
−

- Endurance: performance at start up & shut down (lift off speed)
- Little test data for rotordynamic force coefficients & operation with limit cycles (sub harmonic motions)
- Thermal management for high temperature applications (gas turbines, turbochargers)
- Predictive models lack validation for GFB operation at HIGH TEMPERATURE

Foil Bearing Models

ASME JGT 2008, v130, 2010, v132;
ASME GT 2007-27249
ASME J. Tribol., 2006, v128



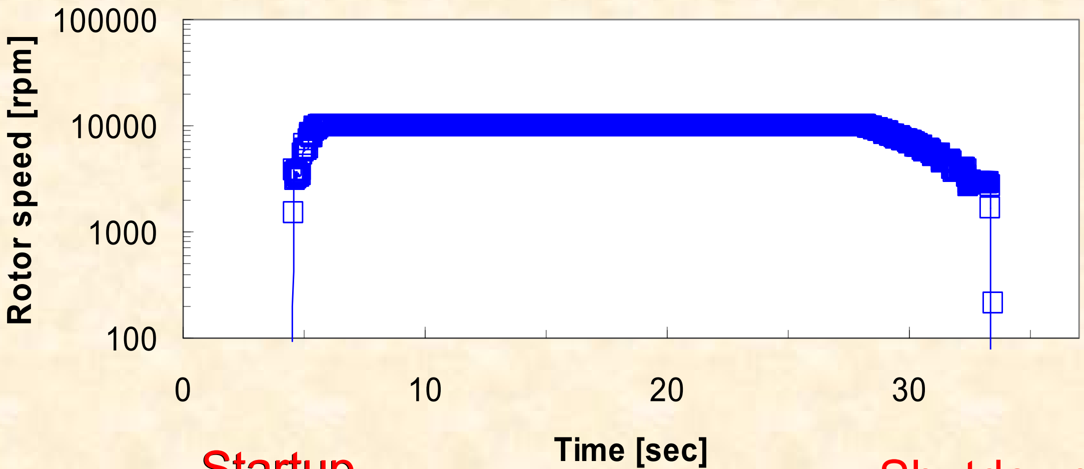


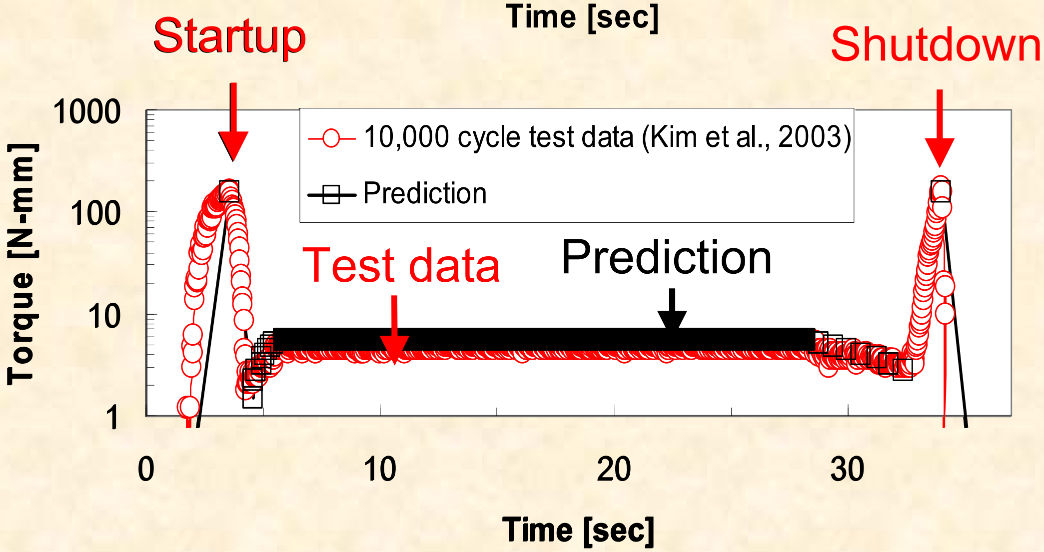
Predicted gas film pressure field

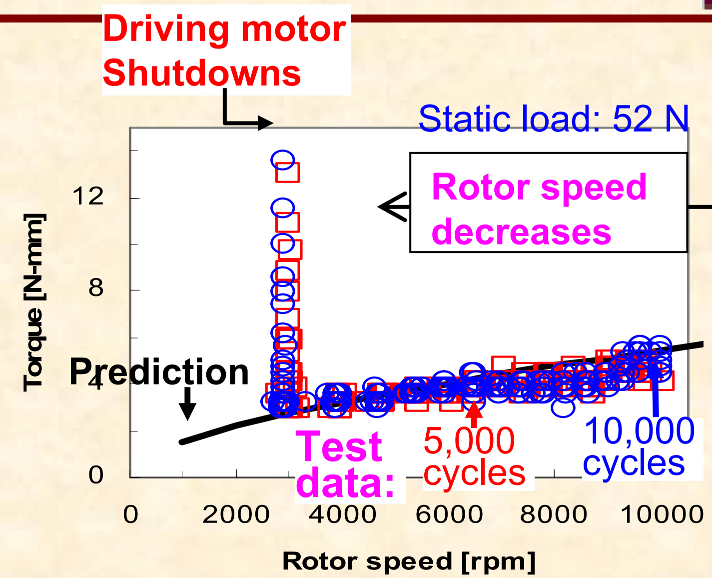
Fast PC codes integrate foil structure with gas film hydrodynamics – GUI driven

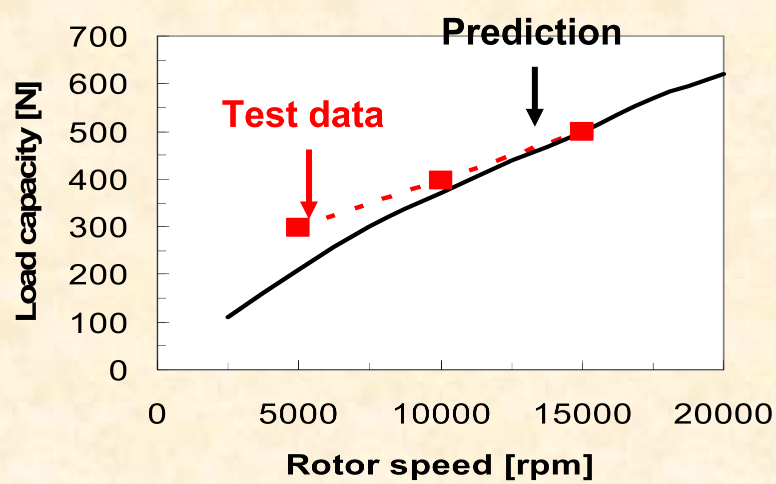
Accuracy of Foil Bearing Model Predictions

KIST test data (2003)







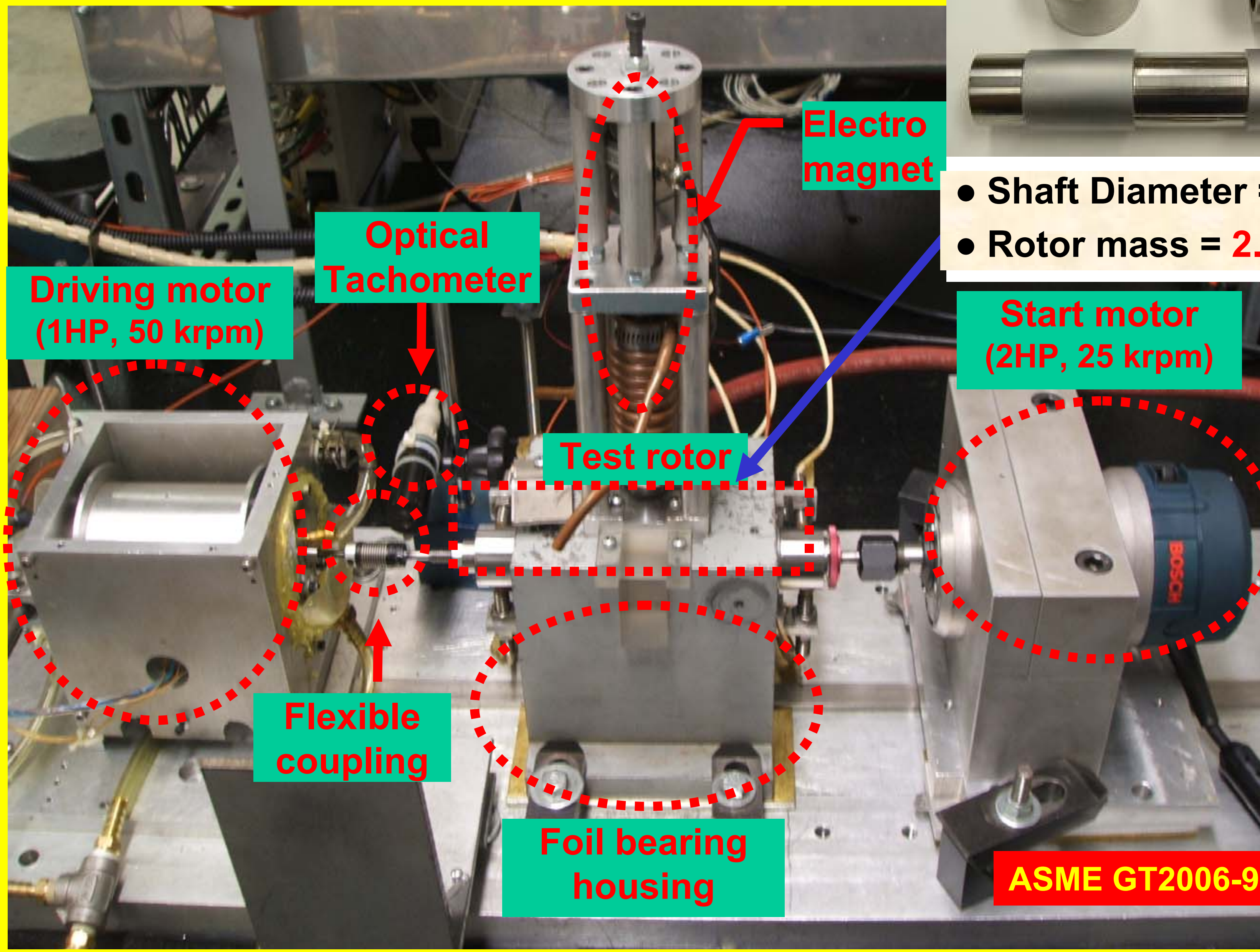


Model validation: Static load performance

AIAA-2007-5094

Foil Bearing Test Rig

- Shaft Diameter = 1.500”
- Rotor mass = 2.2 lb

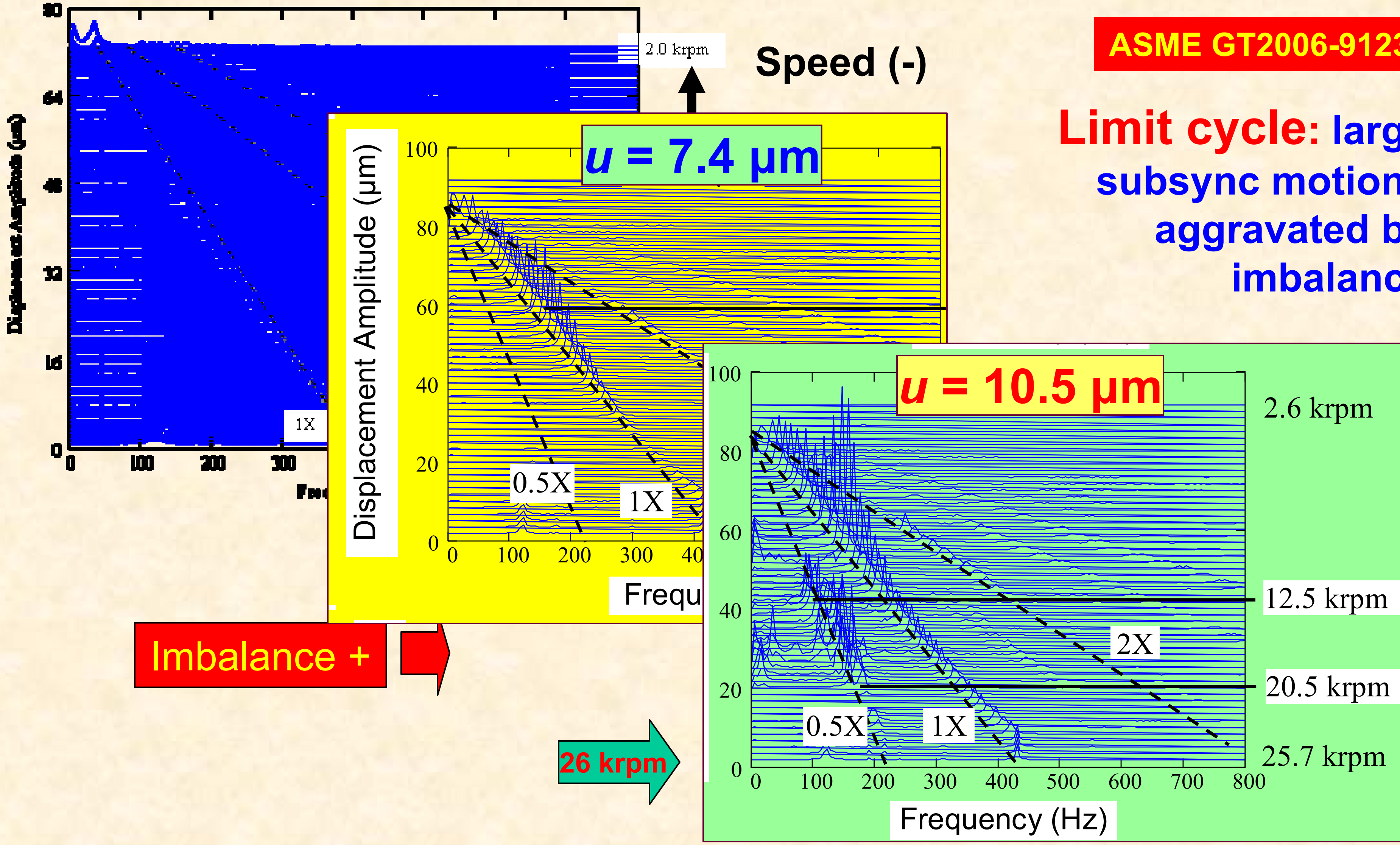


ASME GT2006-91238

Effect of imbalance on RBS response

ASME GT2006-91238

Limit cycle: large subsync motions aggravated by imbalance

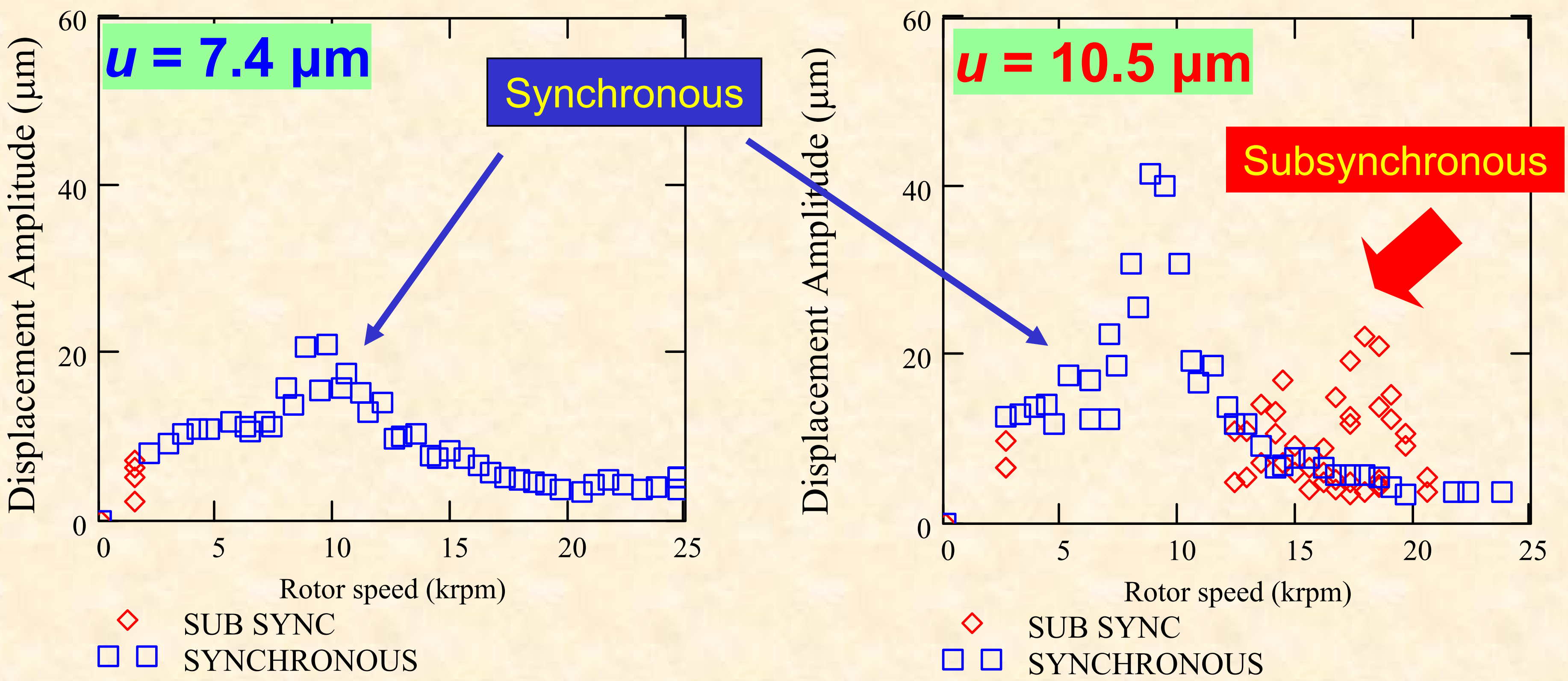


Amplitudes of subsynchronous motions INCREASE as imbalance increases (forced nonlinearity)

Effect of imbalance on RBS whirl motions

Synchronous and subsynchronous motions for two imbalances

AIAA-2007-5094

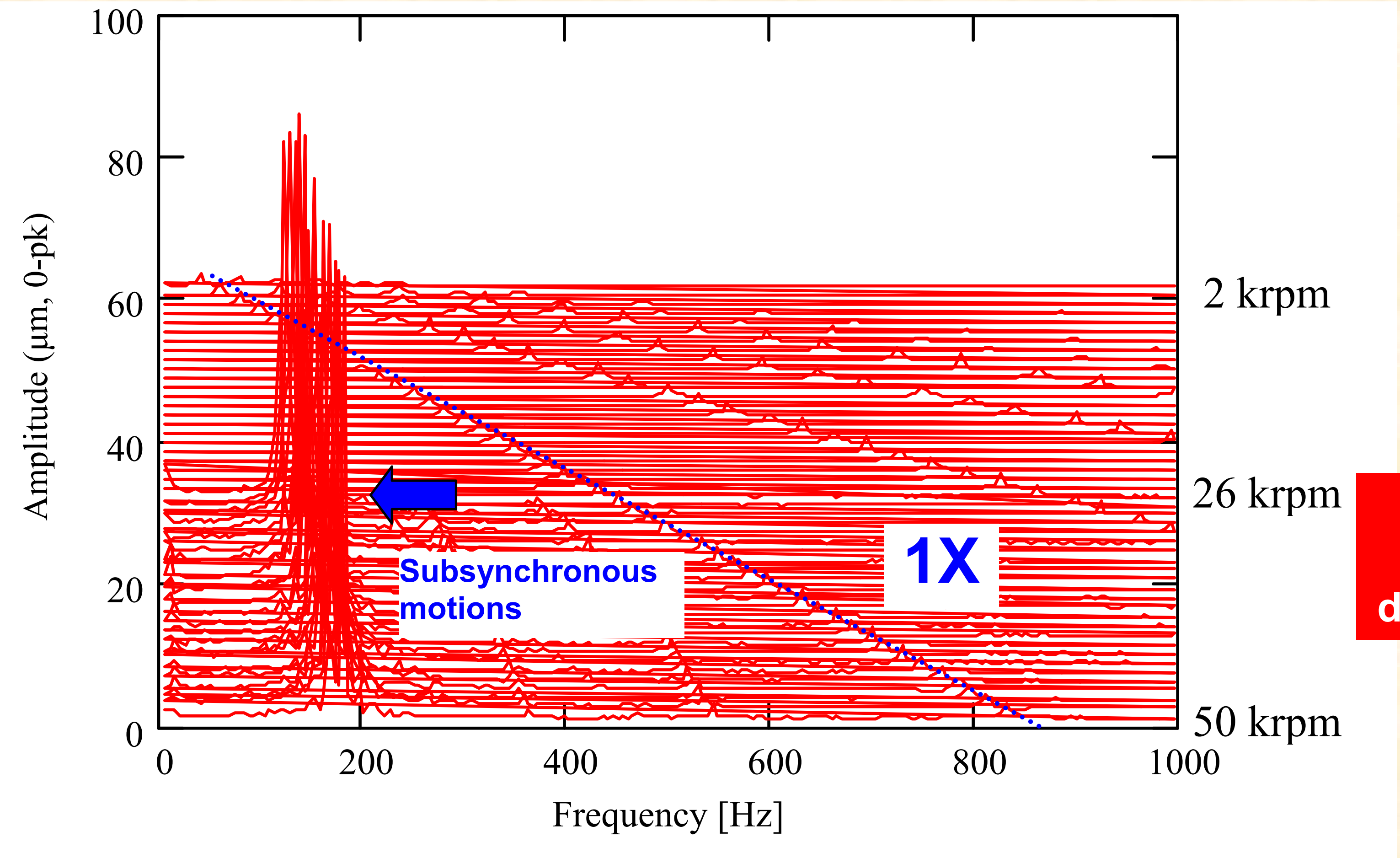


Severe subsync motions (limit cycle) aggravated by imbalance. Non linear forced response

Rotordynamic instability?

Coast down from 50 krpm (833 Hz)

ASME JGT, 209, v31



Rotor speed decreases

Large amplitudes locked at natural frequency (50 to 27 krpm) …… but stable limit cycle!

What causes the subsynchronous motions?

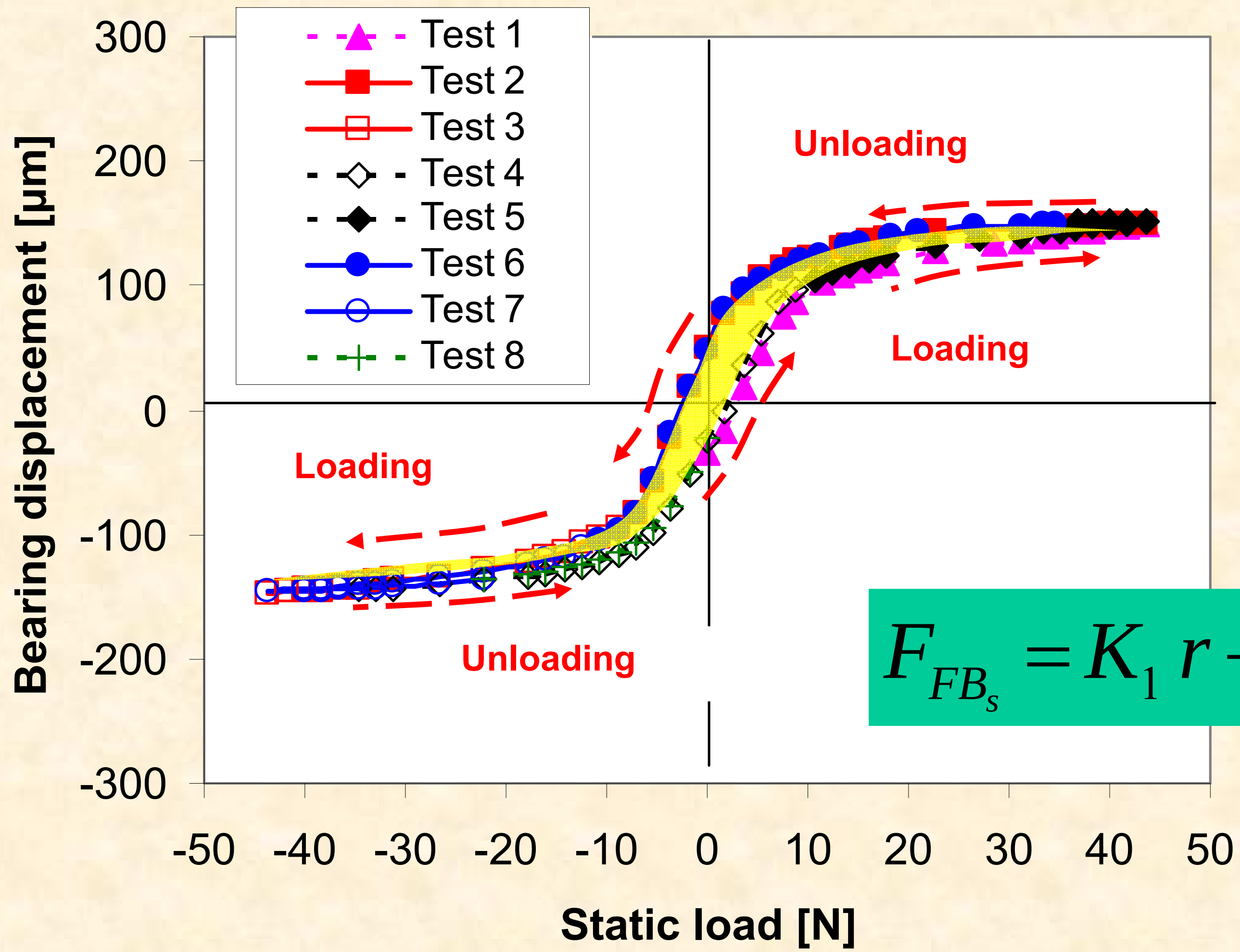
What causes the excitation of natural frequency?

All GFB models predict (linearized) rotordynamic force coefficients.

No model readily available to predict nonlinear rotordynamic forced response

FB: stiffness & energy dissipation

AIAA-2007-5094



Eight cyclic load - unload structural tests

$$F \neq K X$$

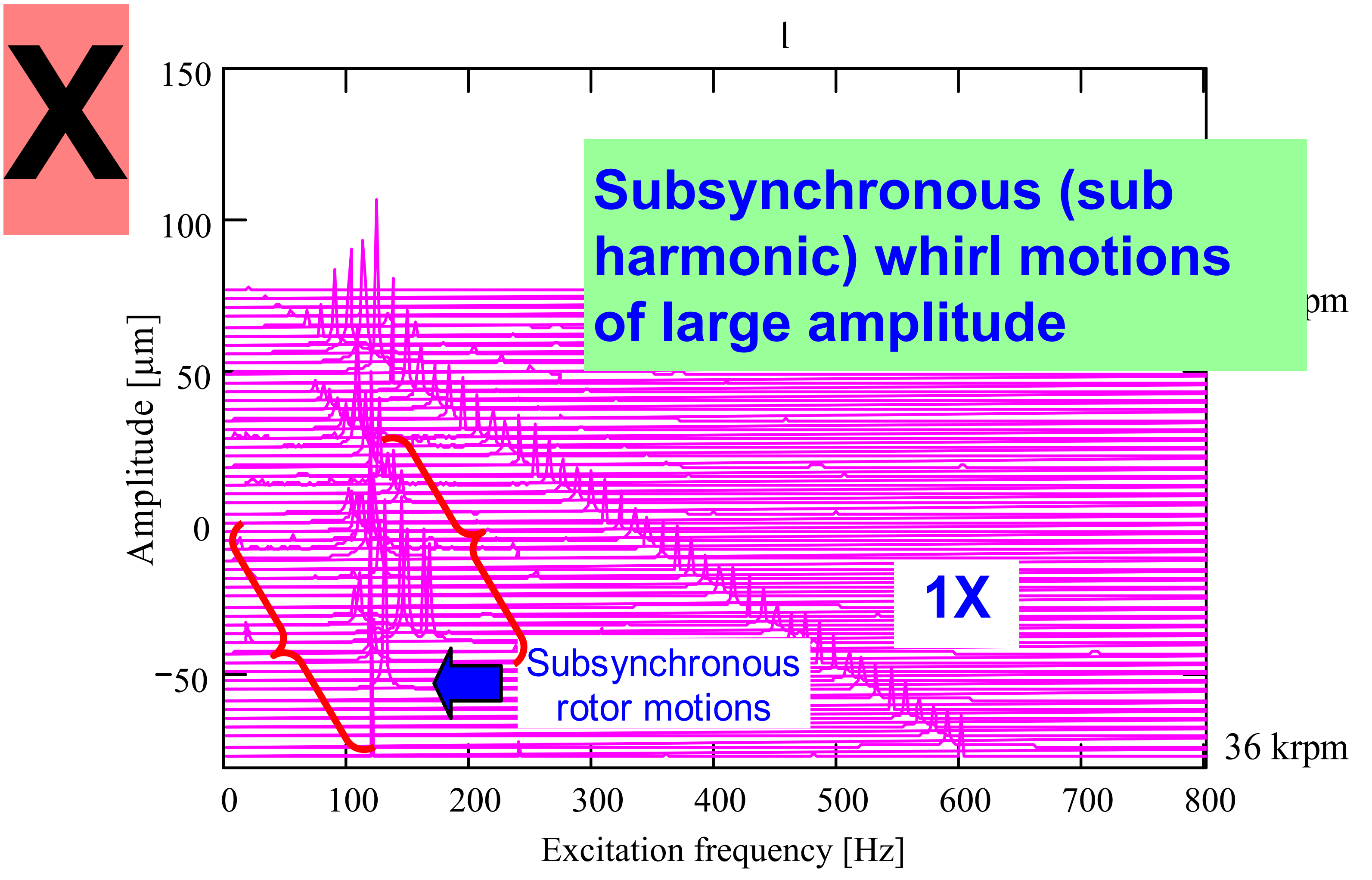
$$F_{FB_s} = K_1 r + K_2 r^2 + K_3 r^3$$

FB structure is non linear (stiffness hardening), a typical source of sub harmonic motions for large (dynamic) loads. Hysteresis loop gives energy dissipation

Waterfall of predictions for rotor-GFB system

AIAA-2007-5094

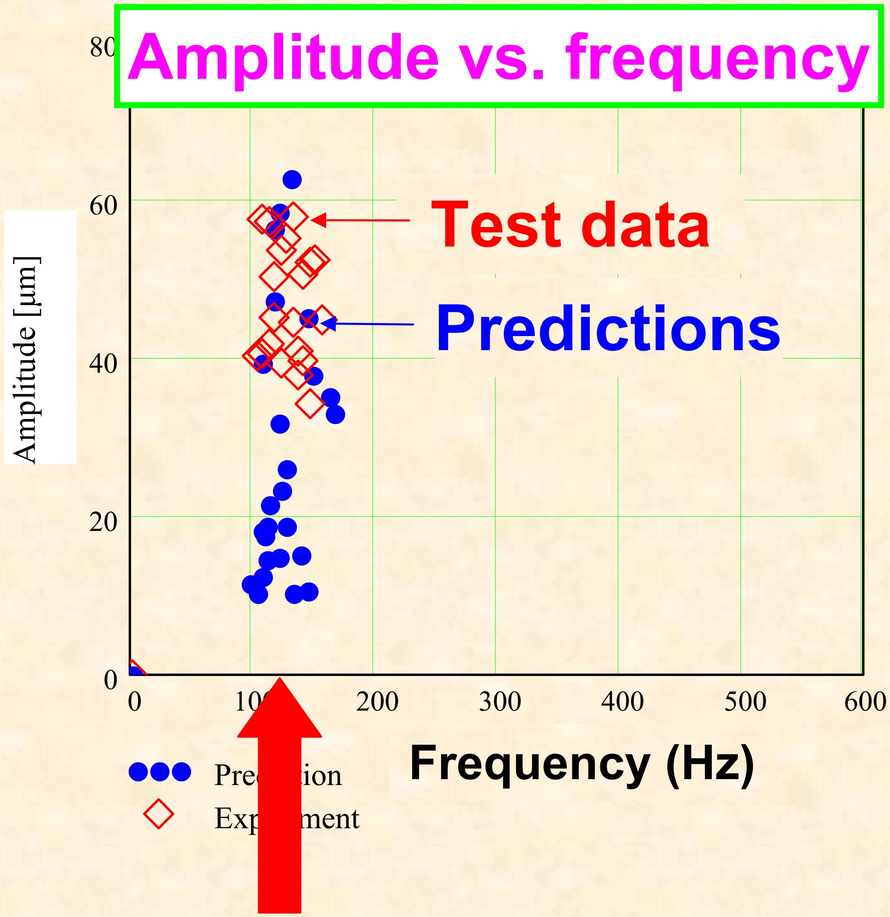
Rotor speed: 30 →1.2 krpm (600 →20 Hz)
Imbalance displacement, *u* = 12 μm (Vertical motion)

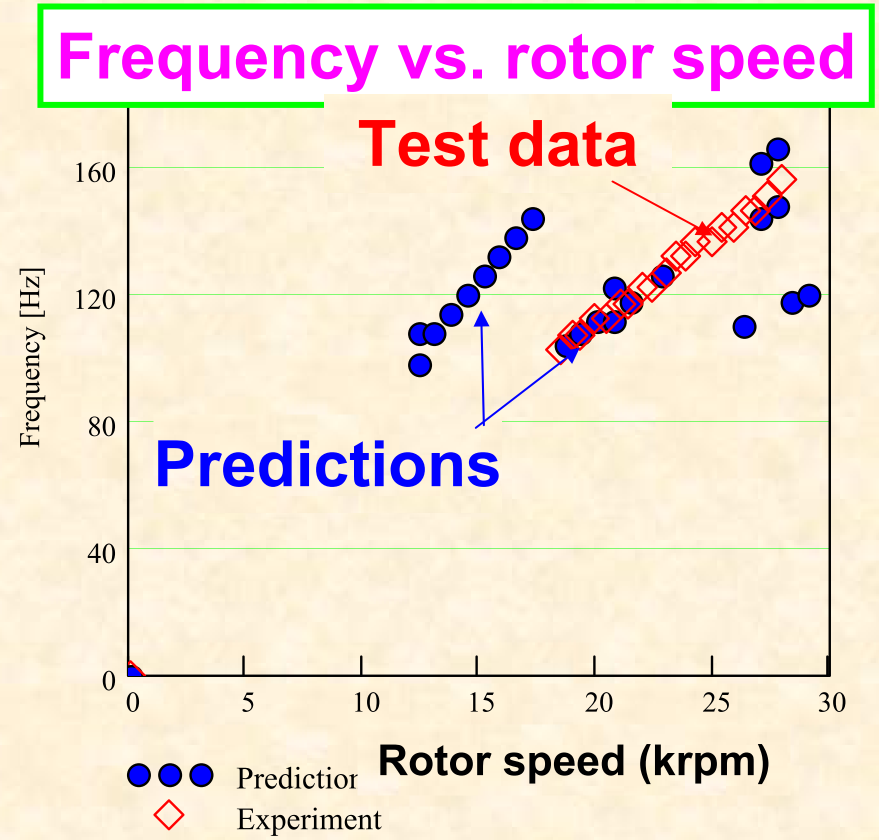


Amplitude and frequency of whirl motions

Comparison to test data

AIAA-2007-5094

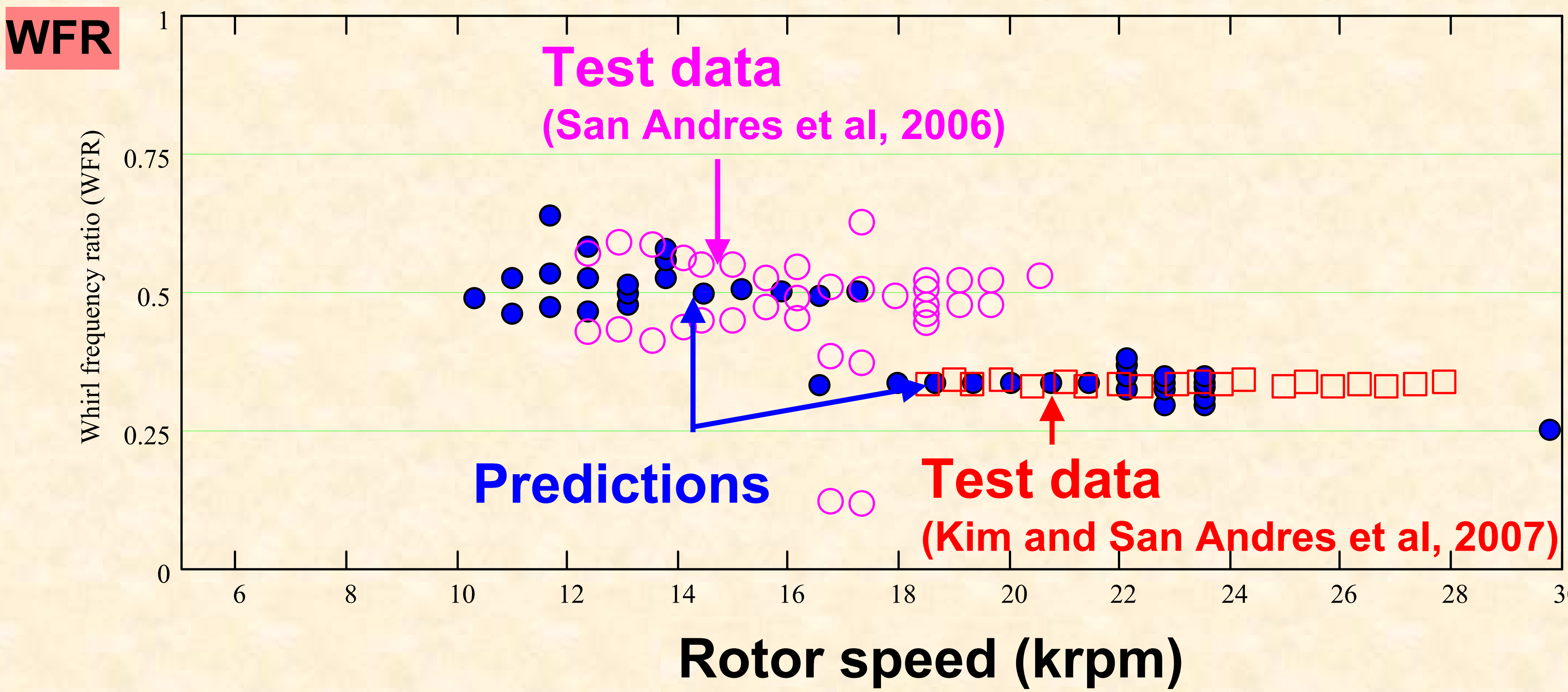




Whirl frequencies within a narrow band enclosing natural frequency (132 Hz) of RBS

Whirl frequency ratio of rotor bearing system

AIAA-2007-5094



P& T show bifurcation of motion into 1/2 & 1/3 WFRs

Gas Foil Bearings

AIA-2007-5094

Closure 1

Instability or forced nonlinearity?

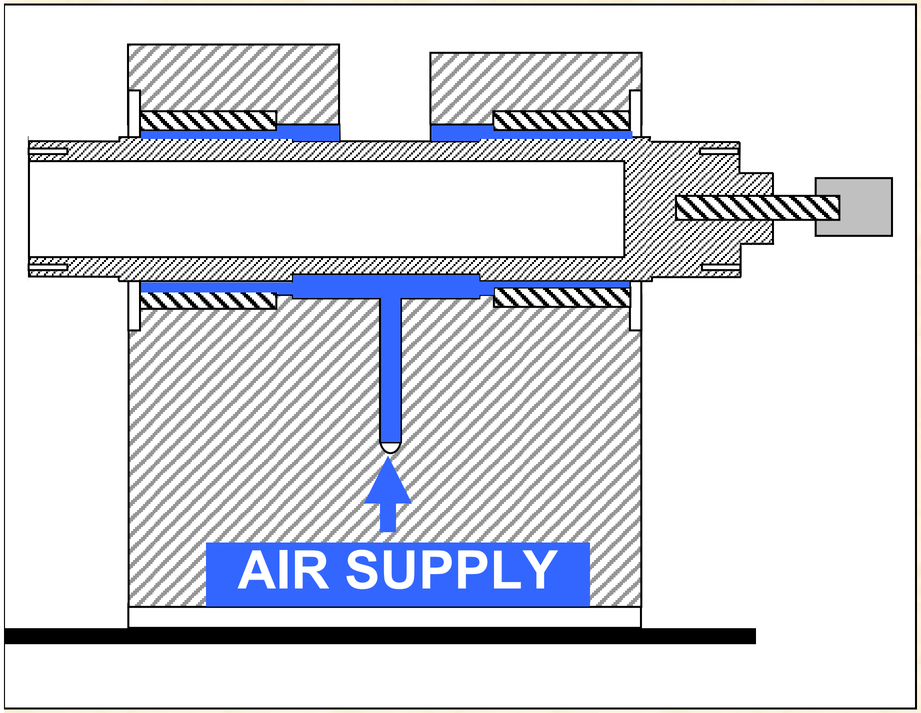
- **FB structure is highly non linear, i.e. <u>stiffness hardening</u>: a common source of sub harmonic motions for large (dynamic) loads.**

- **Subsynchronous frequencies track shaft speed at ~ ½ to 1/3 whirl ratios, locking at system natural frequency.**

- **Model predictions agree well with rotor response measurements (Duffing oscillator with multiple frequency response).**

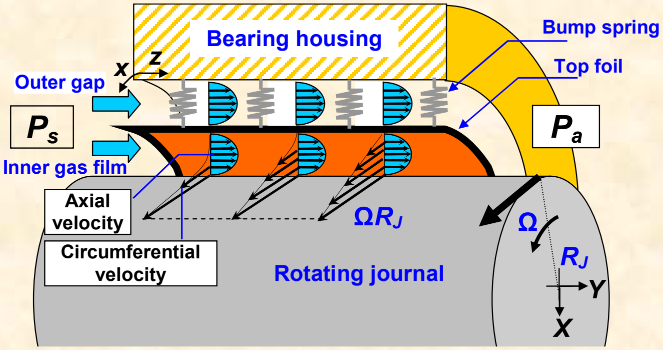
Effect of cooling flow on rotordynamics

ASME JGT, 209, v31



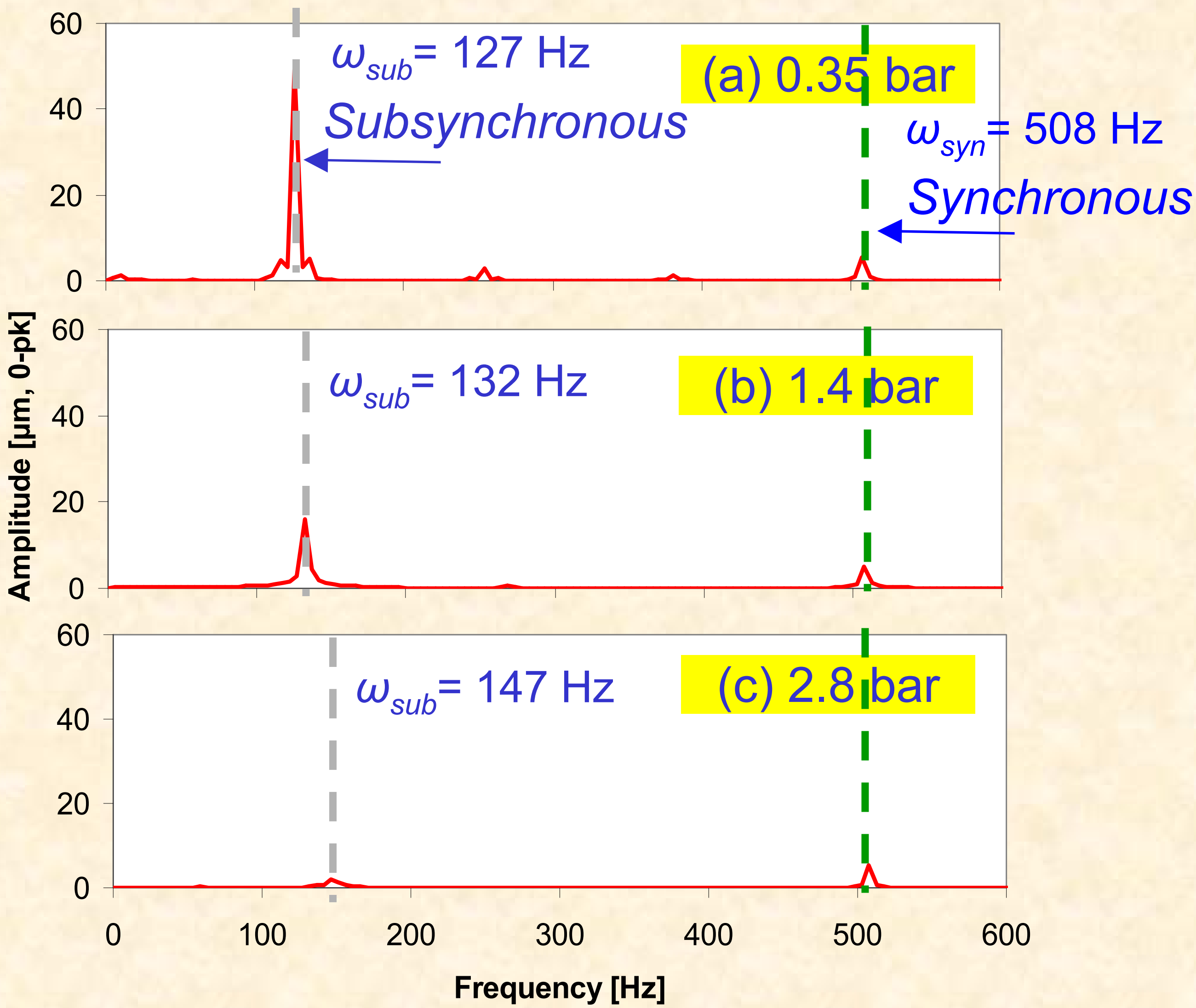
Typically foil bearings DO not require pressurization.

Cooling flow is for thermal management: to remove heat from drag or to reduce thermal gradients in hot/cold engine sections



Side effect: Axial flow retards evolution of circumferential flow velocity

Effect of side flow on rotordynamics



ASME JGT, 209, v31

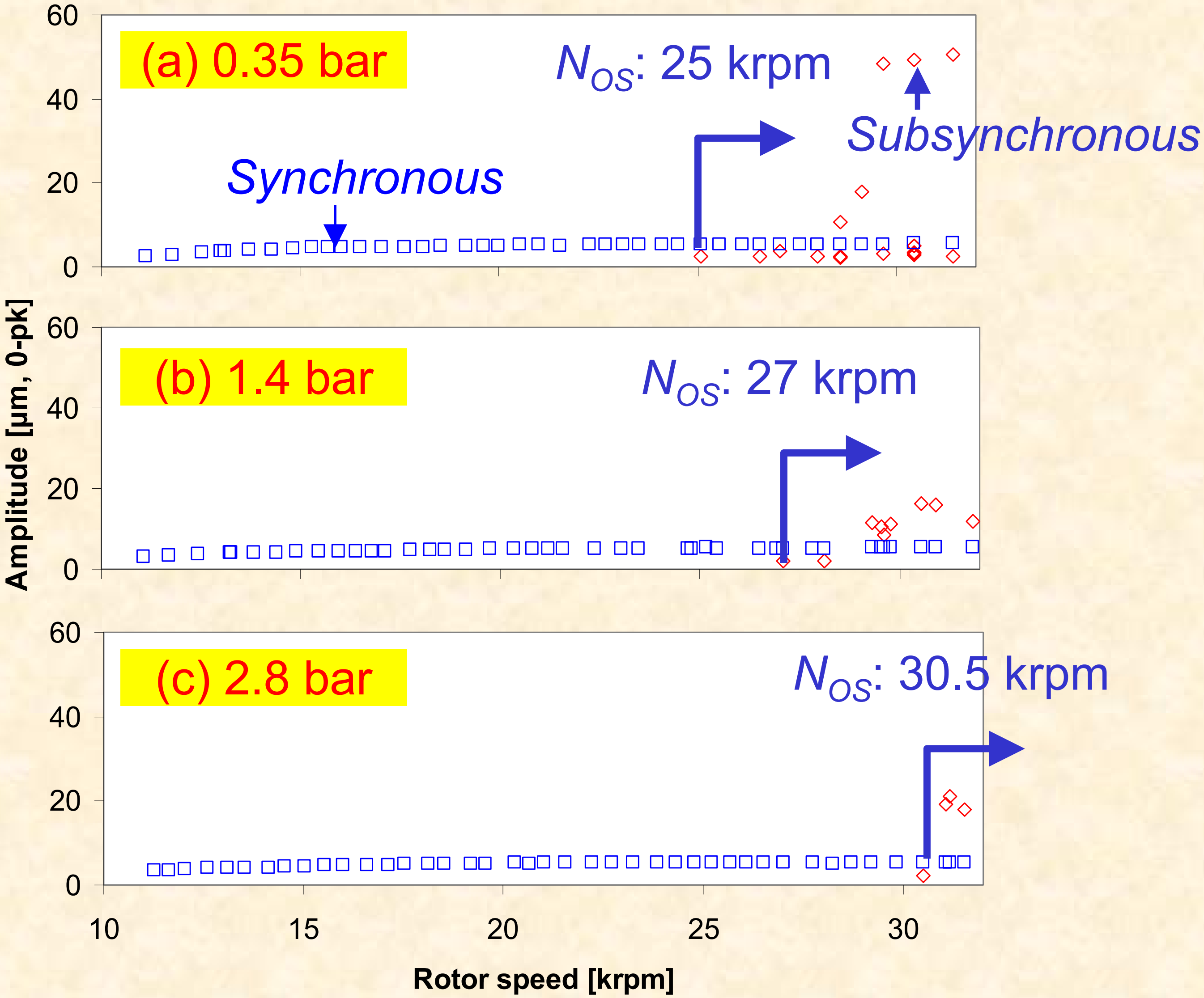
***For Ps* ≥ 2.8 bar rotor subsync. whirl motions disappear; (stable rotor response)**

Whirl frequency locks at RBS natural frequency (not affected by level of feed pressure

FFT of shaft motions at 30 krpm

Effect of side flow on rotordynamics

ASME JGT, 209, v31

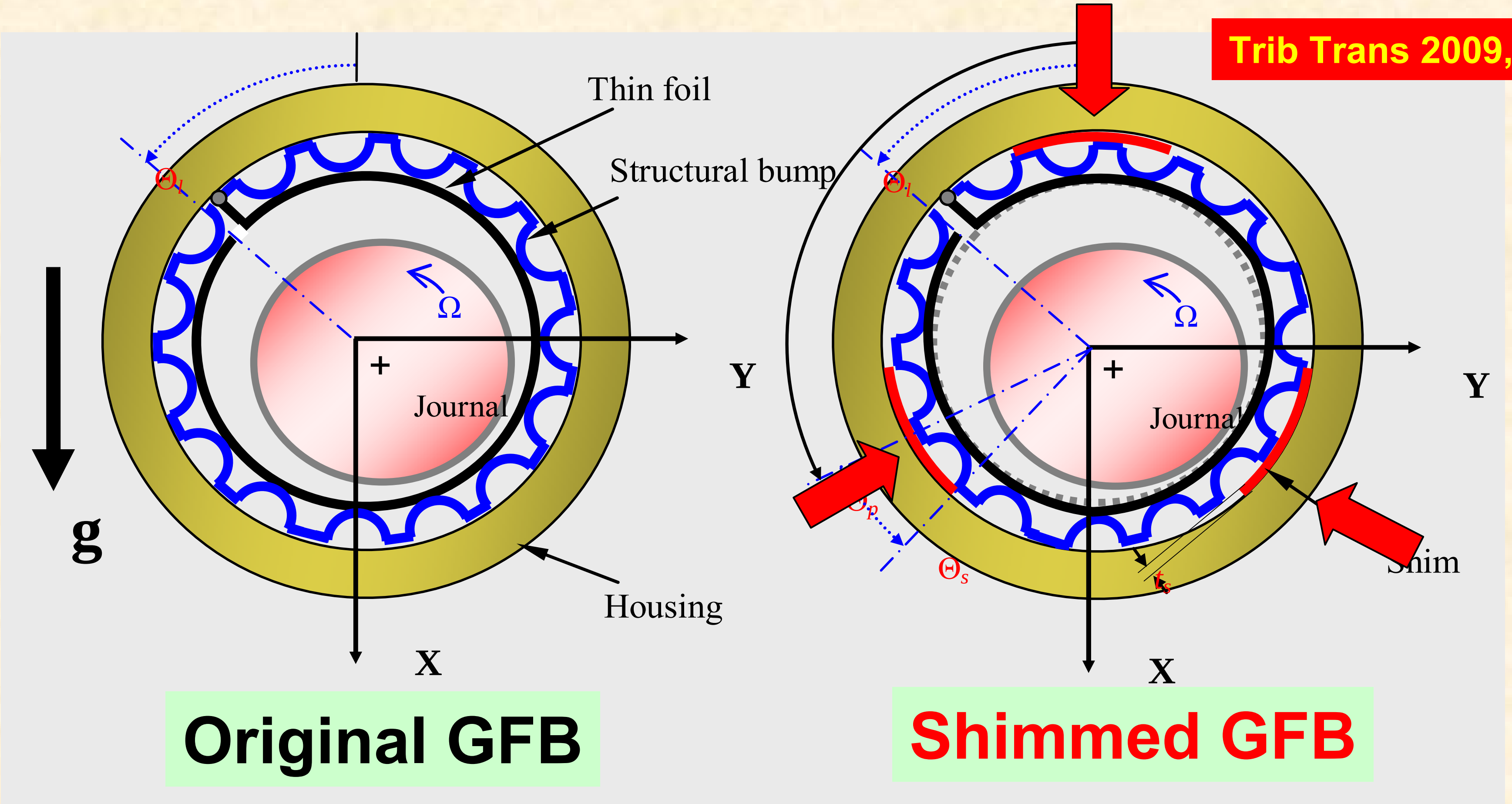


Delay of large amplitude subsynchronous rotor motions with increase in axial cooling flow

Onset of subsynchronous whirl motions

Effect of preload on rotordynamics

Trib Trans 2009, v52

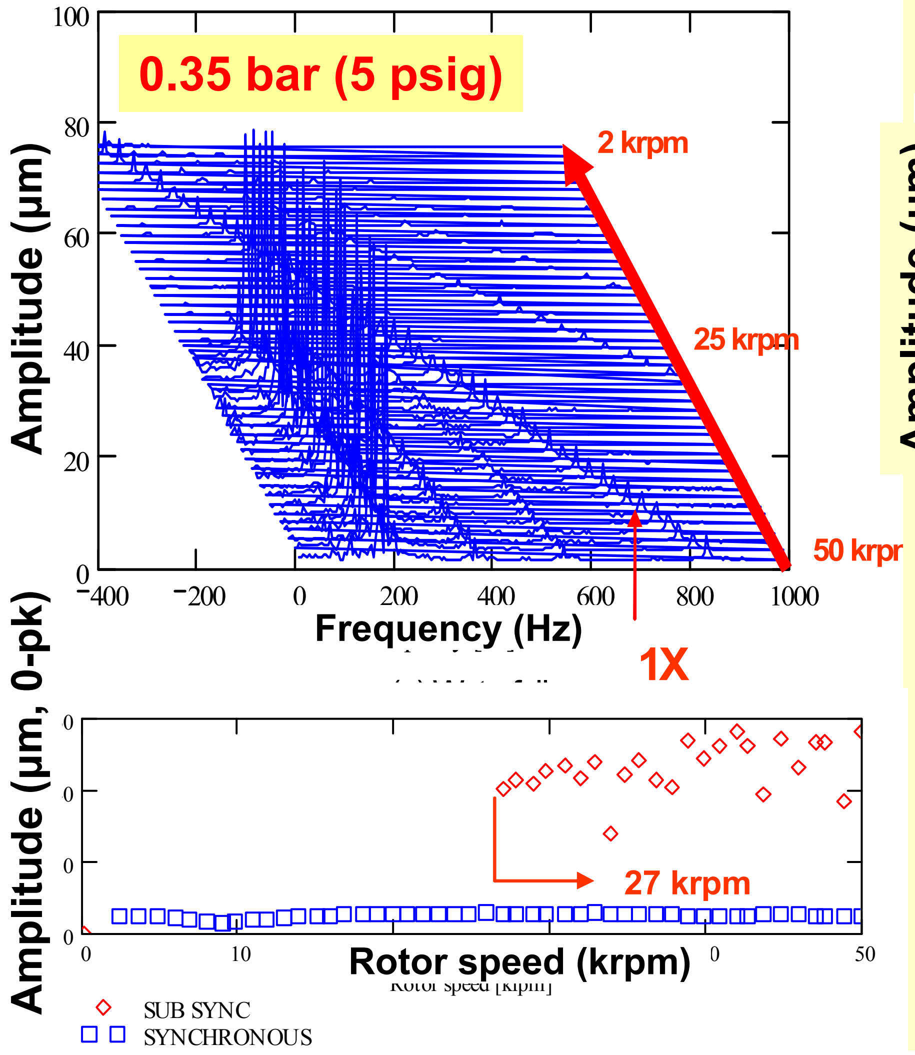


Inserting metal shims underneath bump strips introduces a preload (centering stiffness) at low cost – typical industrial practice

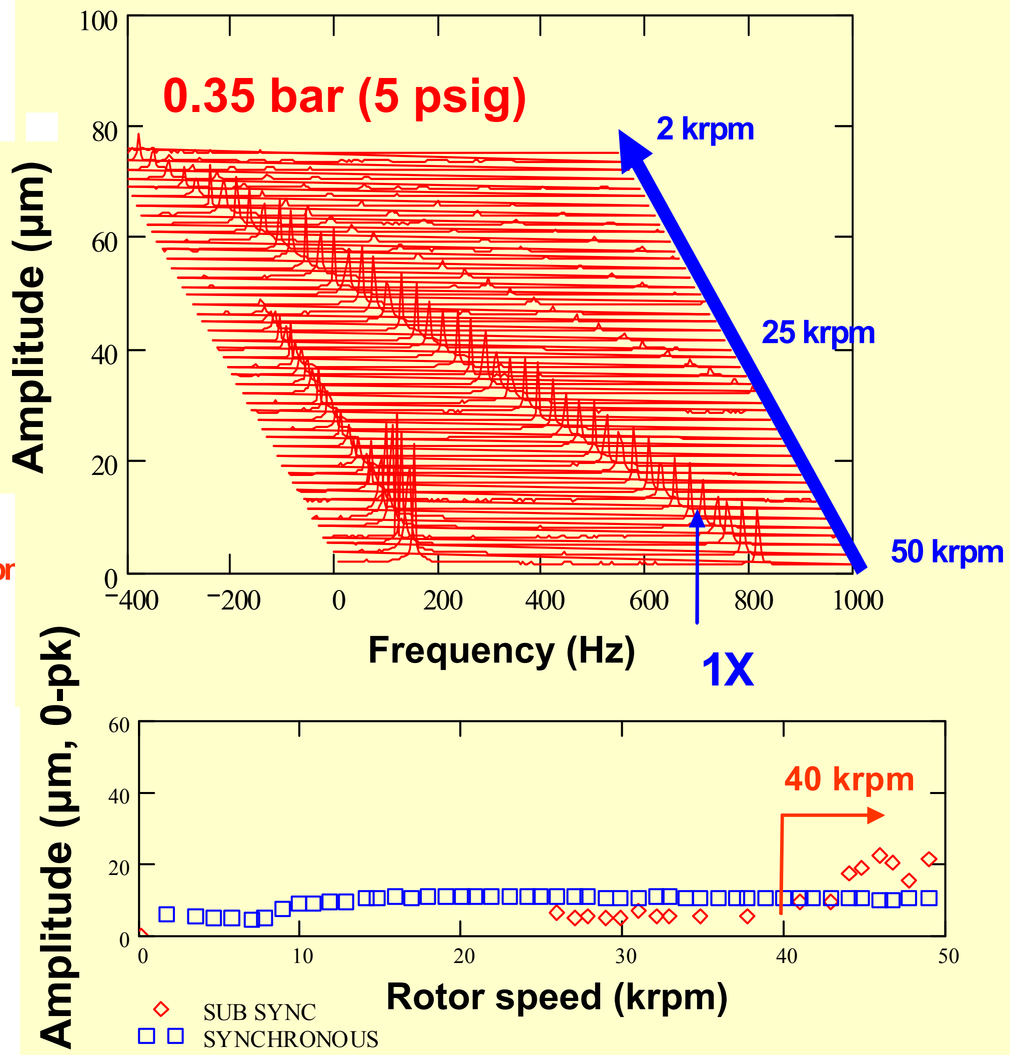
Gas Foil Bearing with Metal Shims

Trib Trans 2009, v52

Original GFBs



Shimmed GFBs



Gas Foil Bearings

Closure 2

Improved stability with pressure and shims

- **Predictive foil bearing FE model (structure + gas film) benchmarked by test data.**
- **(Cooling) side pressure reduces amplitude of sub sync whirl motions**
- **Preloads (shims) increase bearing stiffness and raise onset speed of subsync. whirl.**
- **Predicted rotor 1X response and GFB force coefficients agree well with measurements.30**

➢ **Foil Bearings survive severe subsynchronous motions and abusive operation!**

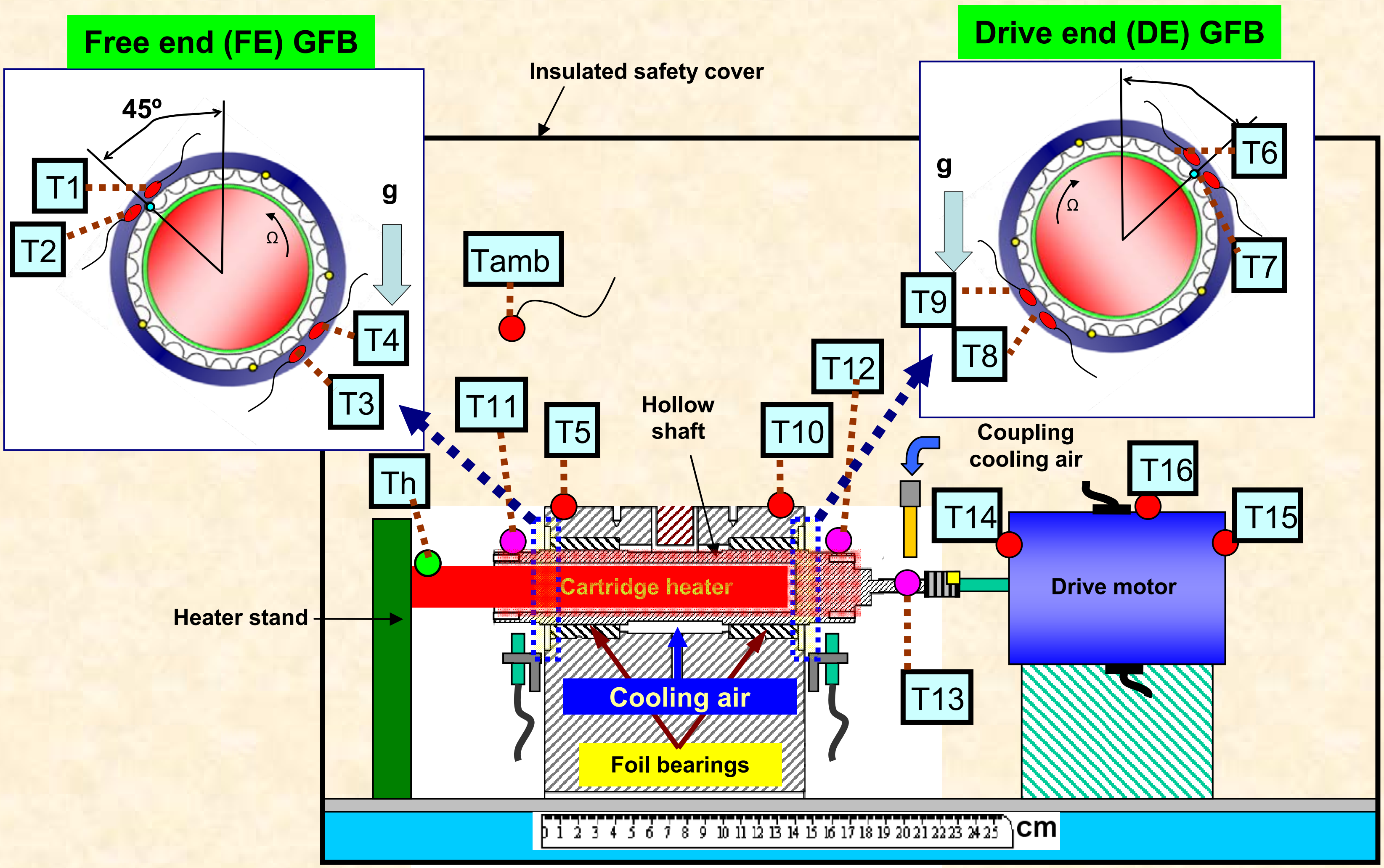
Foil Bearings Thermal Management

Gases have little thermal capacity. Cooling flow needed for thermal management: to remove heat from shear drag or to reduce thermal gradients from hot to cold engine sections

What is effect of rotor temperature on dynamic performance of rotor-GFB system?

- Measure bearing & rotor temperatures & rotordynamic performance for increasing shaft temperatures
- Realize effectiveness of side cooling flow on thermal management

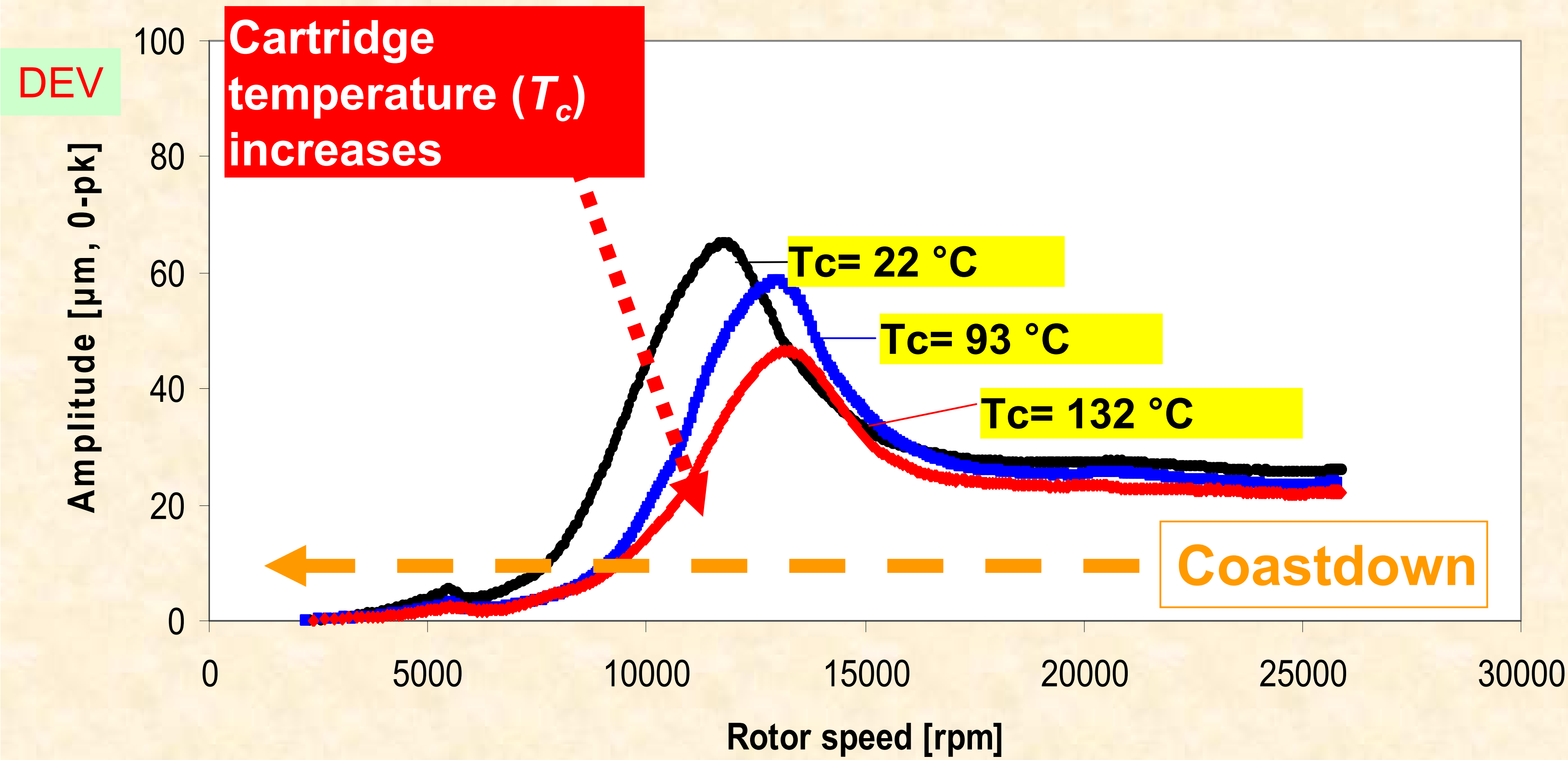
Temperatures in test rig



Thermocouples: 1 x heater, 2 x 4 FB outboard, 2 x Bearing housing outer surface, 1x Drive motor, 1 x ambient + infrared thermometers 2 x rotor, rotor surface temperature (Total = 17)

Rotordynamic response for hot rotor

ASME J. Tribol., 2010, v132

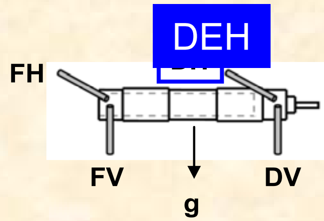


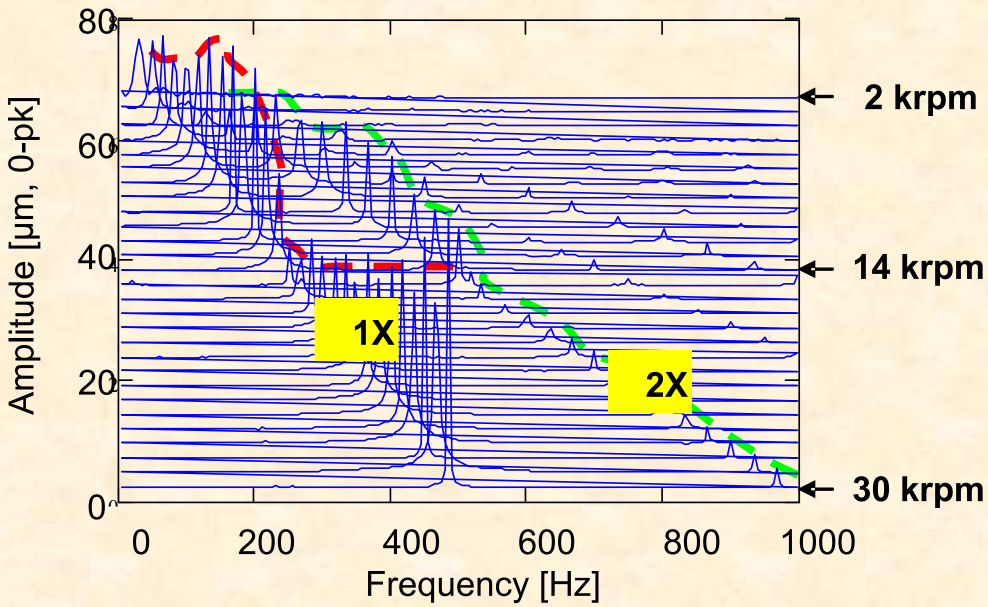
As T_c increases, critical speed increases by ~ 2 krpm and the peak amplitude decreases.

Waterfalls of rotor motion

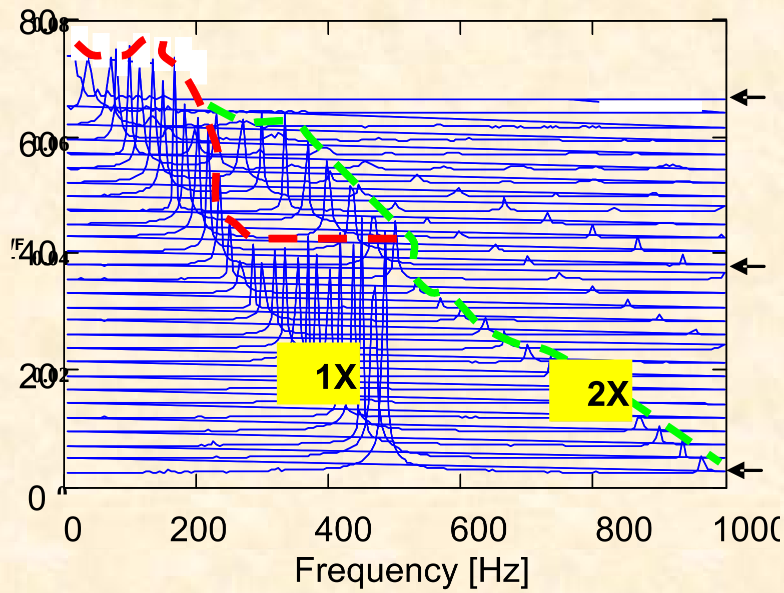
ASME GT 2010-22981

Baseline. No forced cooling





(a) Heater off



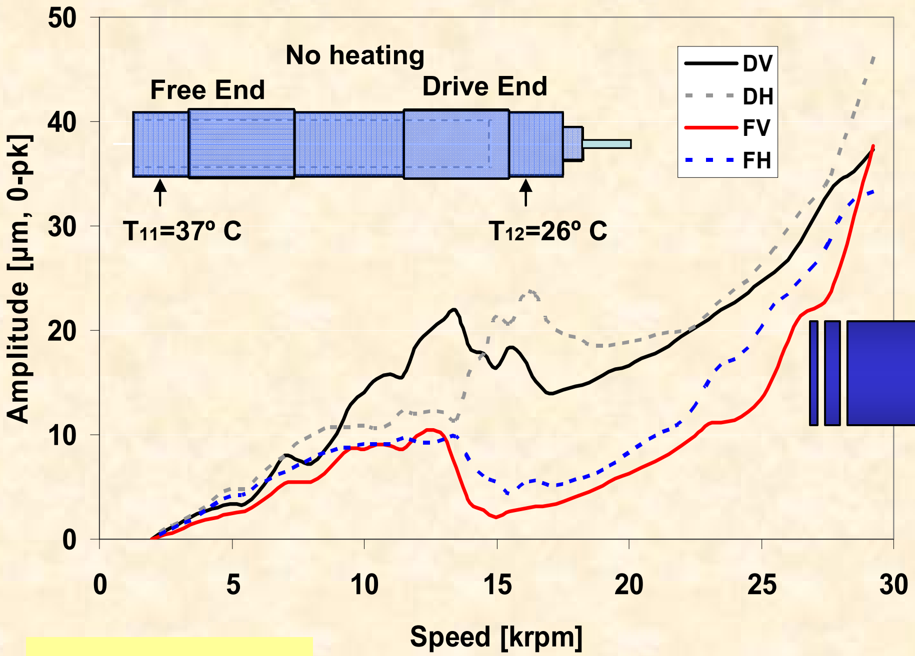
(a) Heater on, T_{hs}=360 C

Similar responses – free of sub synchronous whirl motions

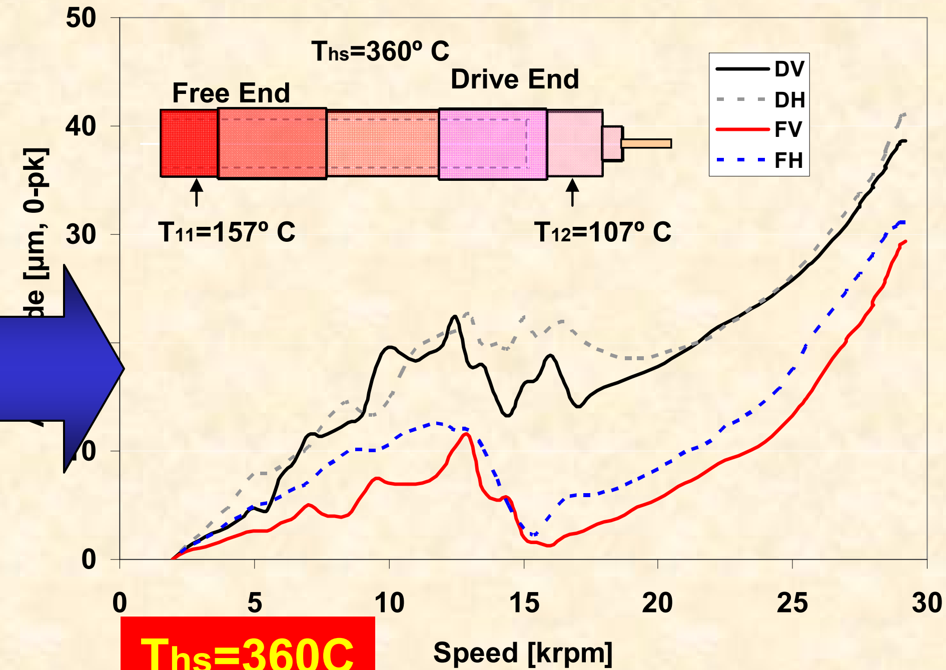
Rotor 1X response for cold & hot conds

No forced cooling

ASME GT 2010-22981



No heating



T_{hs}=360C

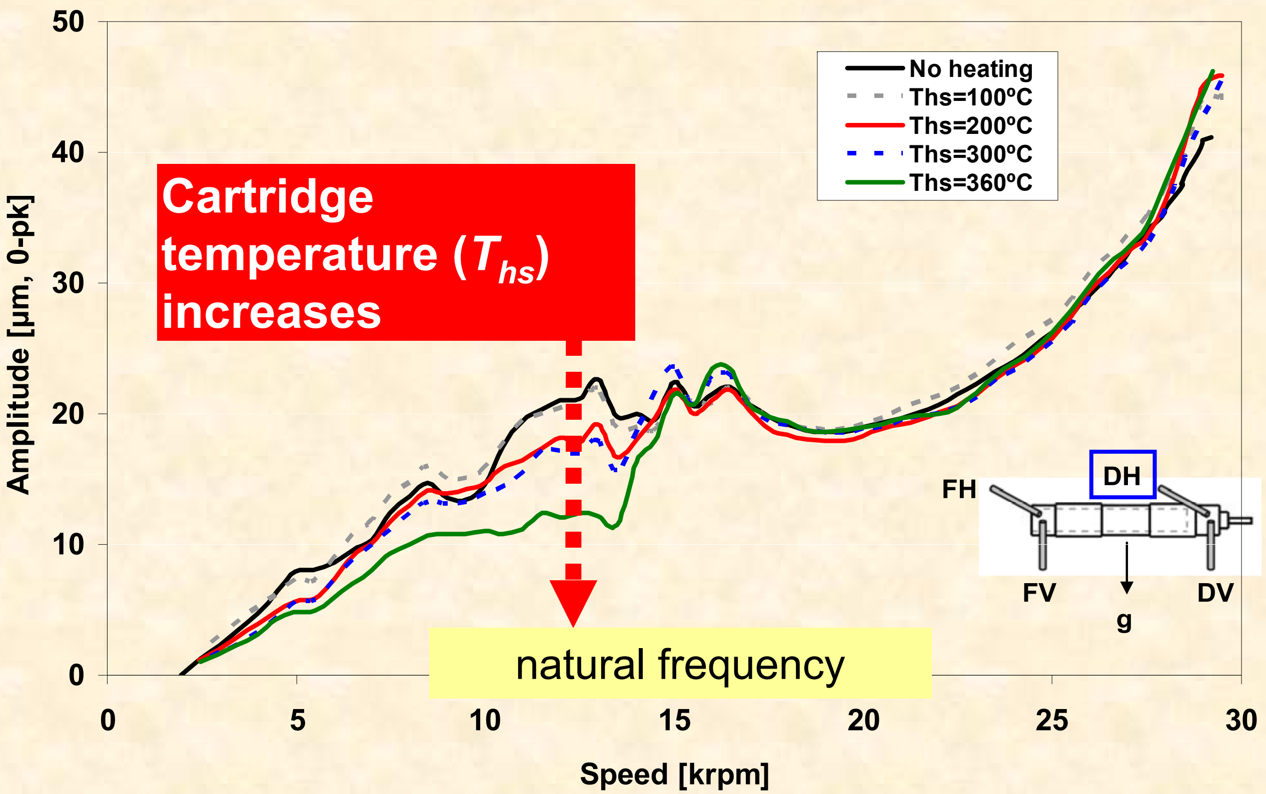
Critical speed (Rigid body) ~ 13 krpm
Elastic mode at 29 krpm

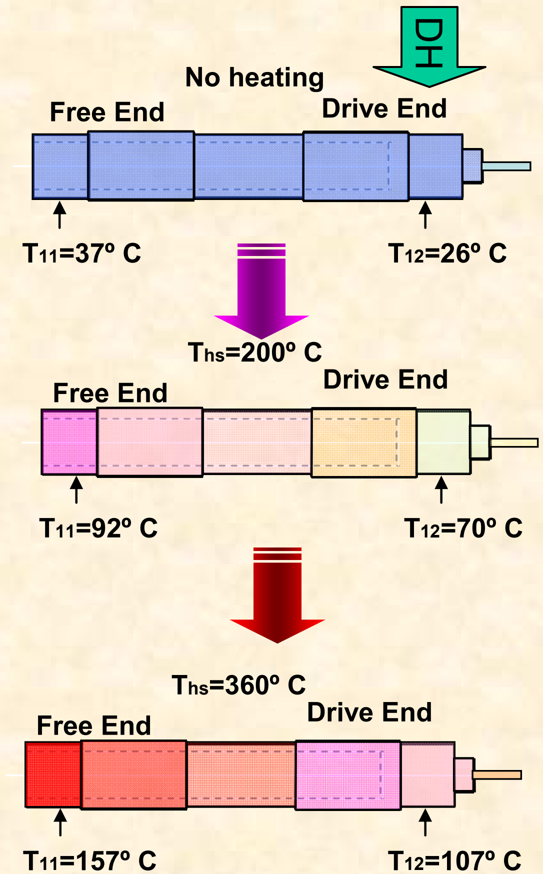
No major differences in responses between cold and hot

Rotor 1X response for cold & hot conds

ASME GT 2010-22981

Heater up to 360C. No forced cooling



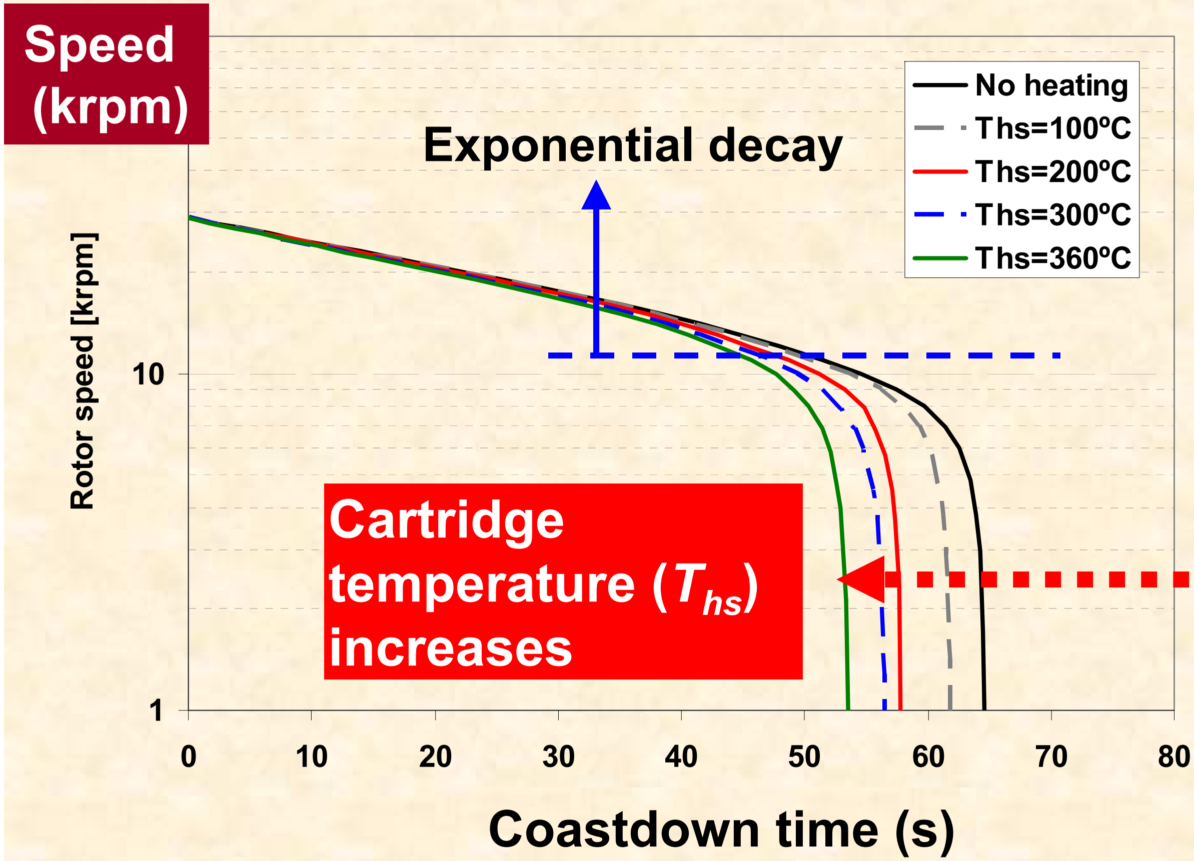


As T_{hs} increases to 360ºC, peak amplitudes between 7~15 krpm decrease

Time for rotor coast down

Effect of temperature

ASME GT 2010-22981



Heater up to 360C.

No forced cooling

Long time to coastdown : very low viscous drag

Coastdown time reduces as rotor heats (lesser clearance)

Gas Foil Bearings

Closure 3

Thermal management

ASME GT2010-22981

- **For operation with hot shaft, rotor motion reduces while crossing critical speed.**

- **As rotor and bearing temperatures increase, air becomes more viscous and bearing clearances decrease; hence coastdown time decreases.**

- **Thermal management with cooling streams works best at high temperatures and flow rates ensuring turbulent flow.**

- **Foil Bearings survived high temperature operation – Still working !**

Metal Mesh Foil Bearings

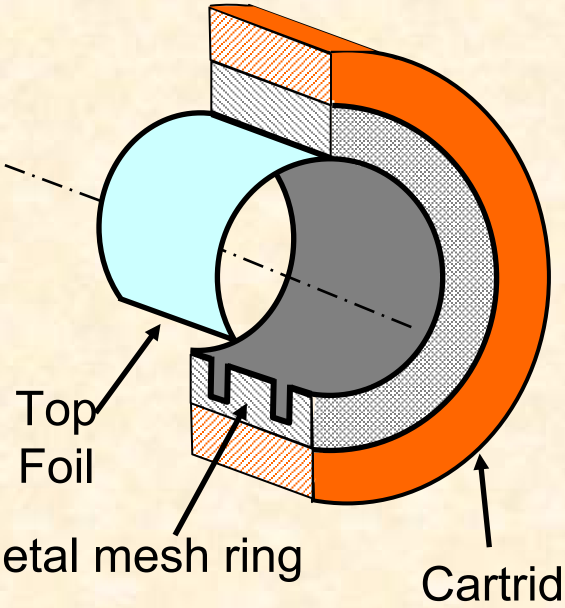
Metal Mesh Foil Bearing (MMFB)

Bearing Cartridge, metal mesh ring and top foil

Hydrodynamic air film between rotating shaft and top foil

Applications: ACMs, micro gas turbines, turbo expanders, turbo compressors, turbo blowers, automotive turbochargers, APUs

- **Large damping (material hysteresis) offered by metal mesh**
- **Tolerant to misalignment,**
- **Wide temperature range**
- **Coatings to reduce friction at start-up & shutdown**



MMFB Assembly

ASME GT2009-59315

Simple construction and assembly procedure

BEARING CARTRIDGE

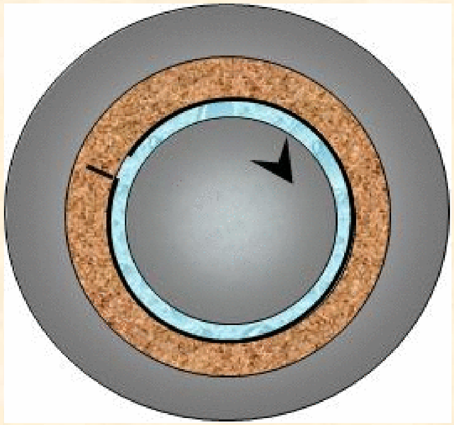
METAL MESH RING

TOP FOIL

Metal Mesh Foil Bearings (+/-)

+

- NO temperature limits
- Resilient structure with lots of material damping.
- Simple construction (in comparison to other foil bearings)
- Cheap!



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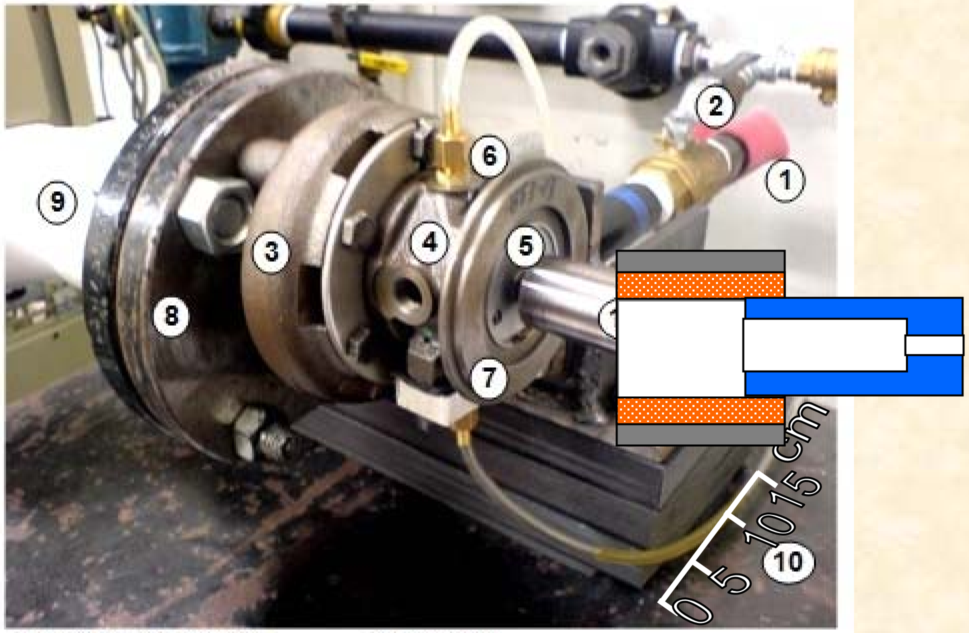
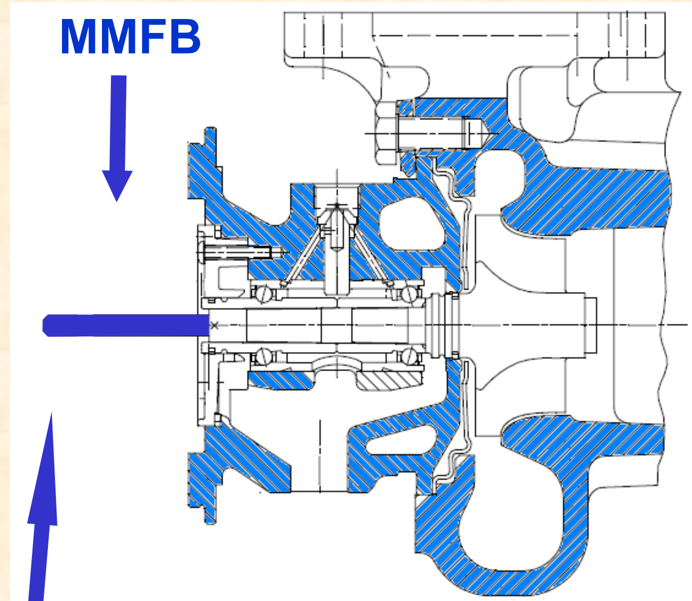
- Metal mesh tends to sag or creep over time
- Damping NOT viscous. Modeling difficulties
- Unknown rotordynamic force coefficients

MMFB rotordynamic test rig



1. 9.30 bar Air Supply
2. Throttle Valve
3. Turbine Housing
4. Center Housing
5. Stub Shaft
6. Oil Inlet
7. Oil Outlet
8. Turbine Outlet Safety structure
9. Turbine exhaust
10. ¾" Thick Steel Tabletop
11. Test journal (28mm outer diameter hollow shaft)



TC cross-sectional view

Max. operating speed: 75 krpm
Turbocharger driven rotor
Regulated air supply: 9.30bar

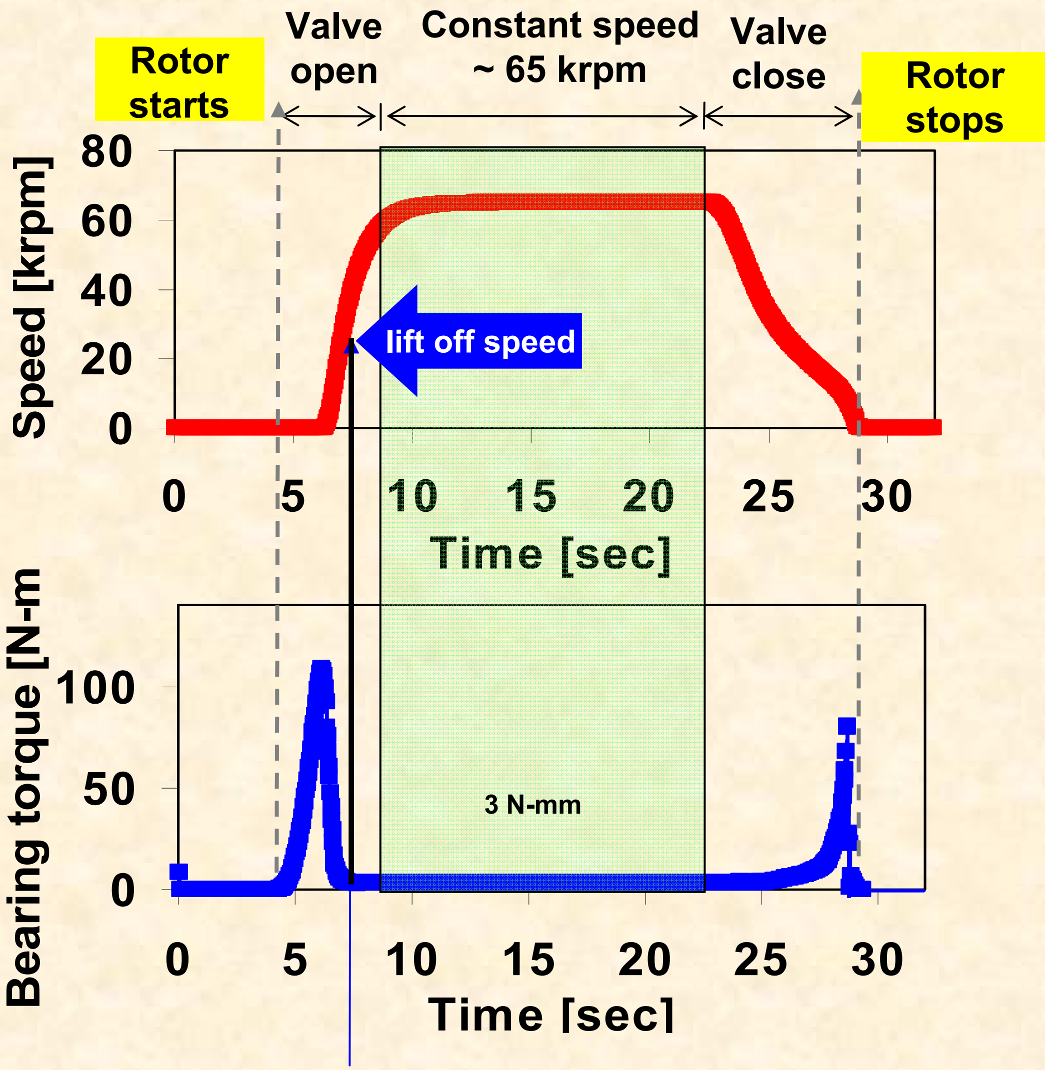
Journal press fitted on Shaft Stub

Journal: length 55 mm, 28 mm diameter , weight=0.22 kg

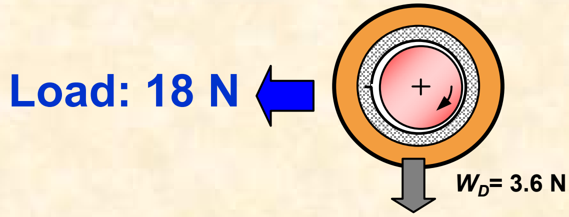
Twin ball bearing turbocharger
Model T25

ASME GT2010-22440

Lift off speed and torque



2009 AHS 65th Annual forum

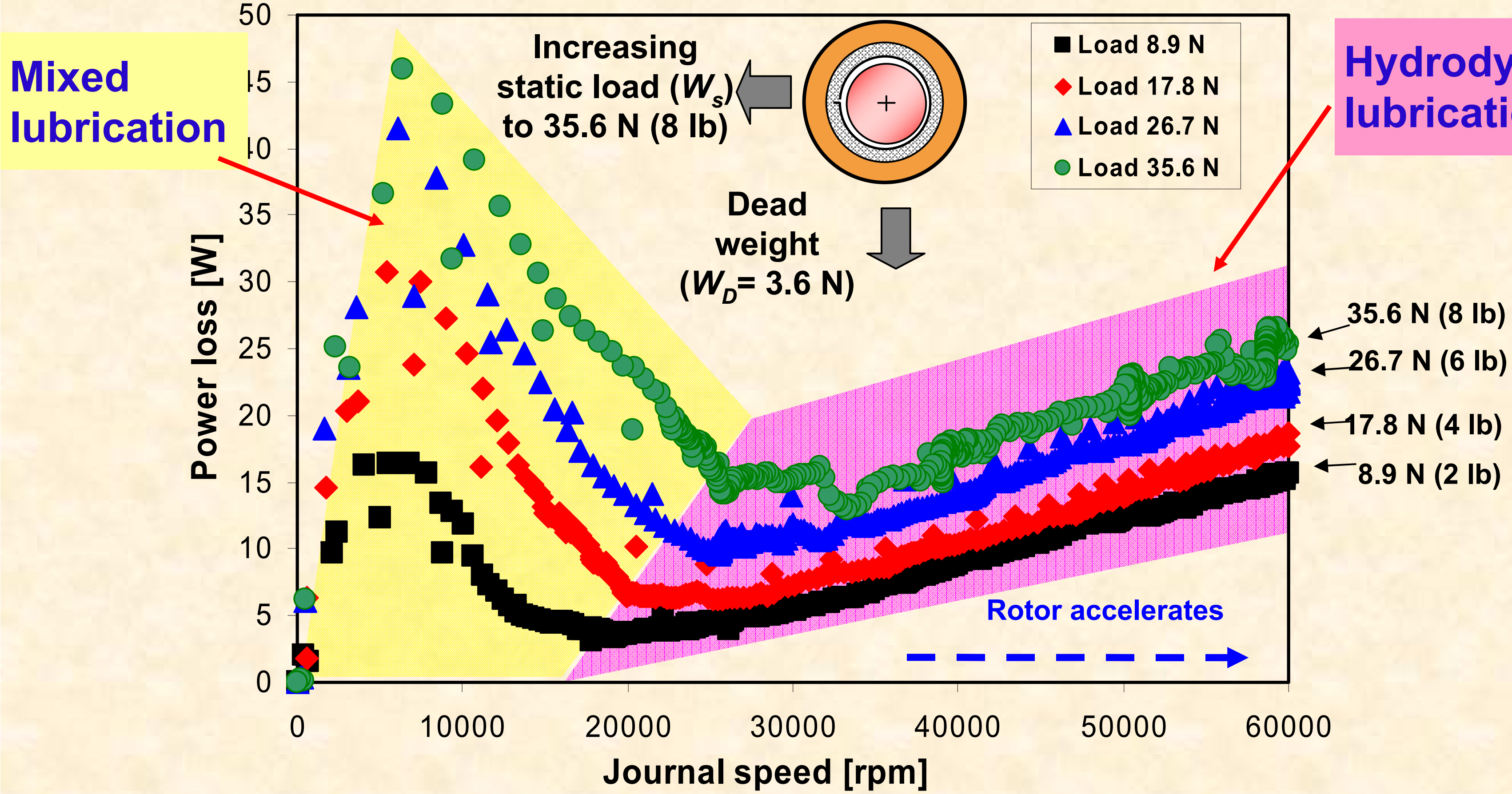


START UP to 65 krpm and SHUT DOWN

Once airborne, drag torque is ~ 3 % of Startup 'breakaway' torque

Lift off speed at lowest torque : **airborne operation**

MMFB power loss vs rotor speed



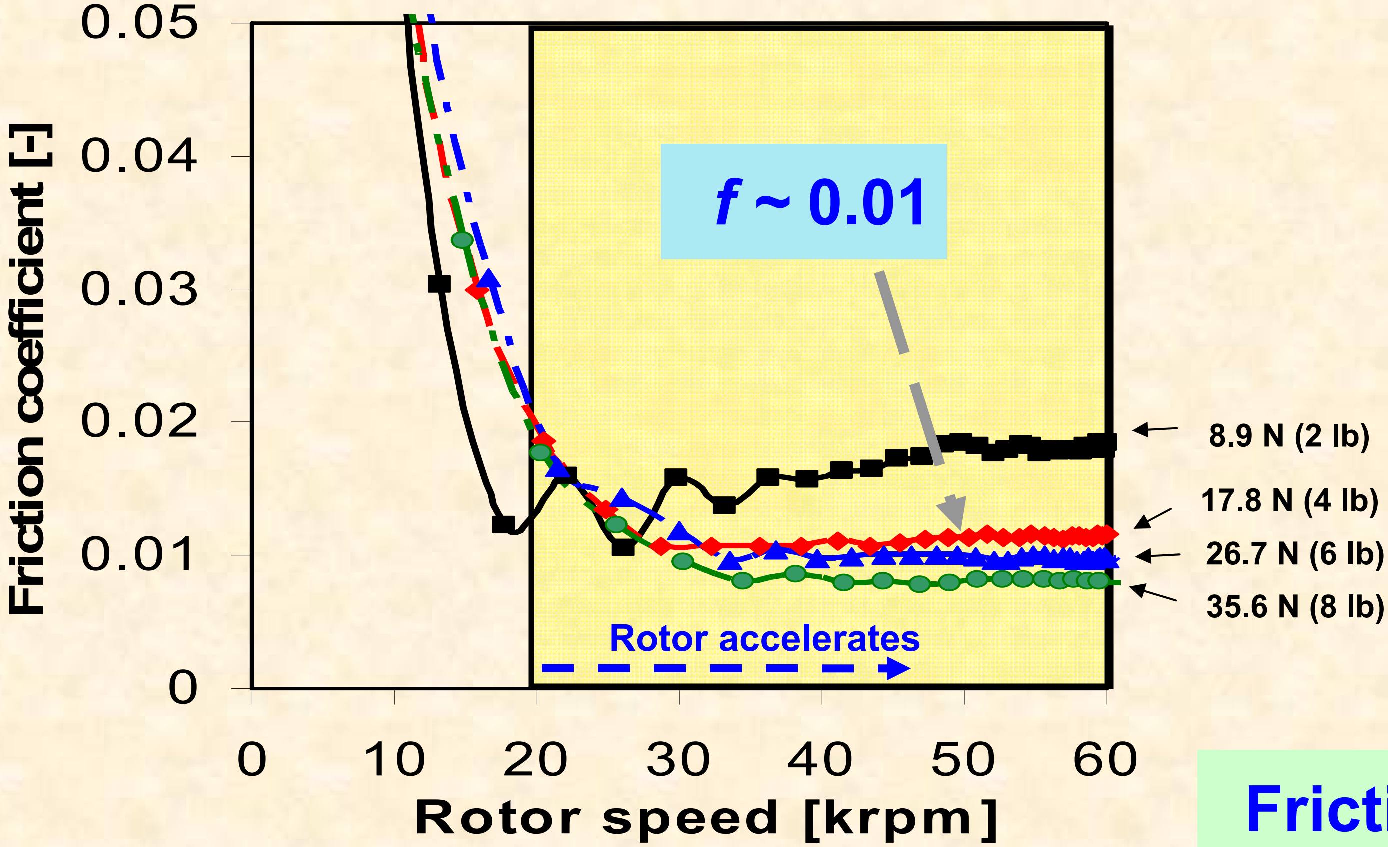
ASME GT2010-22440

Power loss decreases to min during mixed lubrication, then increases with increasing rotor speed

Friction coefficient vs rotor speed

f = (Torque/Radius)/(Static load)

2009 AHS 65th Annual forum



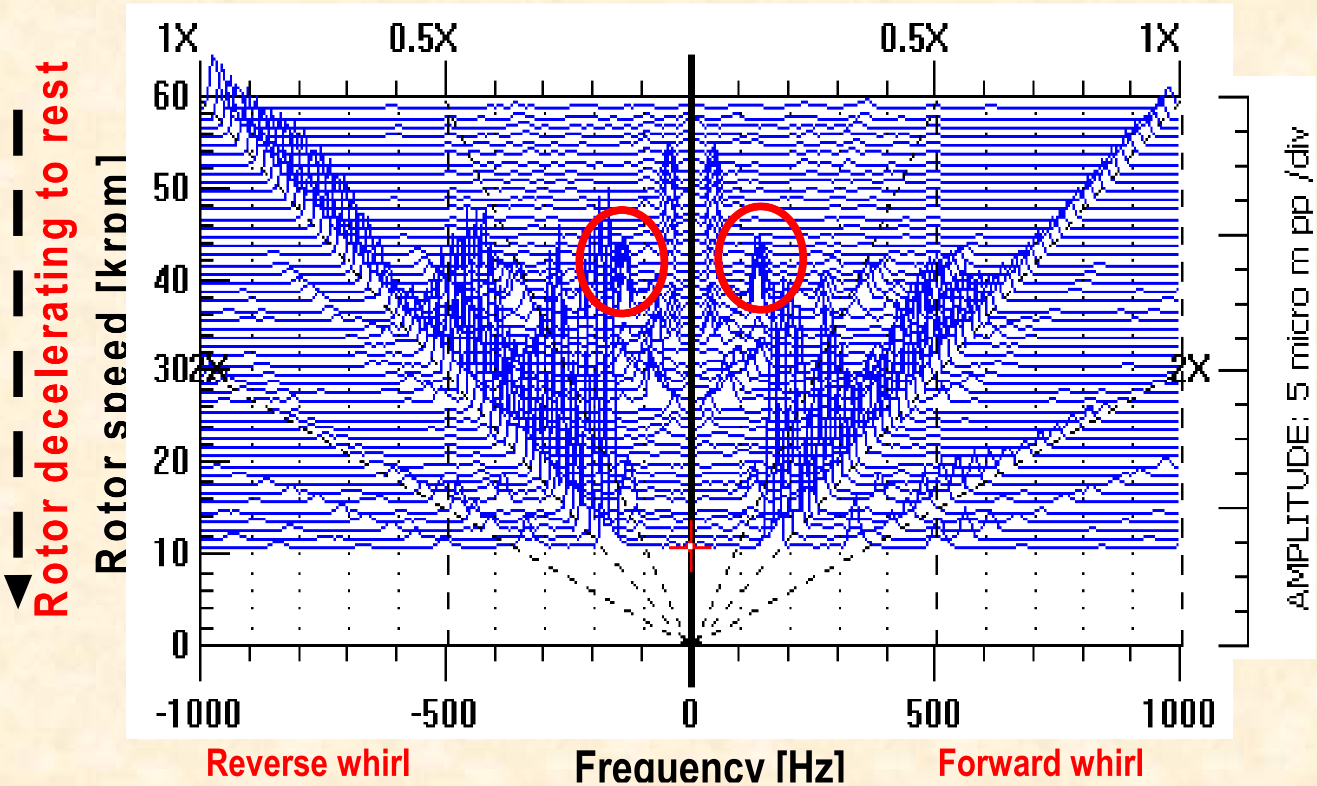
f ~ 0.3-0.4

Dry sliding → Airborne →

Friction coefficient (*f*) decreases with increasing static load

Waterfall of rotor-MMFB motions

H load = 18 N



Large sub harmonic motions locked at natural frequency

½ frequeny whirl absent with larger applied loads

ASME GT2010-22440

Metal mesh foil bearings have similar "forced" nonlinearity issues as bump-type foil bearings

Metal Mesh Foil Bearings

Closure

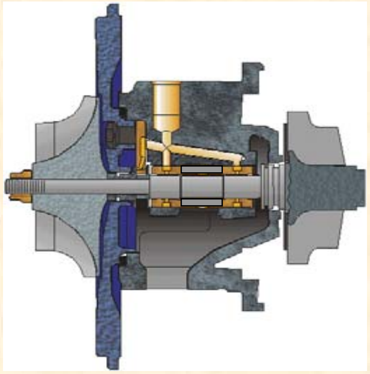
What we've learned so far

- While airborne, MMFB power loss increases with rotor speed (little friction). Min power loss found.
- MMFB structural stiffness and damping coefficients are frequency and amplitude dependent. Predictive model benchmarked against test data.
- Measurements of MMFB rotordynamic force coefficients underway.

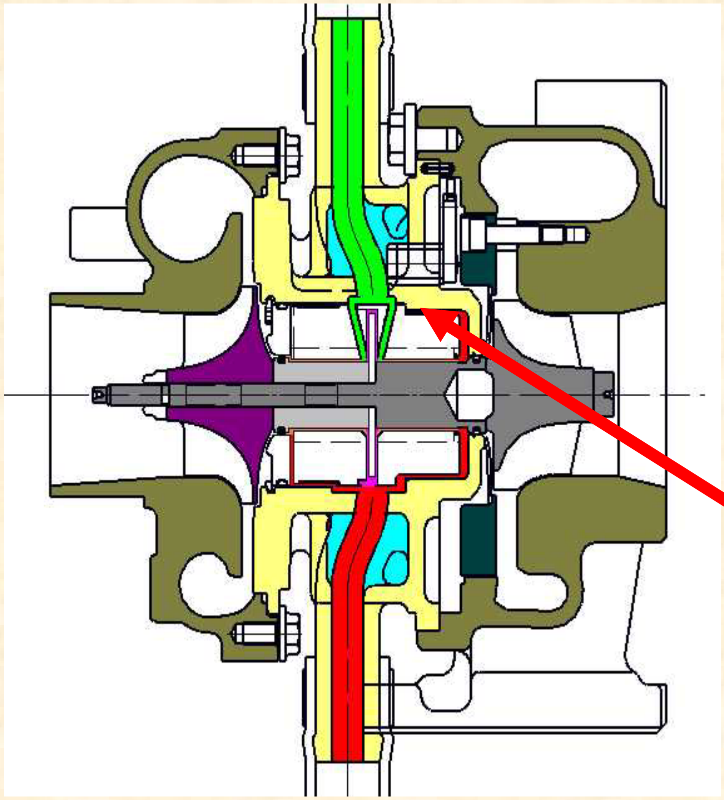
MMFBs are inexpensive gas bearings for oil-free MTM. Use cheap commercially available materials.

Turbocharger Systems **A challenge!**

DETC2007-34136

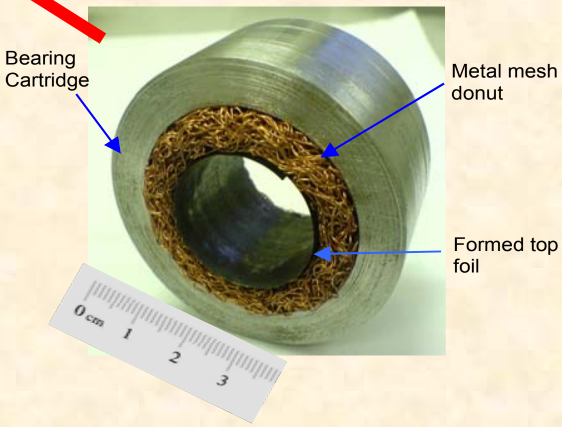


conventional Oil-Bearing



Oil Less Bearing System (2007)

Foil Bearings or **Metal Mesh Bearings** or **Flex Pivot Bearings**



Increased engine efficiency and performance relies on robust rotor-bearing system

The road ahead

Closure: Gas Bearings for MTM

Dominant challenges for gas bearing technology:

- Low gas viscosity requires minute clearances to generate load capacity.
- Damping & rotor stability are crucial
- Inexpensive coatings to reduce drag and wear
- Bearing design & manufacturing process well known
- Adequate thermal management to extend operating envelope into high temperatures

Closure: Gas Bearings for MTM

Other pressing challenges for gas bearing technology:

- **intermittent contact and damaging wear at startup & shut down, and**
- **temporary rubs during normal operating conditions**

Current research focuses on coatings (materials), rotordynamics (stability) & high temperature (thermal management)

Need Low Cost & Long Life Solution!

MTM – Needs & issues reassessed

Largest power to weight ratio,
Compact & low # of parts

Reliability and efficiency,
Low maintenance

Extreme temperature and pressure

Environmentally safe (low emissions)

Lower lifecycle cost ($ kW)

High speed

Rotordynamics &
(Oil-free) Bearings & Sealing

Materials

Coatings: surface conditioning for low friction and wear
Ceramic rotors and components

Manufacturing

Automated agile processes
Cost & number

Processes & Cycles

Low-NOx combustors for liquid & gas fuels
TH scaling (low Reynolds #)

Fuels

Best if free (bio-fuels)

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