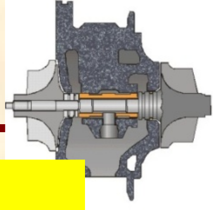


Vehicle Turbocharger Nonlinear Rotordynamics

Modeling and Experimental Validation

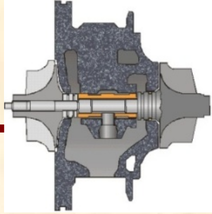
Luis San Andrés

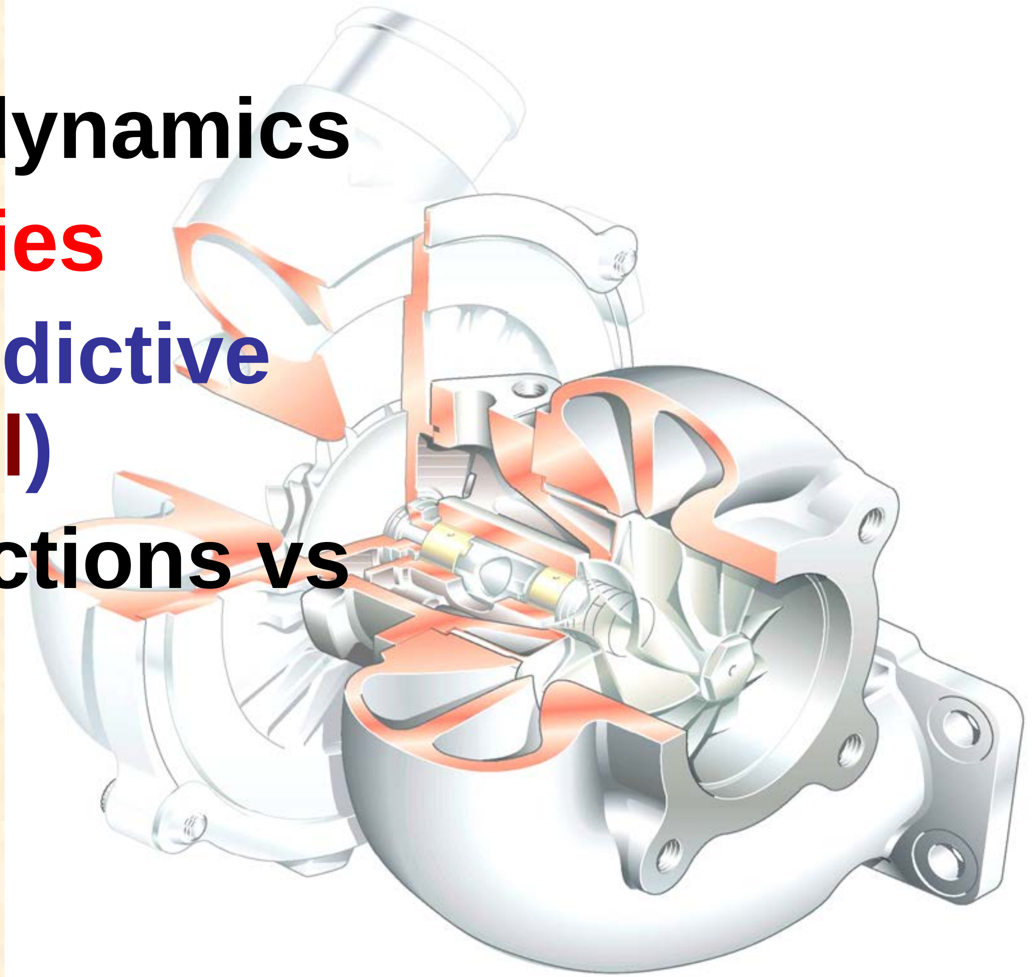
Mast-Childs Tribology Professor

Texas A&M University, Turbomachinery Laboratory

January, 2011

Supported by Honeywell Turbocharger Technologies (HTT)

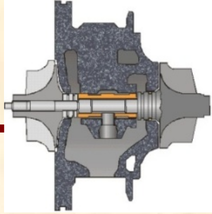


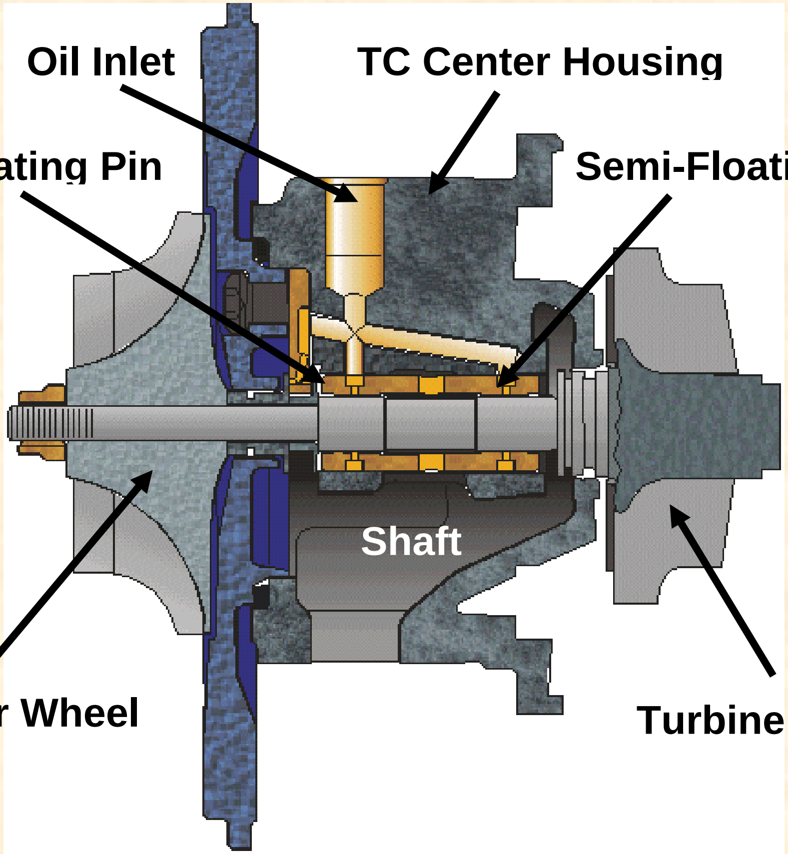


- Introduction to turbocharger rotordynamics
- Experimental facilities
- Development of predictive models (Virtual Tool)
- Comparisons predictions vs test data
- Closure

Overview

TC shaft motions virtual tool

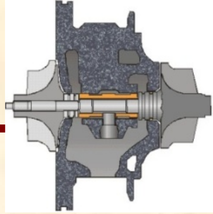




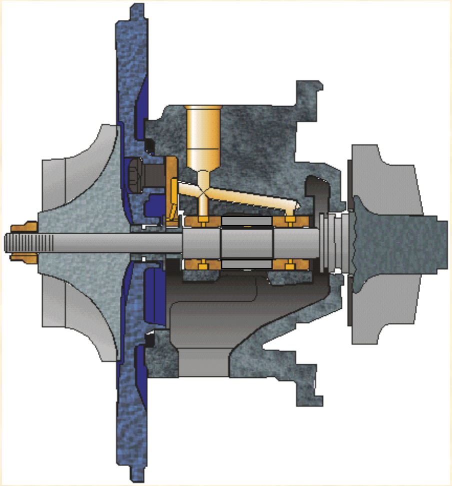
Turbochargers

- **Increase internal combustion (IC) engine power output by forcing more air into cylinder**
- **Aid in producing smaller, more fuel-efficient engines with larger power outputs**

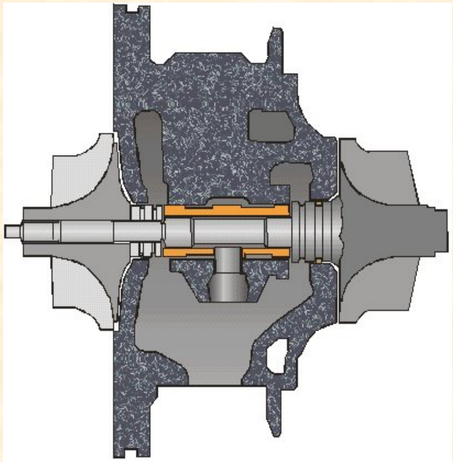
TC shaft motions virtual tool



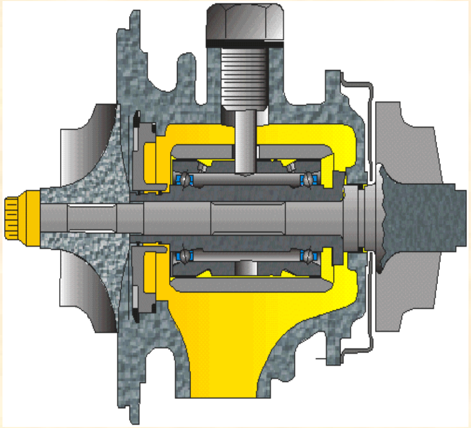
RBS: TC Rotor Bearing System(s)



RBS
Fully Floating Bearing



RBS
Semi Floating Bearing

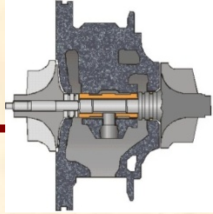


RBS
Ball Bearing

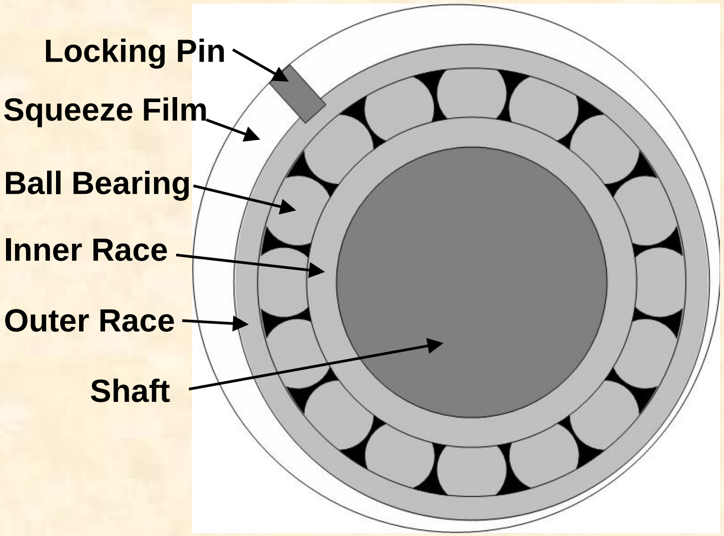
The driver:

Increased IC engine performance & efficiency demands of robust & turbocharging solutions

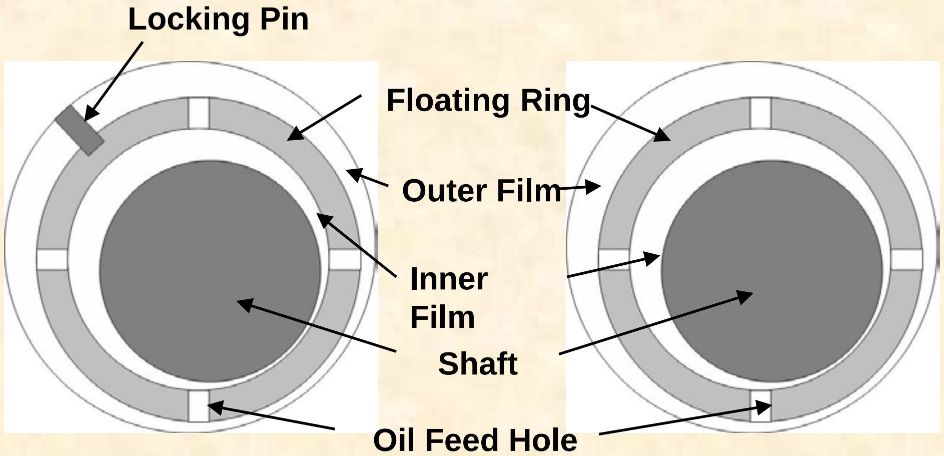
TC shaft motions virtual tool



Bearing types



Ball-Bearing



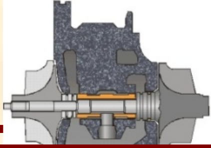
Semi-Floating Ring Bearing (SFRB)

Floating Ring Bearing (FRB)

- Low shaft motion
- Relatively expensive
- Limited lifespan

- Economic
- Longer life span
- Prone to subsynchronous whirl

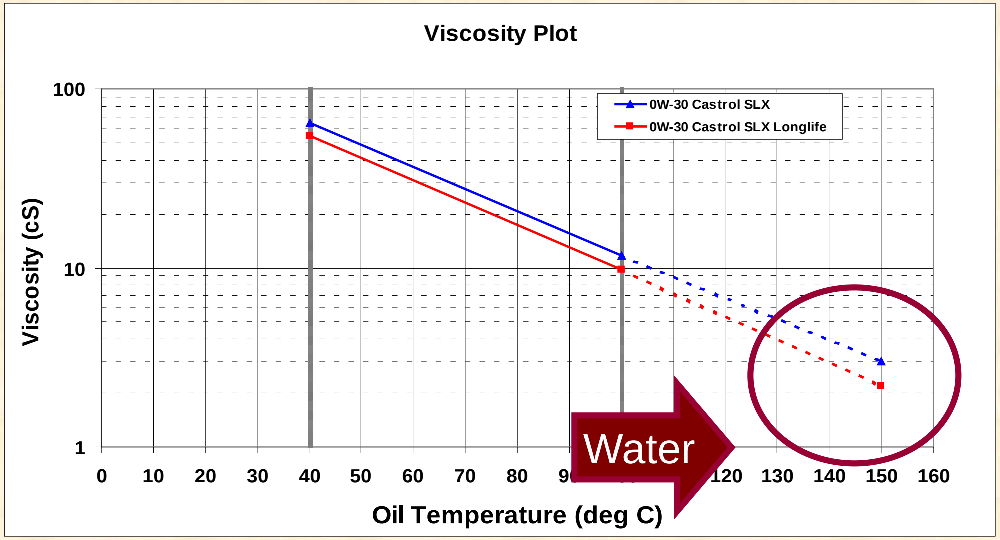
TC shaft motions virtual tool



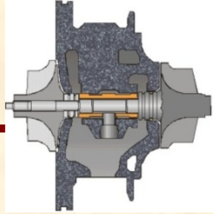
Major challenges: extreme operating conditions

- - Low Oil Viscosity, e.g. 0W30 or 0W20
- - High Oil Temperature (up to 150°C)
- - Low HTHS (2.9); Low Oil Pressure (1 bar)
- - Increased Maximum Turbocharger Speed
- - Variable Geometry Turbo Technology & Assisted e-power start up
- - High Engine Vibration Level
- - More Stringent Noise Requirements

Need predictive too to reduce costly engine test stand qualification



Literature Review: San Andres and students



- TC linear and nonlinear rotordynamic codes – GUI based – including engine induced excitations
- Realistic bearing models: thermohydrodynamic
- Novel methods to estimate imbalance distribution and shaft temperatures
- NL analysis for frequency jumps and noise reduction
- Measured ring speeds with fiber optic sensors

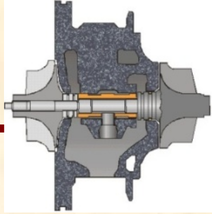
2004	IMEchE J. Eng. Tribology
2005	ASME J. Vibrations and Acoustics ASME DETC 2003/VIB-48418 ASME DETC 2003/VIB-48419
2007	ASME J. Eng. Gas Turbines Power ASME GT 2006-90873
2007	ASME J. Eng. Gas Turbines Power ASME GT 2005-68177
2007	ASME J. Tribology IJTC 2006-12001
2007	ASME DETC2007-34136
2010	ASME J. Eng. Gas Turbines Power ASME GT2009-59108
2010	IFToMM Korea

TC testing: expensive and time consuming → Predictive tool saves time and money

Benchmarked against test data

Predictive tool for shaft motion benchmarked by test data

Main Tasks – KEY OBJECTIVES



1. **Measure shaft motion response in dedicated PV and CV turbocharger test rigs (cold & hot gas)**

Test rigs

2. **Development of software for prediction of (S) floating ring bearing static and dynamic forced response**

XLBRG

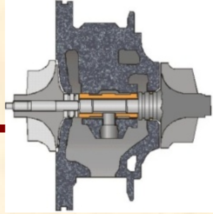
3. **Integration of FRB and SFRB tools into nonlinear rotordynamics code – VIRTUAL LABORATOY**

$XLTRC_2$

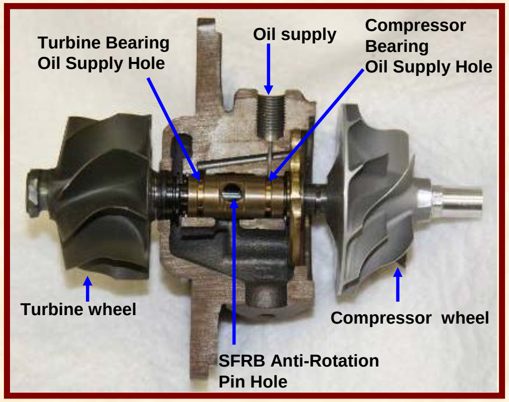
4. **Comparisons of test data to predictions: Validate predictive tool**

Tools

TC shaft motions virtual tool

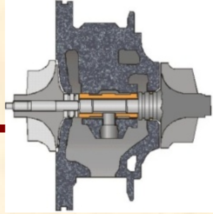


Test rigs for TC rotordynamic performance evaluation



KEY OBJECTIVE # 1

TC shaft motions virtual tool



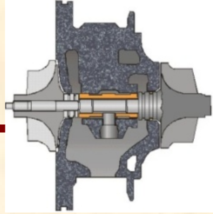
Experiments to measure the rotordynamic response of a turbocharger supported on semi-floating ring bearings and fully floating ring bearings

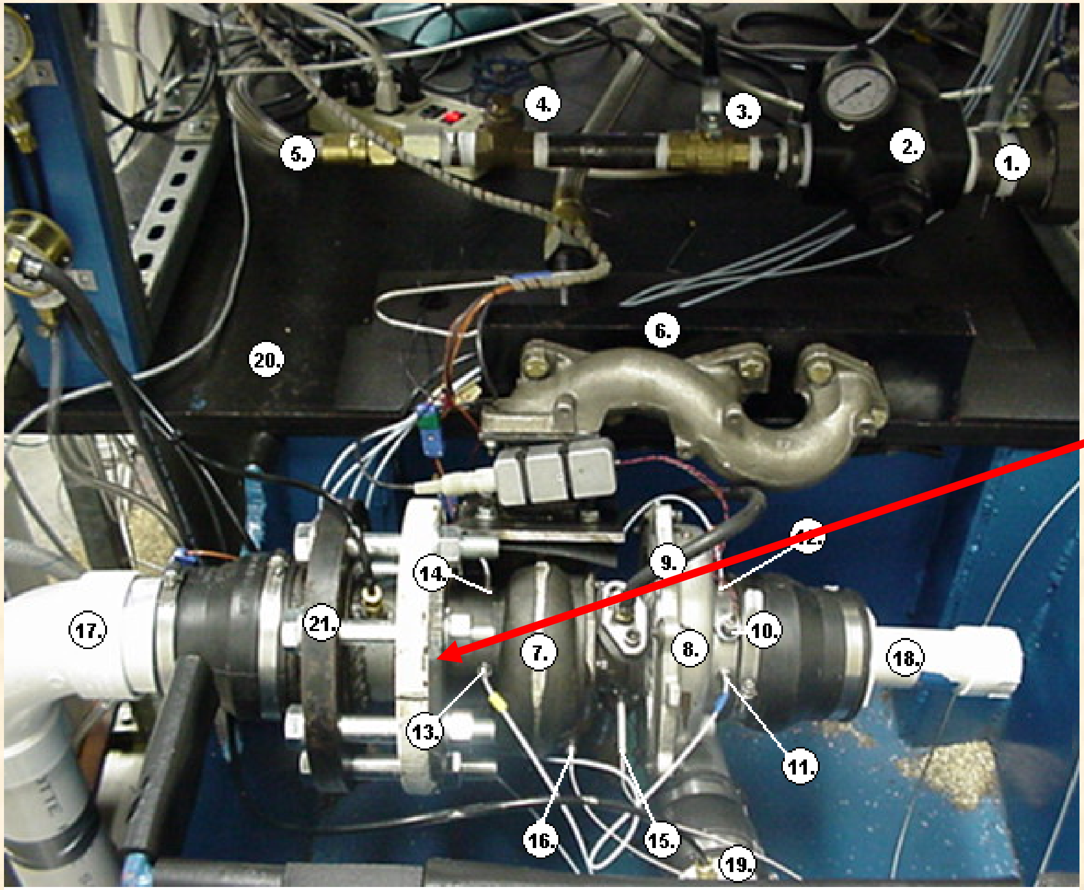
Test Rigs

Construct various test rigs, develop measurement methods, strategy to sensor selection and measurement locations, acquire data, processing tools, etc

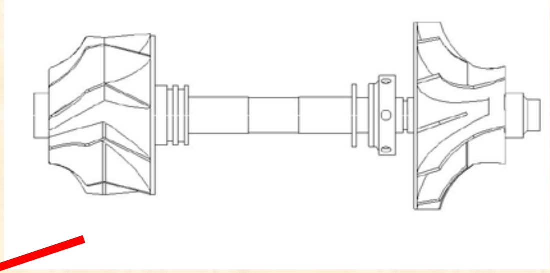
KEY OBJECTIVE # 1

TC shaft motions virtual tool





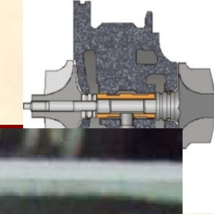
1. High pressure supply
2. Pressure regulator
3. Shut-off valve
4. Turbine flow control valve
5. Flexible Hose
6. Supply Manifold
7. Turbine
8. Compressor
9. Lubricant Supply
10. Infared tachometer
11. Compressor X-Direction Proximity Transducer
12. Compressor Y-Direction Proximity Transducer
13. Turbine X-Direction Proximity Transducer
14. Turbine Y-Direction Proximity Transducer
15. Fiber optic floating ring tachometer (Compressor End)
16. Fiber optic floating ring tachometer (Turbine End)
17. Turbine outlet
18. Compressor inlet
19. Compressor Outlet
20. Steel Table
21. Turbine Outlet Safety Structure

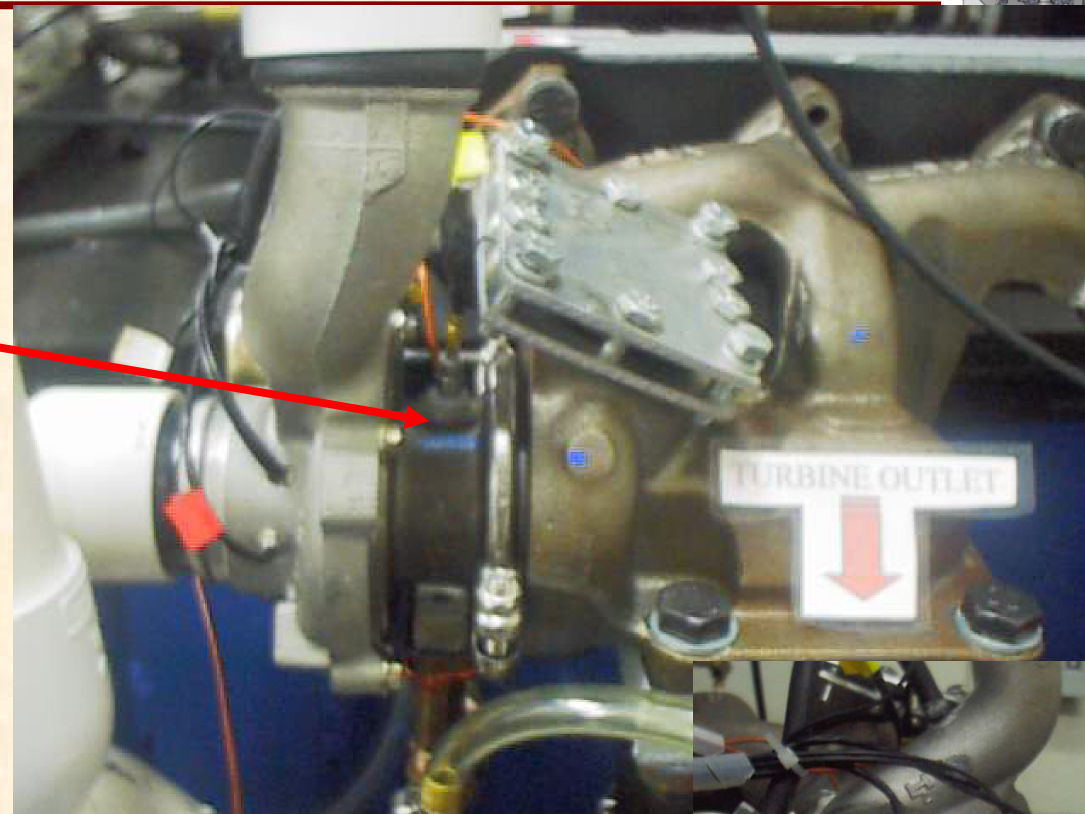


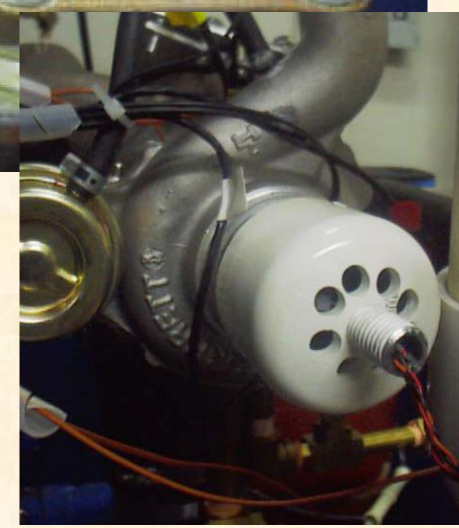
- Infrared tachometer
- RAM BN sensors for shaft motion
- Fiber optics for ring motion detection

TAMU TC test rig **2002**

TC shaft motions virtual tool



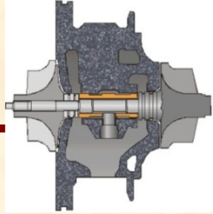


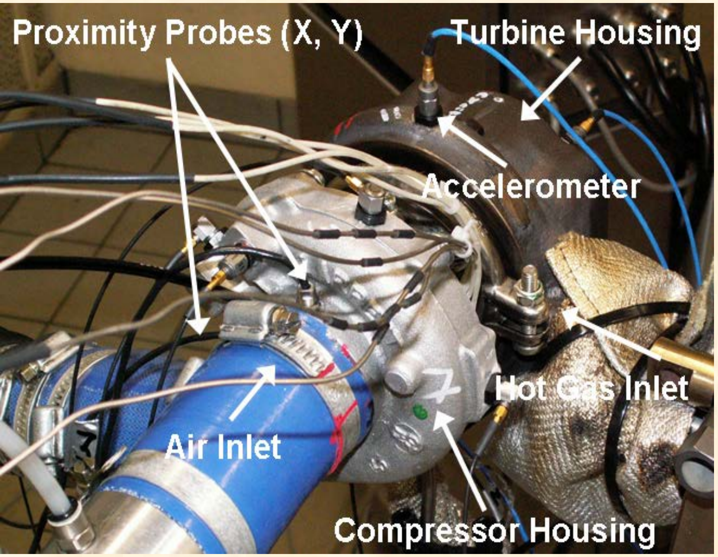


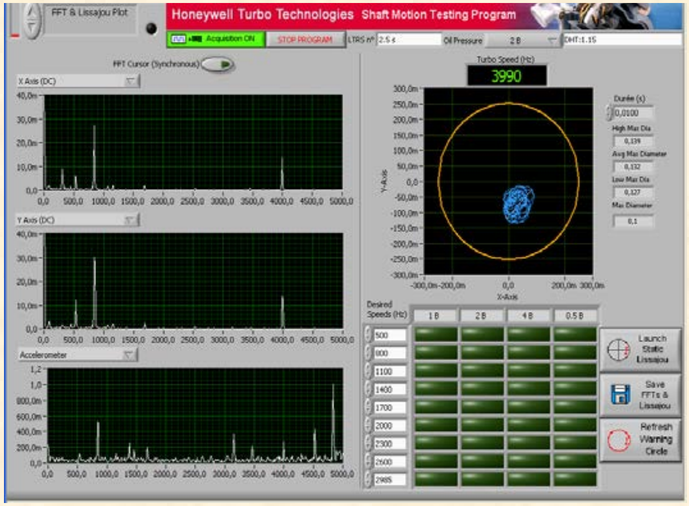
- Infrared tachometer
- KAMAN sensors for shaft displacement at compressor side
- Accelerometers for casing motion
- 240 krpm max (4 KHz)

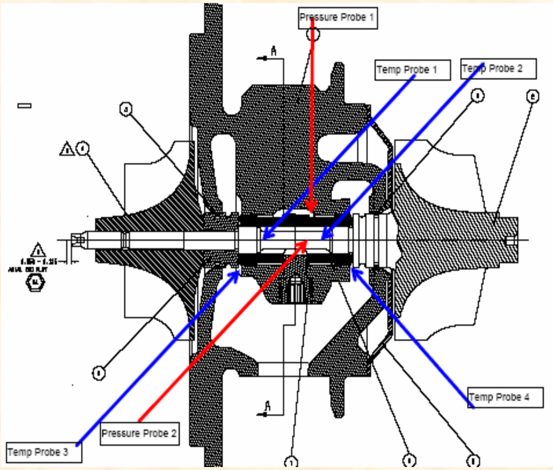
TAMU TC test rig **2004**

TC shaft motions virtual tool





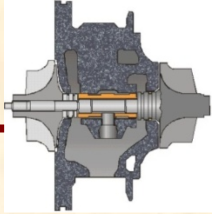


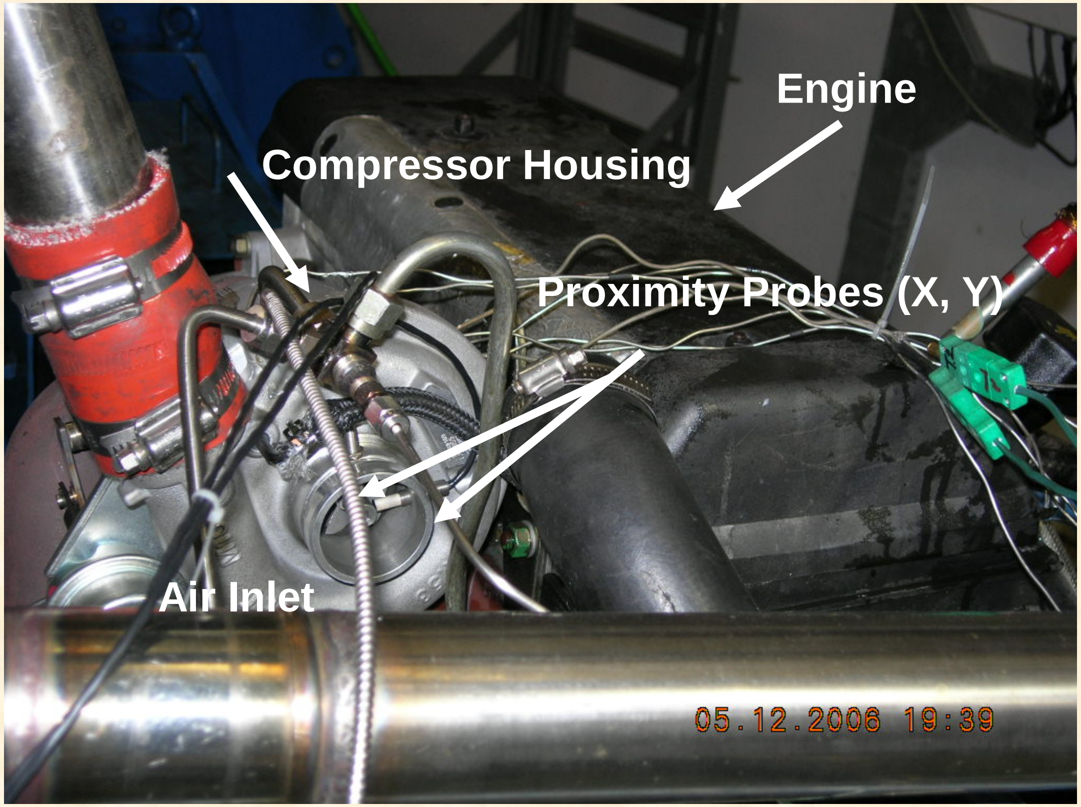


- **KAMAN sensors for shaft displacement at compressor side**
- **connection to shakers**
- **300 krpm max (5 KHz)**

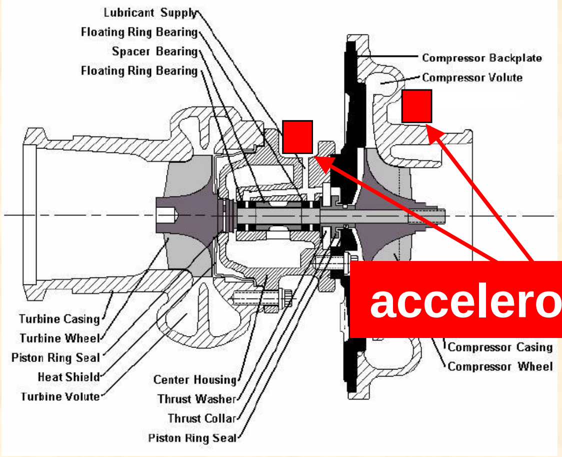
TC gas stand test rig – HTT (France) 2008

TC shaft motions virtual tool



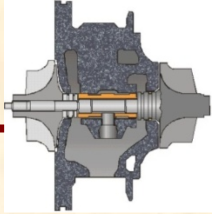


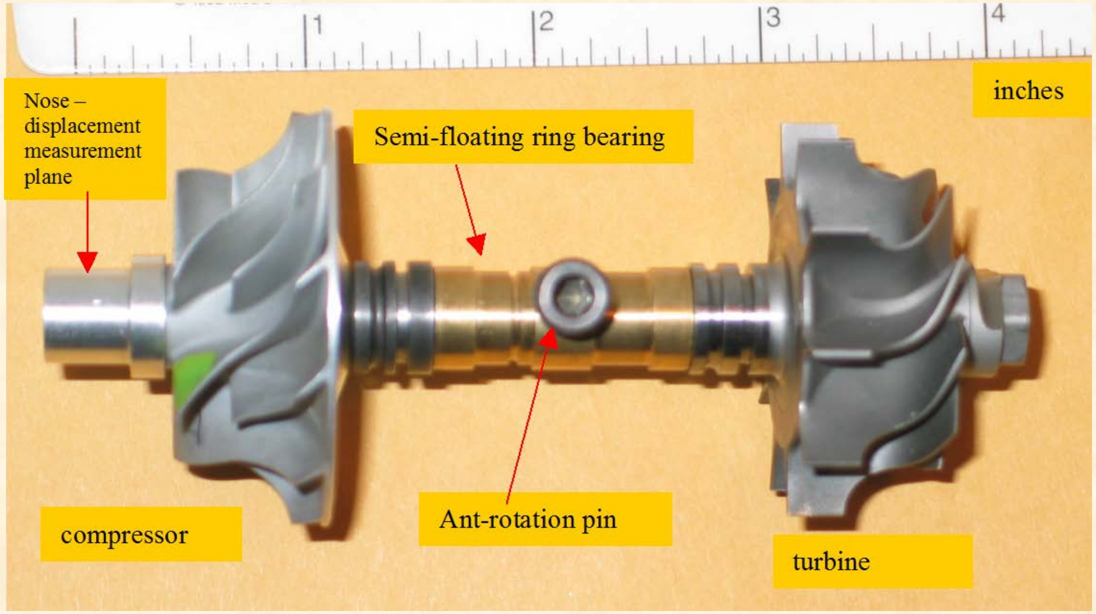
3-axes accelerometers: engine isolated atop a large shaker table



TC engine stand test rig–HTT (Shanghai) 2008

TC shaft motions virtual tool

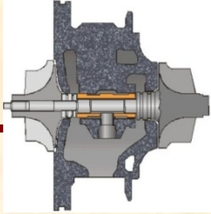




Shaft speed 25 - 240 krpm, Oil 5W-30,
150 C inlet temperature, feed pressure 1- 4 bar

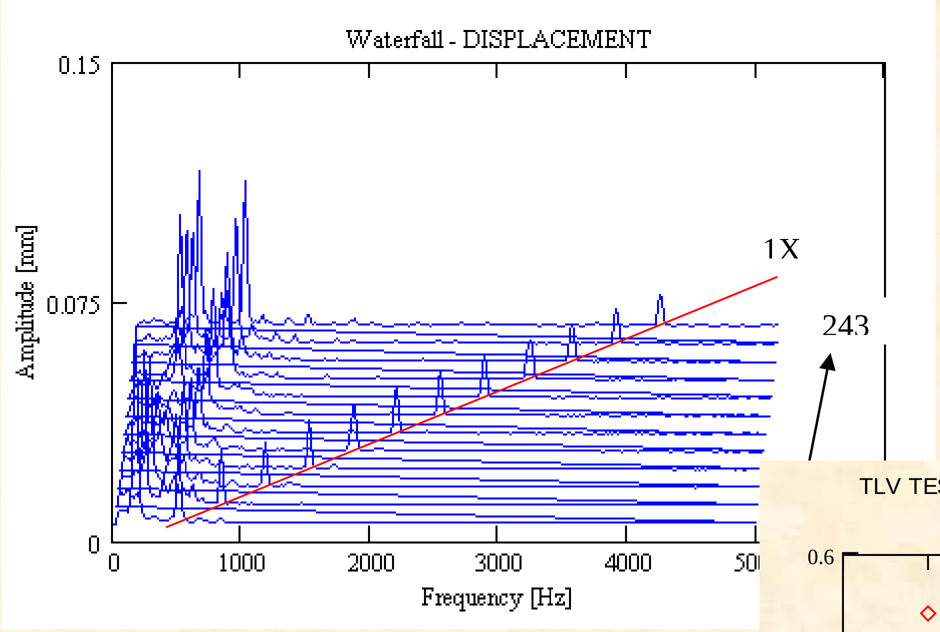
Measure rotordynamic response of PV turbocharger

TC shaft motions virtual tool

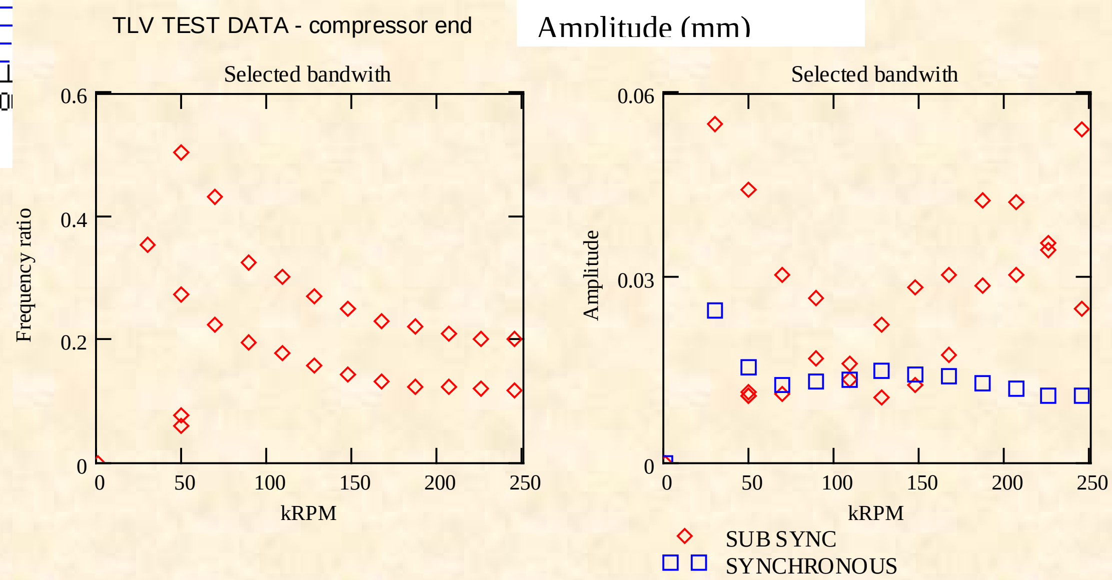


TEST DATA - Compressor End

TLV TEST DATA



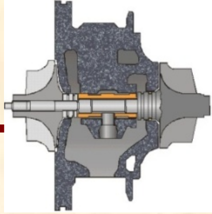
Dominance of sub synchronous motions at all speeds

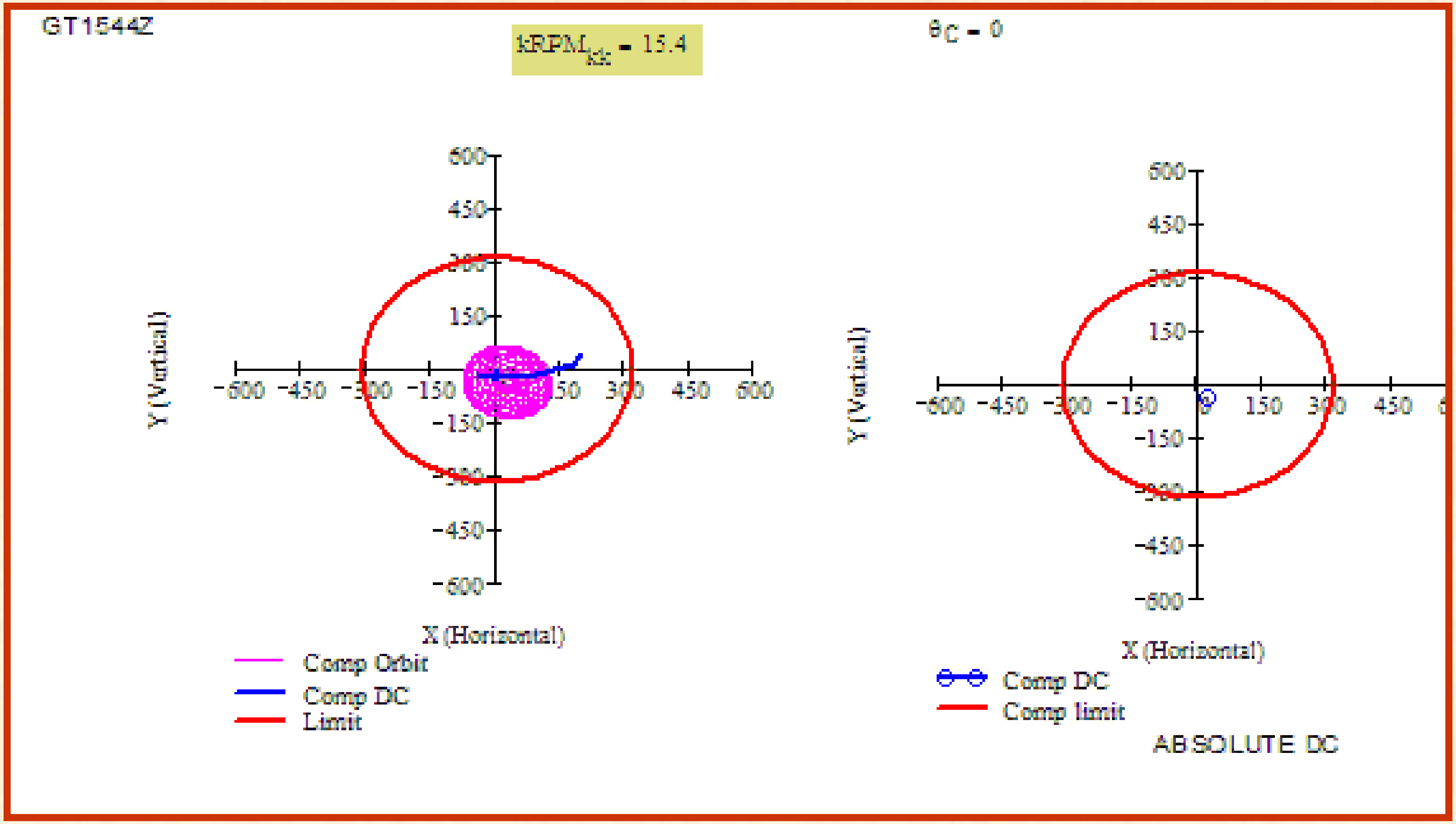


waterfall compressor end shaft motions

whirl frequency ratio and amplitudes (mm) of vibration. Oil supply pressure = 1 bar, T=150 C

TC shaft motions virtual tool

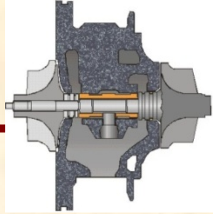


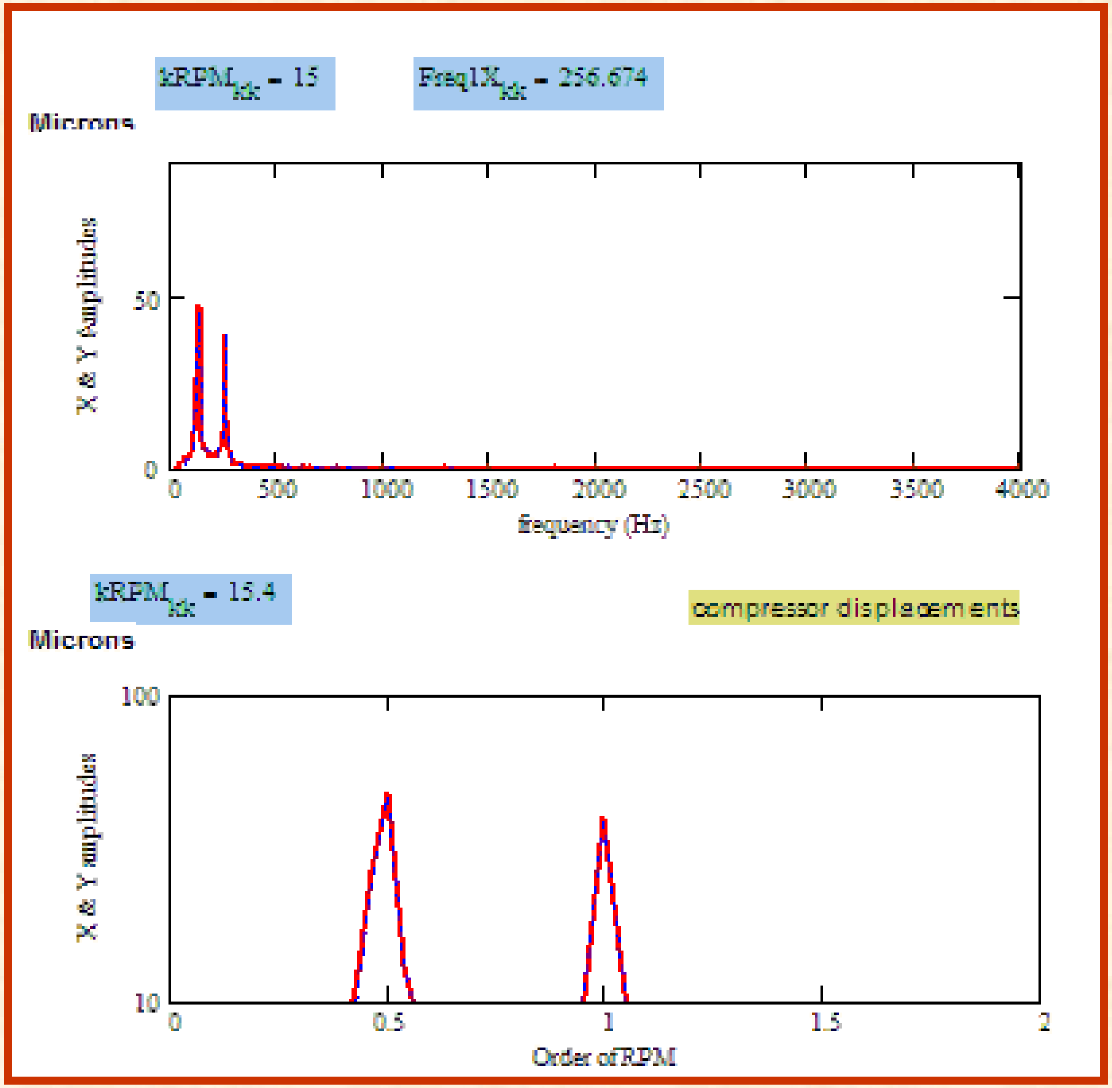


TAMU TEST DATA

TC failure (cold air operation) 10 - 110 krpm : Oil ISO VG 10

TC shaft motions virtual tool



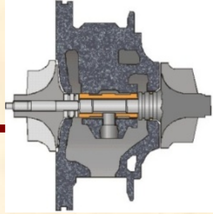


Purpose of analysis is to reduce risk for this type of failure

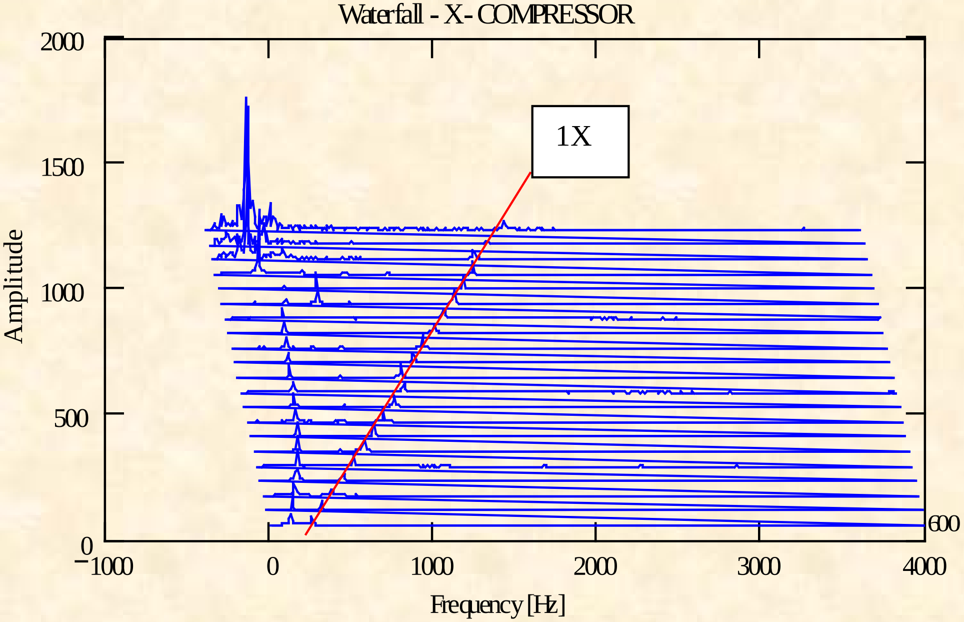
TAMU TEST DATA

TC failure (cold air operation) 10 - 110 krpm ; Oil ISO VG 10

TC shaft motions virtual tool



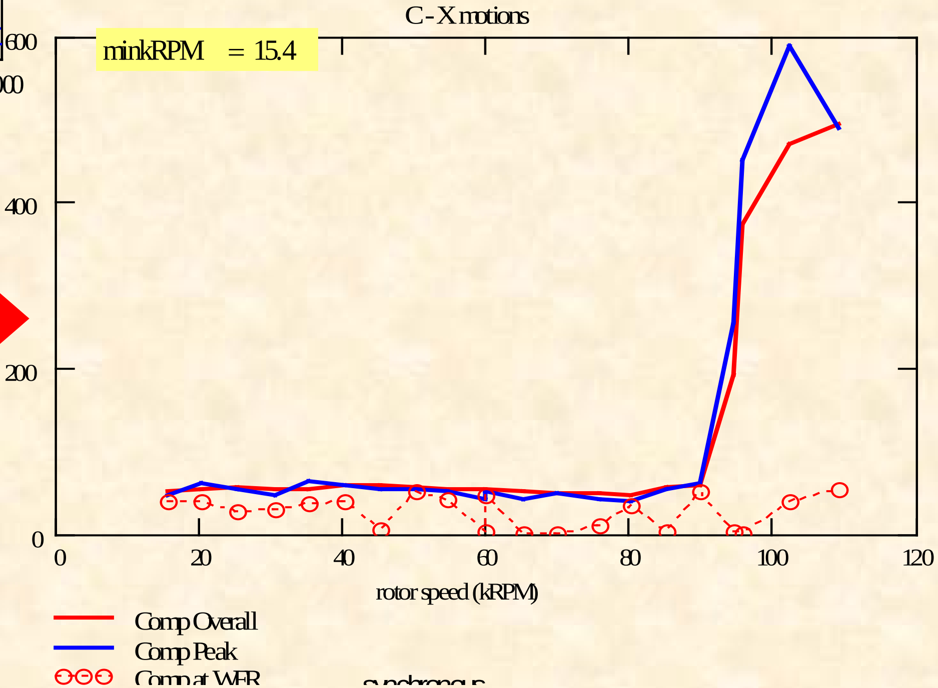
TAMU TEST DATA



CX max = 589.28
microns

maxkRPM = 109

minkRPM = 15.4

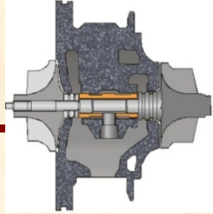


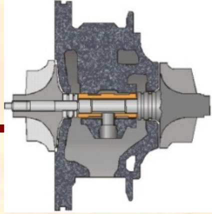
TC failure

(cold air operation)

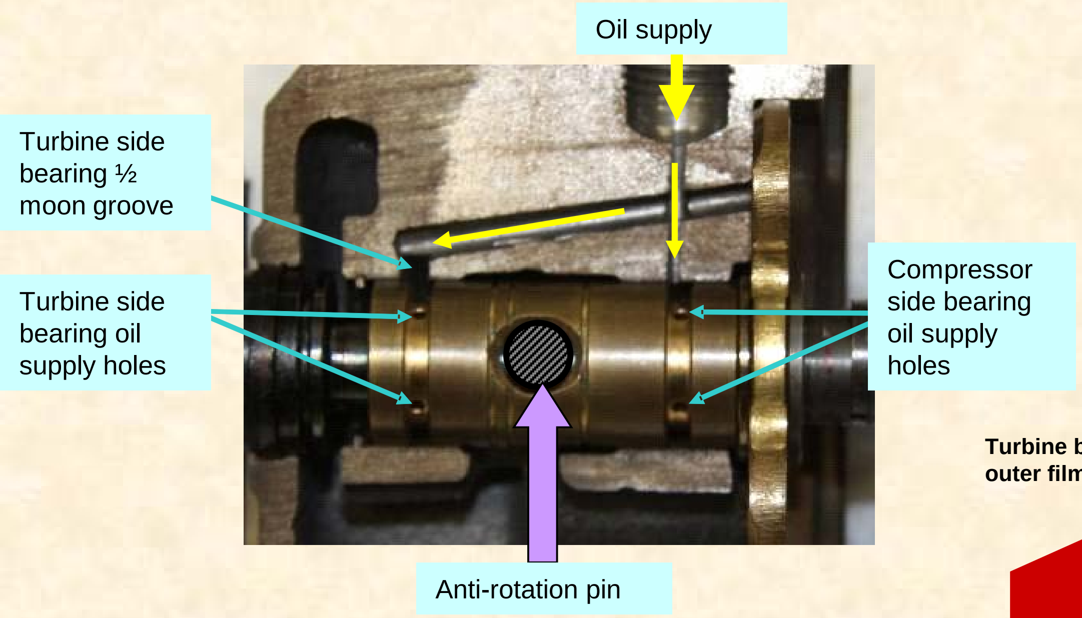
10 - 110 krpm : Oil ISO VG 10

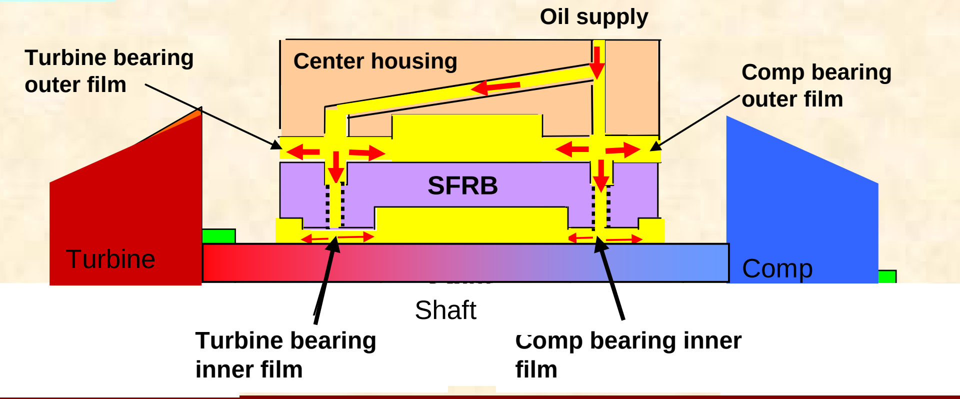
TC shaft motions virtual tool





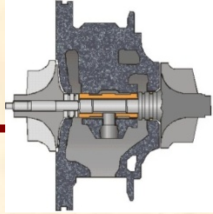
TC fluid film bearings





KEY OBJECTIVE # 2

TC shaft motions virtual tool



Development of software for prediction of (semi) floating ring bearing (S-FRB) static and dynamic forced response

XLBRG Tool

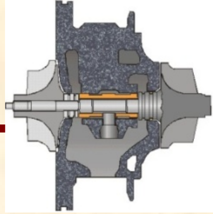
EXCEL & Fortran FEM code for prediction of FRBs and SFRBs forced response (static and dynamic)

Finite length bearing model with global thermal balance and shear thinning effects

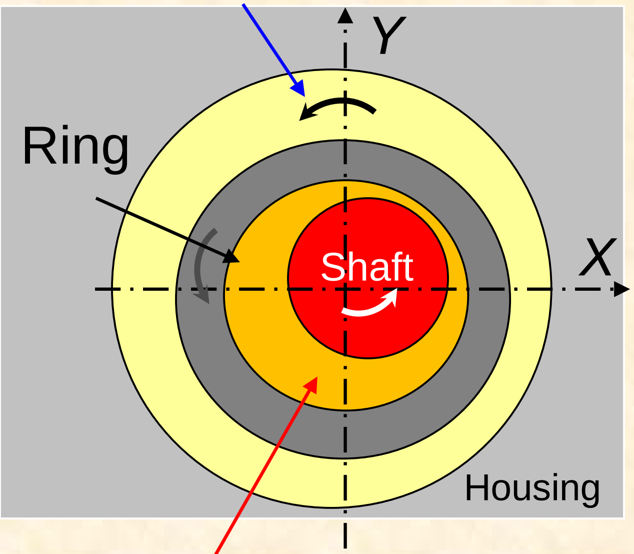
Interface to XLTRC^2 software for rotordynamics analysis

KEY OBJECTIVE # 2

Models for fluid films



Reynolds Equations



Outer film pressure, *Po*

$$\nabla\left\{\frac{h_o}{12\mu_o}\nabla\left(P_o\right)\right\} = \left\{\dot{e}_{X_R} + e_{Y_R}\frac{\Omega_R}{2}\right\}\cos\Theta + \left\{\dot{e}_{Y_R} - \frac{\Omega_R}{2}e_{X_R}\right\}\sin\Theta$$

Film thickness: $h_o = c_o + e_{X_R}\cos(\Theta) + e_{Y_R}\sin(\Theta)$

Inner film pressure, *Pi*

$$\nabla\left\{\frac{h_i}{12\mu_i}\nabla\left(P_i\right)\right\} = \left\{\delta\dot{e}_X + \delta e_Y\frac{\Omega_+}{2}\right\}\cos\Theta + \left\{\delta\dot{e}_Y - \frac{\Omega_+}{2}e_X\right\}\sin\Theta$$

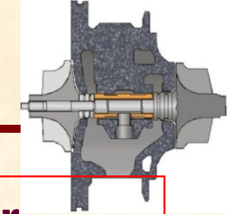
Film thickness: $h_i = c_i + \delta e_X\cos(\Theta) + \delta e_Y\sin(\Theta)$

$$\delta e_X = e_{X_J} - e_{X_R};\ \delta e_Y = e_{Y_J} - e_{Y_R};\ \Omega_+ = \frac{\Omega_J + \Omega_R}{2}$$

- **Balance of drag torques** from outer and inner oil films
- **Thermal energy transport** (heat conduction & convection)

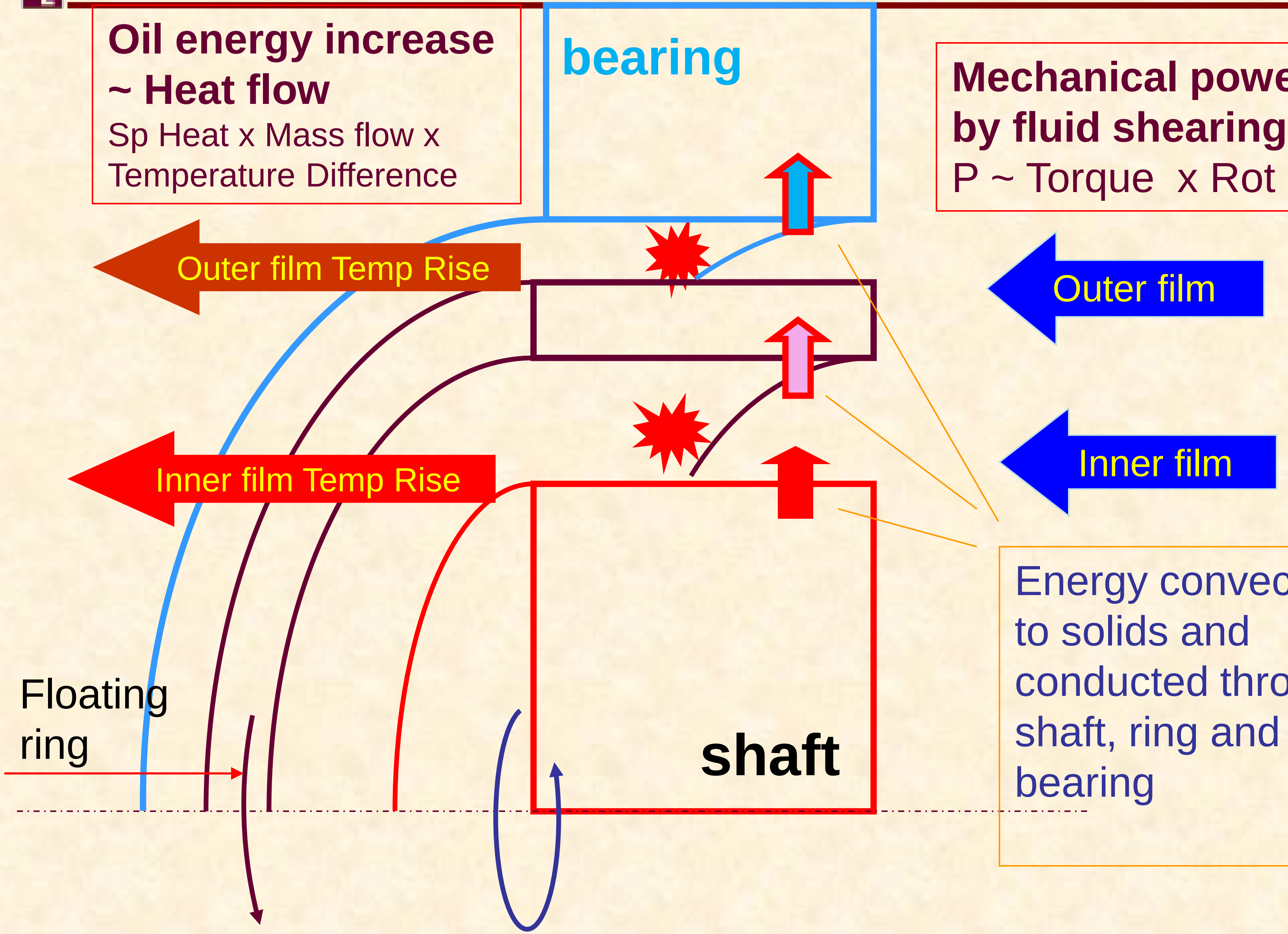
2004 IMEchE J. Eng. Tribology

Lumped Parameter Thermal Model



Oil energy increase ~ Heat flow
Sp Heat x Mass flow x Temperature Difference

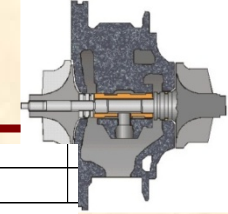
Mechanical power by fluid shearing
P ~ Torque x Rot Speed



Energy convected to solids and conducted through shaft, ring and bearing

2004 IMEchE J. Eng. Tribology

XLBRG® INPUT



Select	
Thermal Model	0
Heat convection model	1

Select	INNER FILM
Geometry	REGULAR

Select	OUTER FILM
Geometry	REGULAR

mn-mn	
mx-mn	

Select: Bearing Model 2

SEMI FLOATING RING

LUBRICANT

Lub param	9	SAE 5W-30
Viscosity	0.00494	Pa-s
Density (kg/m³)	850	
Specific heat (J/kg-C)	1880	

Inner film

Diameter (m)	0.0079	
Lengths (m)	0.0046	0.0000
Cold Radial Clearance(m)	7.50E-06	
Hot Radial Clearance	9.76E-06	

Outer film

Diameter (m)	0.014	m	
Lengths (m)	0.0062		0.0000
Cold Radial Clearance (m)	3.50E-05		
Hot Radial Clearance	2.72E-05	m	

BUTTON PIN

0.0000	Axial length [m]
0	Arc length [deg]
0	Circumferential l
0.0	WARNING: Value no

Pressures (bar)

Discharge	0	0
Cavitation	0	bar

Number pads	1	
Pad Arc Angle	360	deg
Leading Edge Pad 1	0	deg
Pad preload	0	-
Pad offset	0	

Select Bearing case: Fixed RING

	0.85	Desired Static dis
	3.71E+05	Recommend Stiff
X-stiffness	9.11E+05	N/m
Y-stiffness	9.11E+05	N/m

Temperatures

COLD	20.0	°C
Operating SHAFT	195.4	°C
CASING	150.0	°C
RING	172.7	°C
Inner-Outer Difference Inlet	0.0	°C

Turbine	700 °C
Defect temp ratio	0.13
Oil Supply Press	4
Inlet Pressure Lo	0.9

RING

		m			
Outer side groove depth	0.0000	m	Mass	0.0098	kg
ner side groove depth	0.0000	m	Moment of inertia	3.10E-07	kg-m²
			Weight	0.0581	N

Centrifugal pressure loss coefficients

Inner film	0.00
Outer film	0.00

FEED Side load factors		N/bar
Load	5.43	5.73
Compr side	5.43	5.73
Turb Side	12.4	11.6
Total	17.81	17.36
	high speed	low speed
typ speeds	240000	30000

-1.46E-06
5.779

MATERIAL PROPERTIES

	Ring	Casing	Rotor	
Thermal Coeff. Exp.	1.80E-05	1.25E-05	1.24E-05	1/deg C
Specific Heat	377.00	550.00	519.00	J/kg*deg C
Conductivity	58.12	53.60	42.70	W/m*deg C
Density	8500.00	7150.00	7833.00	kg/m^3
	brass	cast iron	steel	

comment

Run XLBRG_v8.0 code

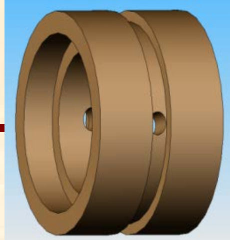
select

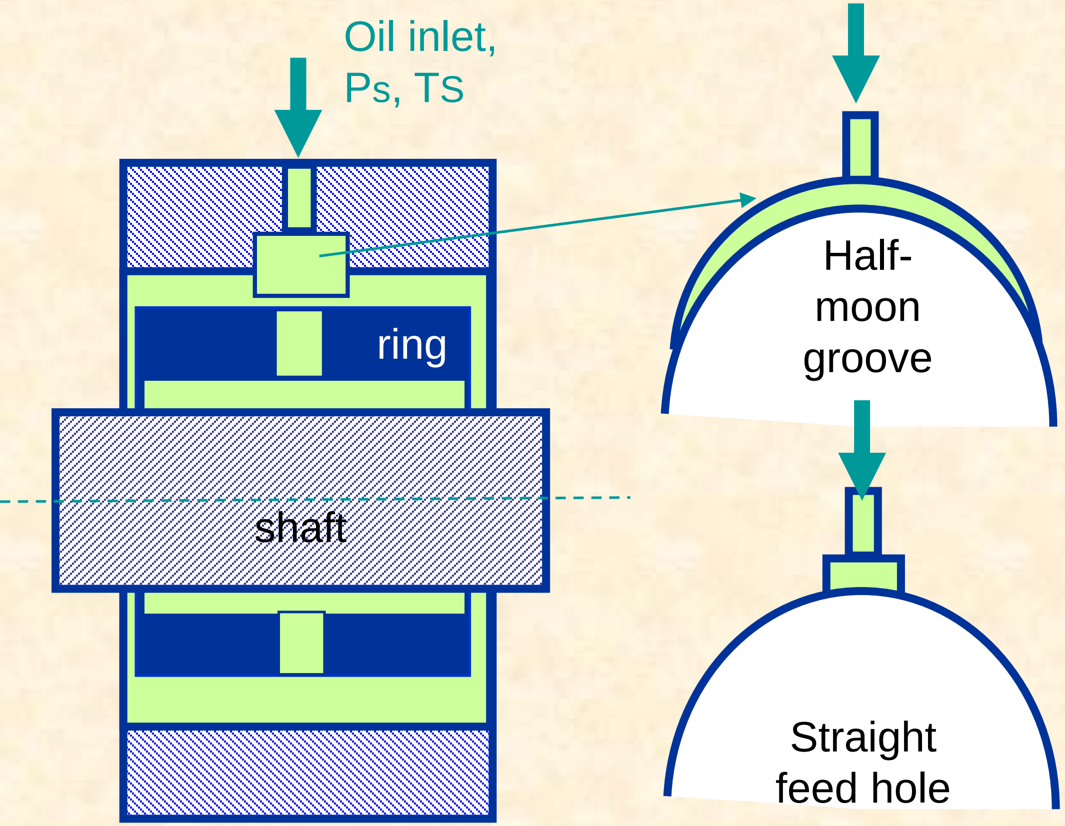
Update

Geometry (cold) – L,D,C
Fluid Type (commercial oil)
Material properties
Operation (speed and load)

Example: Turbine side bearing

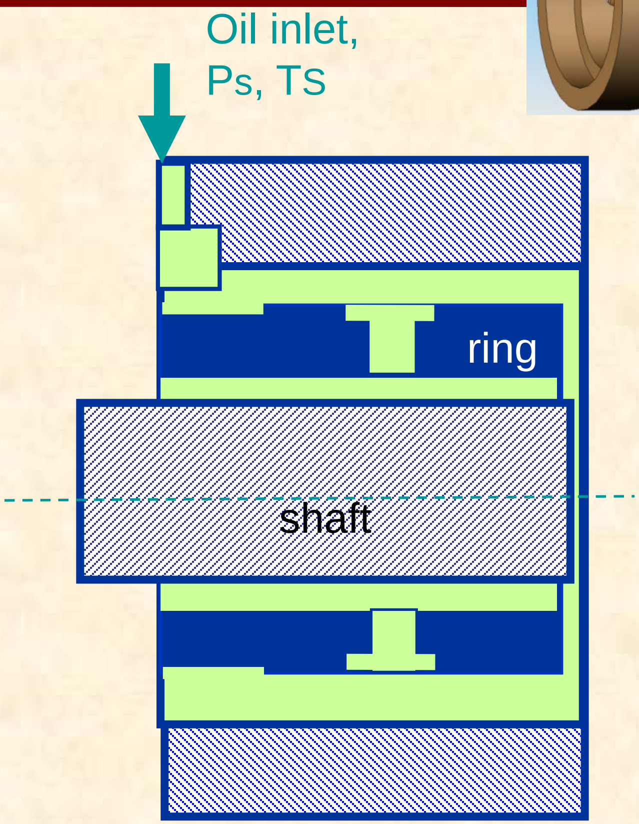
XLBRG®: types of bearings





Oil supply in bearing

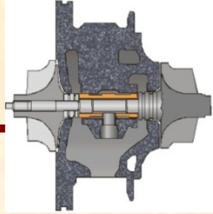
Types of oil supply



Oil supply – outboard side

Figures NOT to scale

XLBRG® INPUT

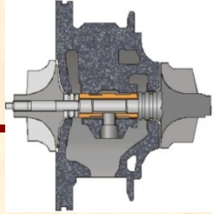


(Semi & Fully) Floating Bearing Ring

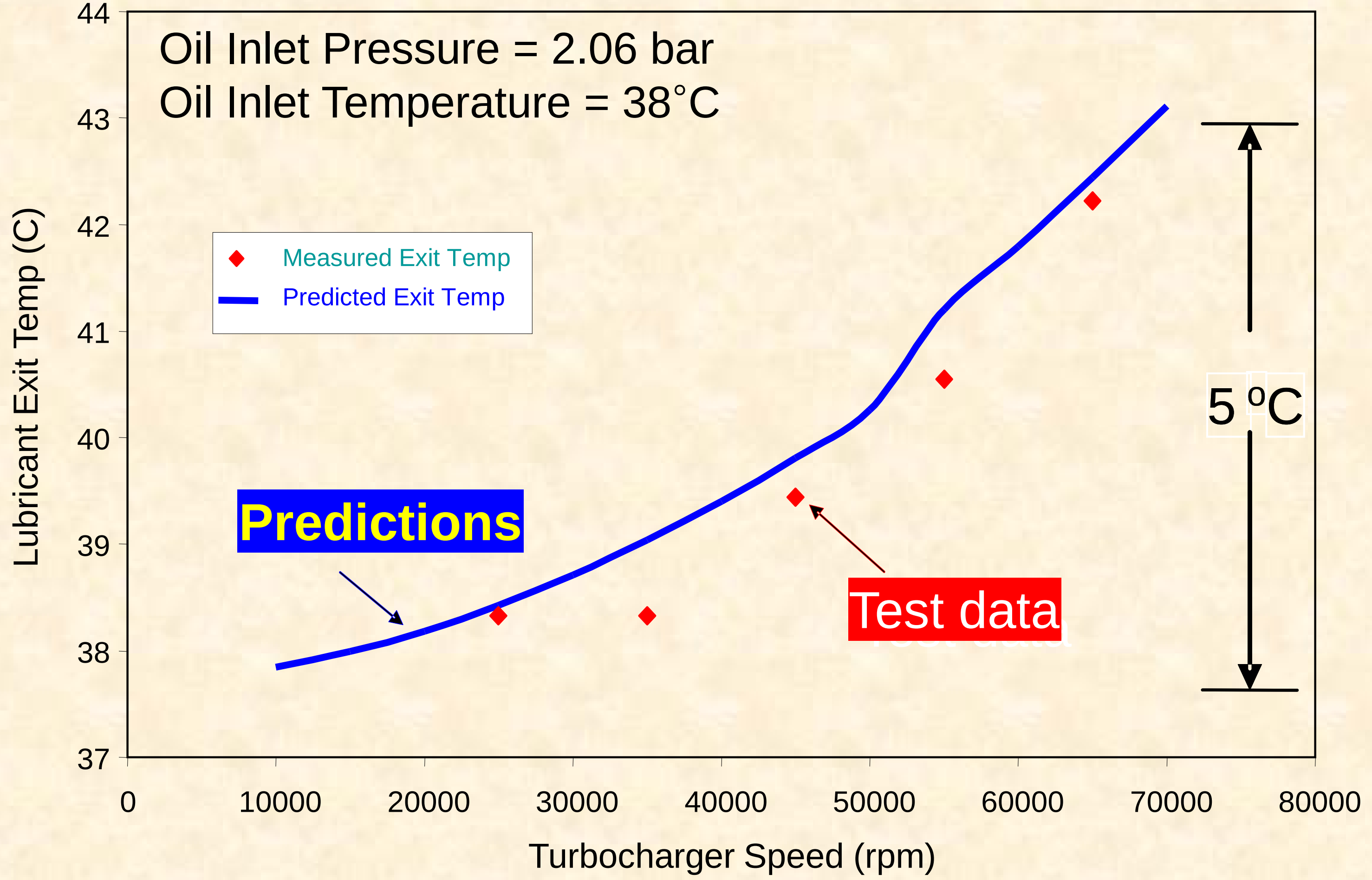
- **Actual geometry** (length, diameter, clearance) of inner and outer films, holes size and distribution
- **Supply conditions**: temperature & pressure
- **Lubricant viscosity** varies with temperature and shear rate (commercial oil)
- **Side hydrostatic load** due to feed pressure
- Temperature of casing
- Temperature of rotor at turbine & compressor sides derived from semi-empirical model: **temperature defect model**

XLBRG® ETHD fluid film bearing model predicts operating clearance and oil viscosity (inner and outer films) and eccentricities (static and dynamic) as a function of shaft & ring speeds and applied (static & dynamic) loads.

XLBRG® Output

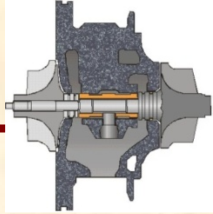


ASME GT2006-90873

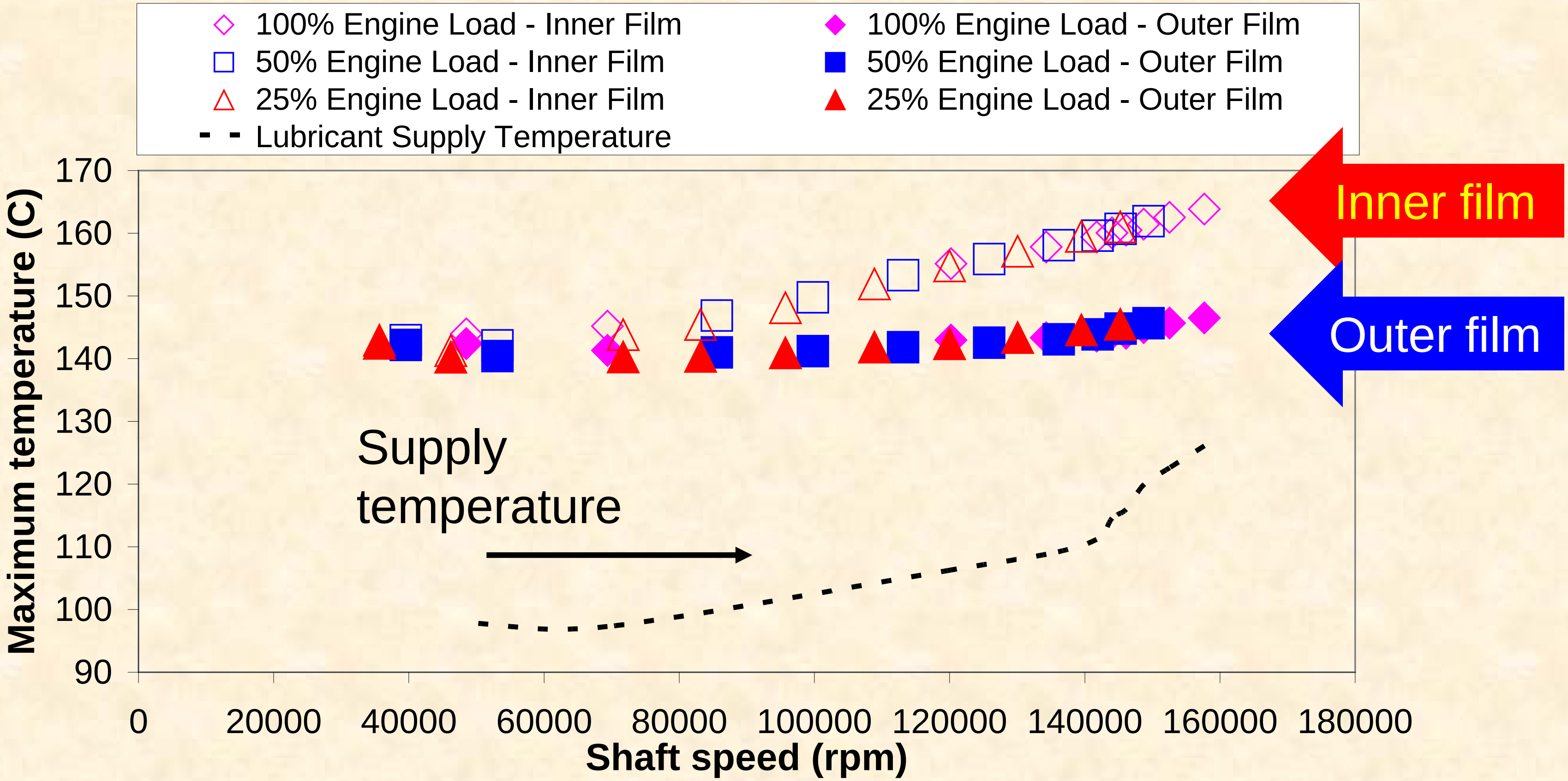


Fluid Exit Temperature – Prediction vs. Test Data

XLBRG® Output



(S)FRB Predictions : Peak film temperatures

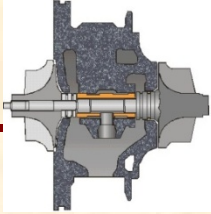


Increase in power losses (with speed) leads to raise in inner film & ring temperatures.

No effect of engine load

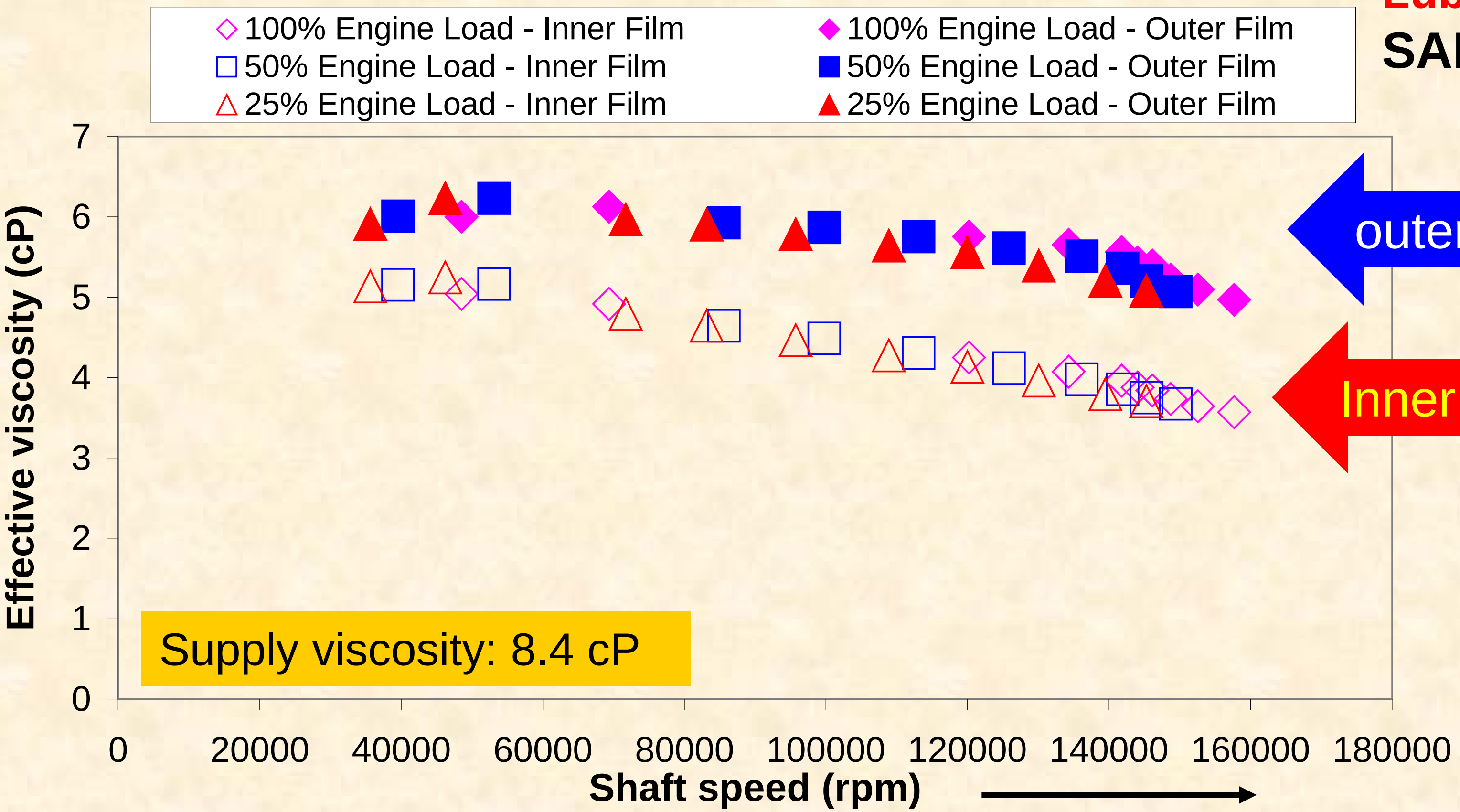
ASME GT 2009-59108

XLBRG® Output



(S)FRB Predictions : Oil effective viscosity

Lubricant type:
SAE 15W - 40



outer film

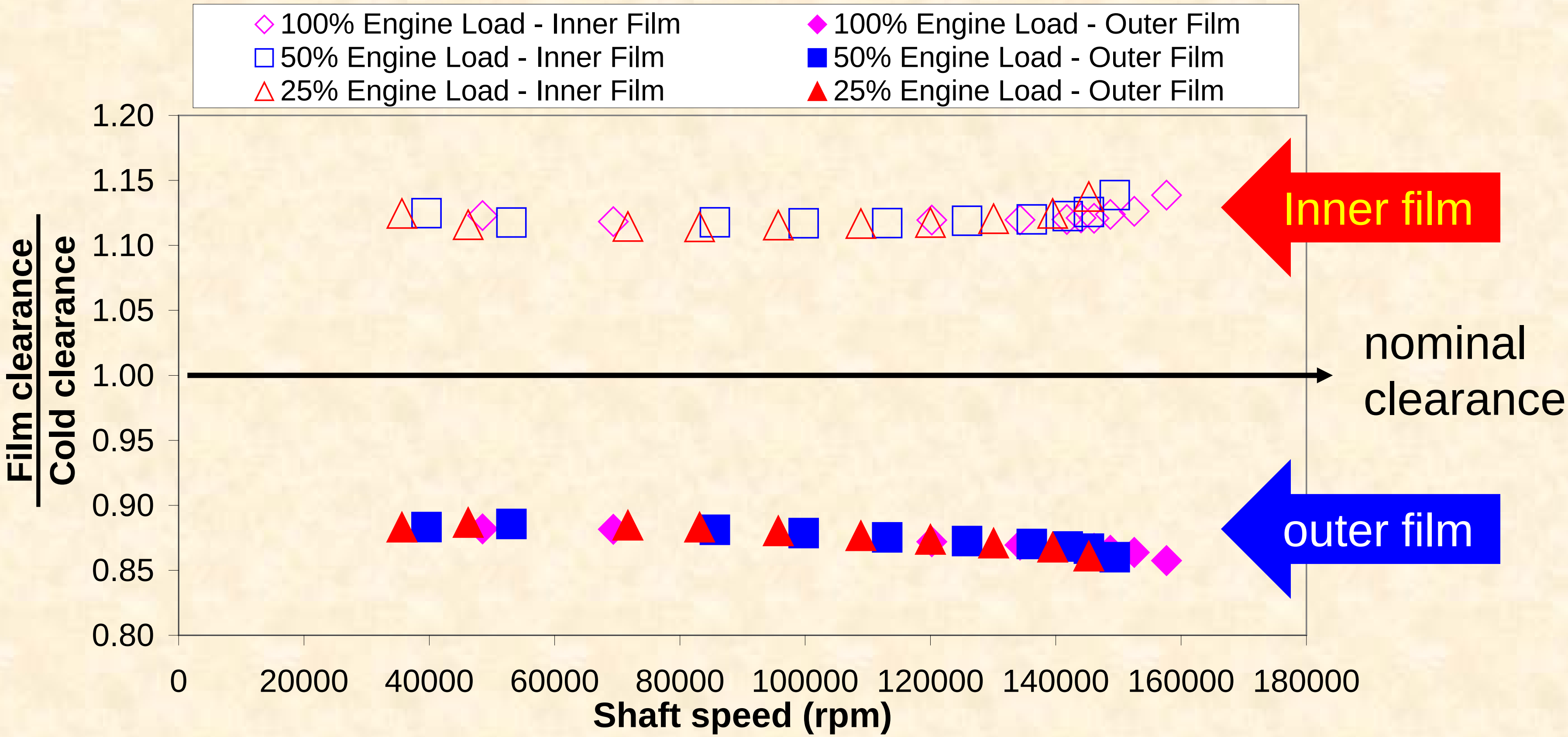
Inner film

Higher film temperatures determine lower lubricant viscosities. Operation parameters independent of engine load

ASME GT 2009-59108

XLBRG® Output

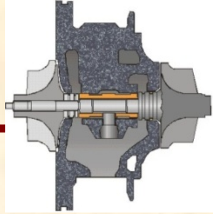
(S)FRB Predictions : Film clearances



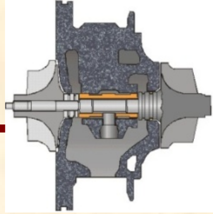
Thermal growth relative to nominal inner or outer cold radial clearance

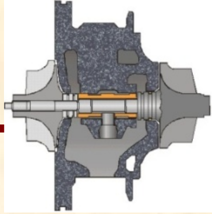
Inner film clearance grows and outer film clearance decreases – RING grows more than SHAFT and less than CASING. Material parameters are important

ASME GT 2009-59108



TC shaft motions virtual tool



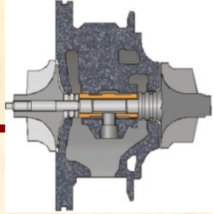


TC rotordynamics

linear and nonlinear

KEY OBJECTIVE # 3

TC shaft motions virtual tool



Integration of FRB and SFRB codes into nonlinear rotordynamics program

XLTRC² Rotordynamics Virtual Tool

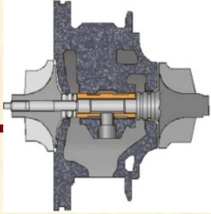
- Beam Finite-Element Formulation
- Real Component-Mode Synthesis (CMS) model
- Multi-line Rotor/Housing Modeling Capability
- **Linear and transient response nonlinear analyses**
- Fully integrated with an extensive suite of support codes
- User-Friendly GUIs for rapid model development and report generation

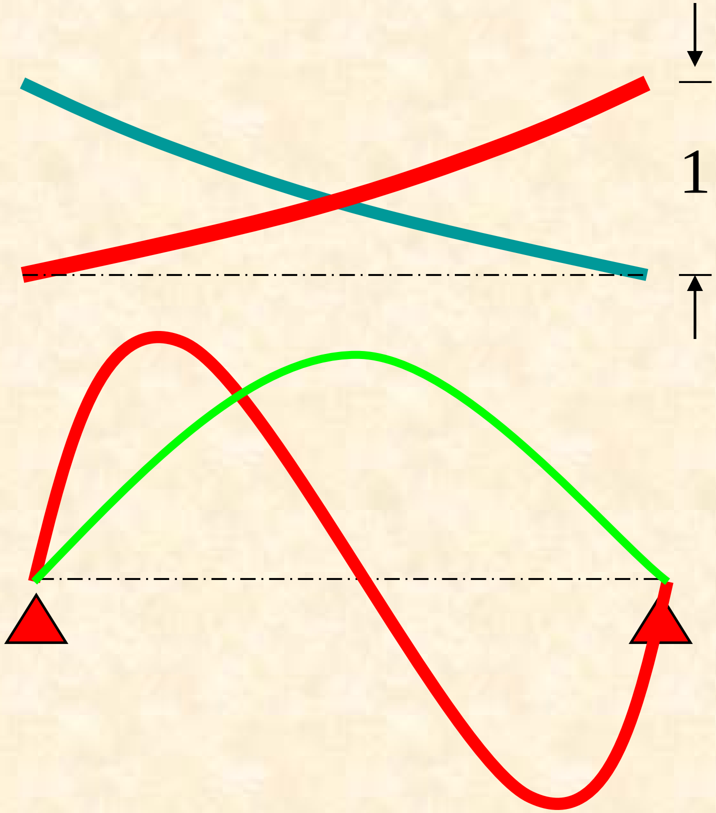
General EOMs

$$\mathbf{M}\,\ddot{\mathbf{q}}+\mathbf{C}\,\dot{\mathbf{q}}-\Omega\,\mathbf{G}\,\dot{\mathbf{q}}+\mathbf{K}\,\mathbf{q}=\mathbf{Q}(t)$$

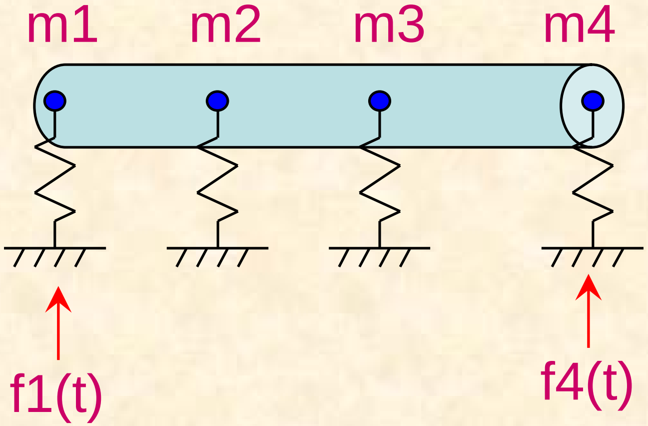
KEY OBJECTIVE # 3

XLTRC² rotordynamics code



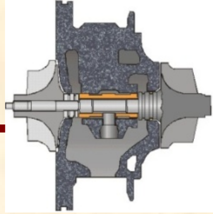


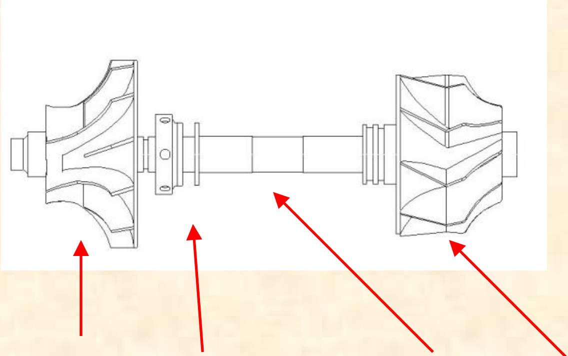
- **Timoshenko-beam, FE-formulation**
- **Calculates real modes**
- **Reduces model dimensionality by using a limited number of modes**



Component-Mode Synthesis (CMS)

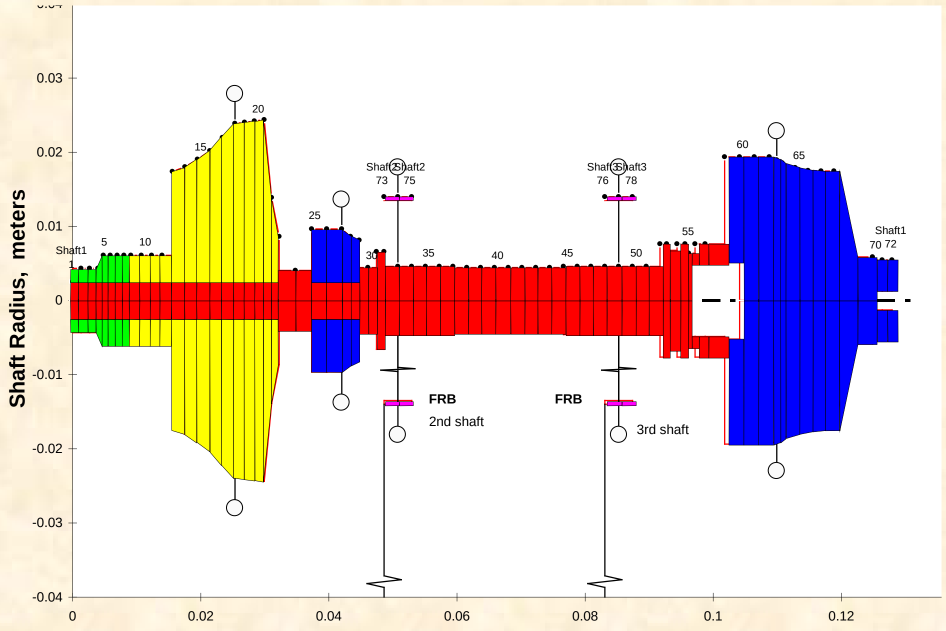
Rotor structural FE models





Compressor thrust disk shaft turbine

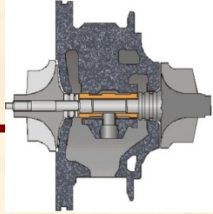
Typical TC rotor hardware



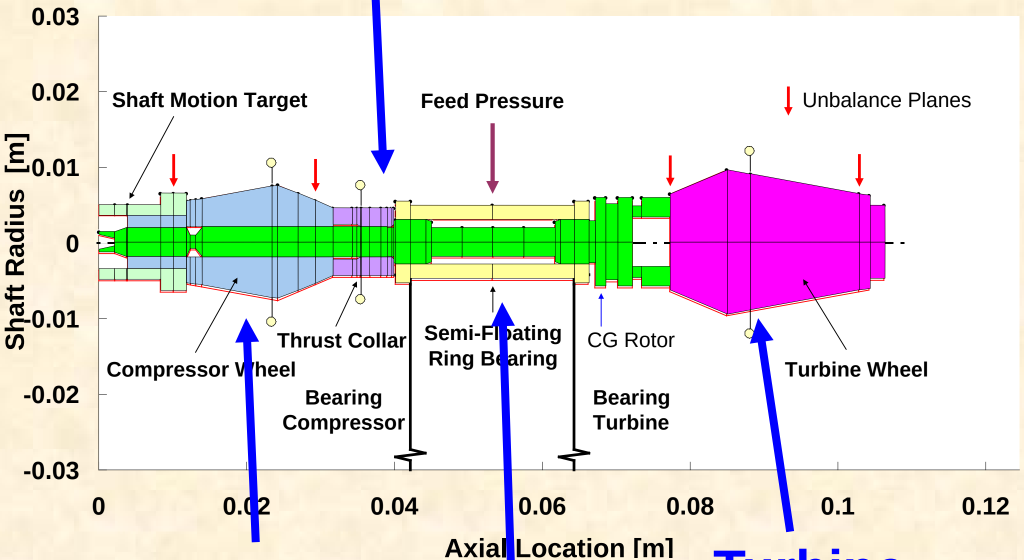
Typical FE rotor structure model

Validate rotor model

Rotor finite element model: 2 shaft model



Thrust Collar



Compressor

SFRB

Turbine

Validate rotor model with measurements of free-fee modes (room Temp)

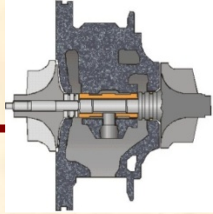
Rotor: 6Y gram
SFRB: Y gram

Static weight load distribution

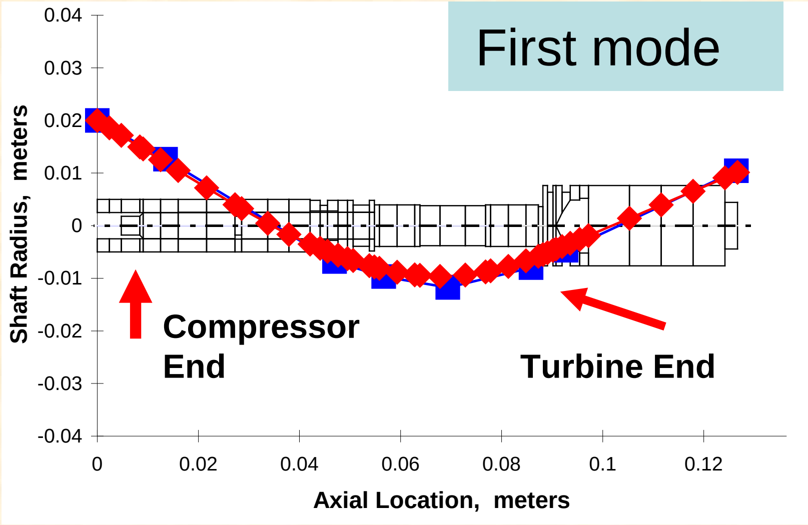
Compressor Side: Z

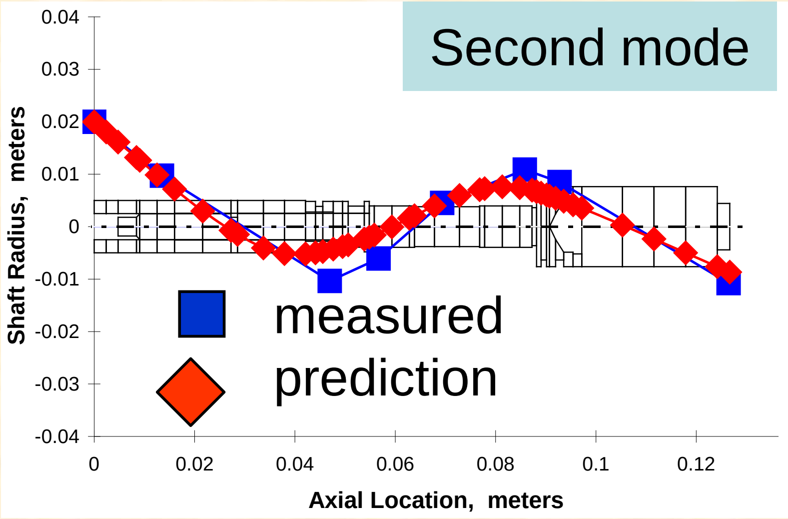
Turbine Side: 5Z

Validate rotor model



Free-free natural frequency & shapes

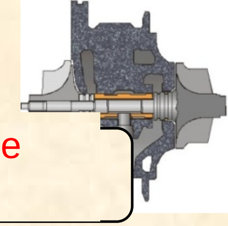




	measured	Predicted	% diff
	KHz	KHz	-
First	1.799	1.823	1.3
Second	4.938	4.559	7.7

Measured and predicted free-free natural frequencies and mode shapes agree: rotor model validation

XLTRC² & XLBRG interfacing



XLTRC²

Linear Model

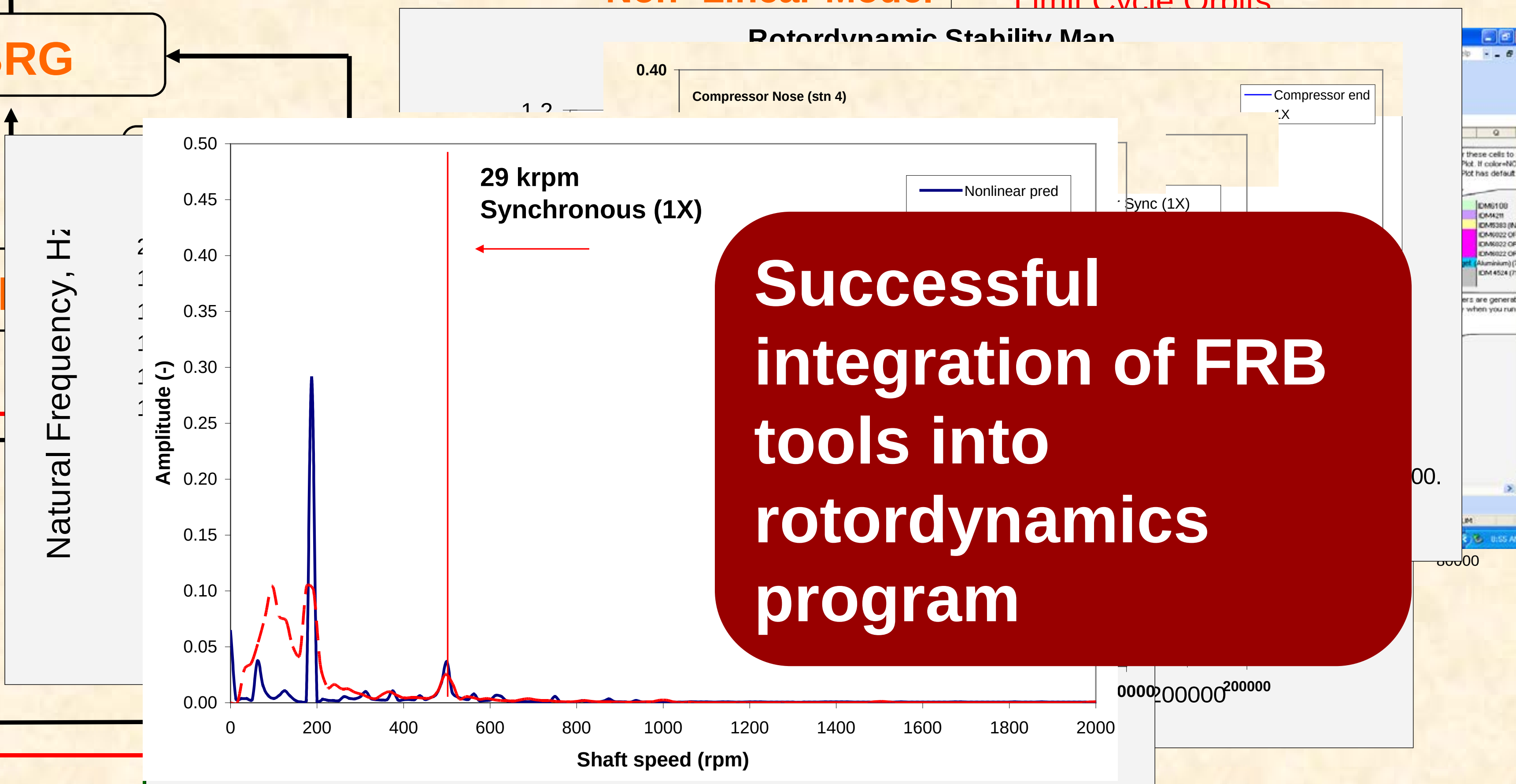
Synchronous response
Eigenvalue analysis

Non- Linear Model

Synchronous response
Subsynchronous motions
Limit Cycle Orbits

XLBRG

XLHY

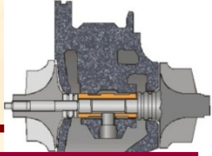


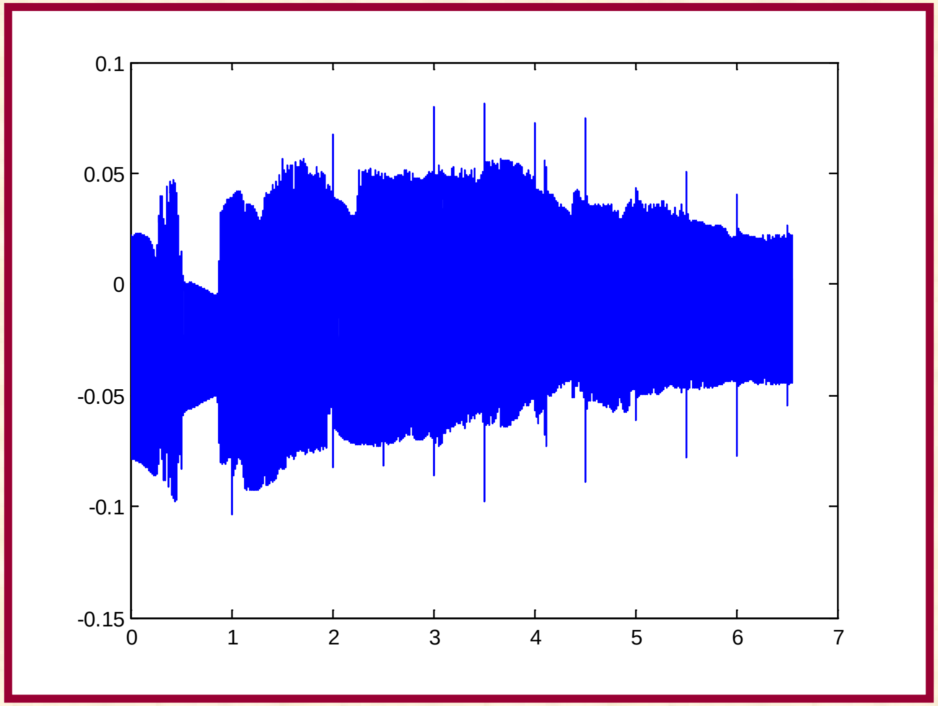
Successful integration of FRB tools into rotordynamics program

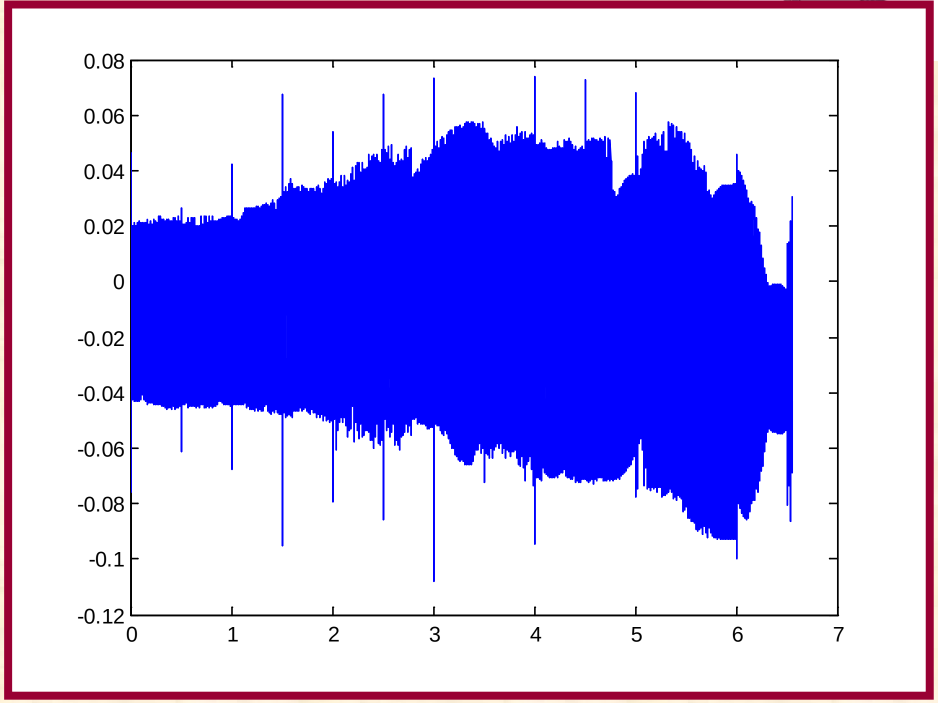
Virtual Laboratory

XLTRC²

NL predictions: typical responses

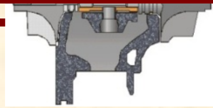






18 krpm → 240 krpm 240 krpm → 18 krpm

Predictions of TC shaft motion response – displacement versus time: rotor acceleration & deceleration

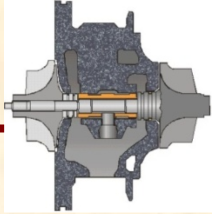


Important:

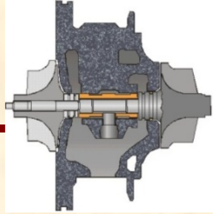
Massive amounts of time domain data rarely show any value (do not add knowledge nor establish firm design rules not even rules of thumb)

Analysis stresses on frequency domain analysis to build waterfalls, find total motion and synchronous motions, filtering of major whirl frequencies to determine effect on rotor elastic motions, calculation of forces transmitted to casing and rotor.

TC shaft motions virtual tool



TC shaft motions virtual tool



Test data vs. predictions

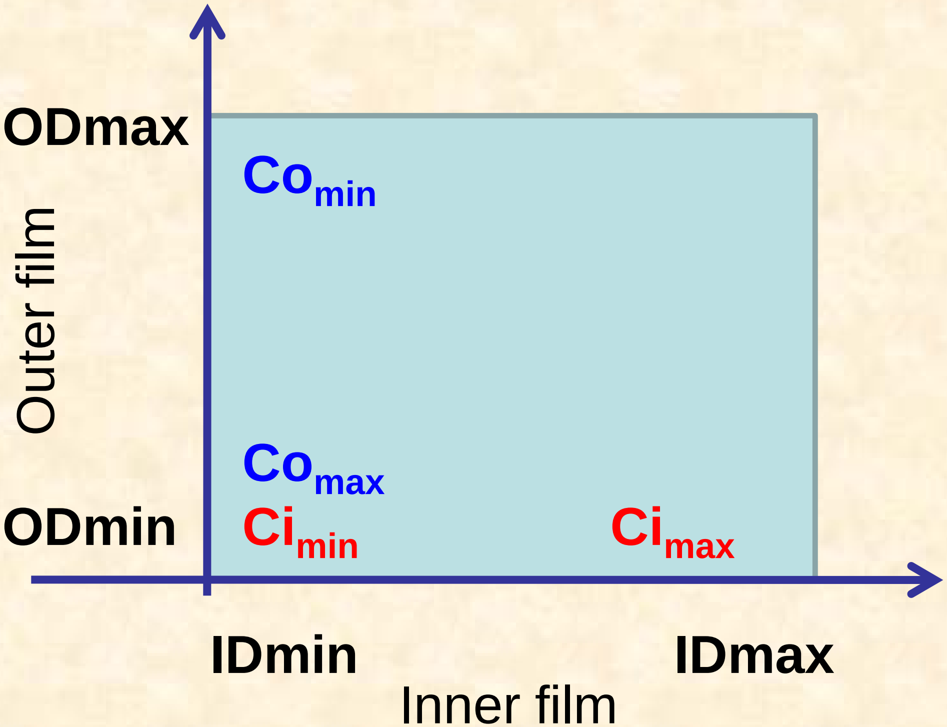
Validations

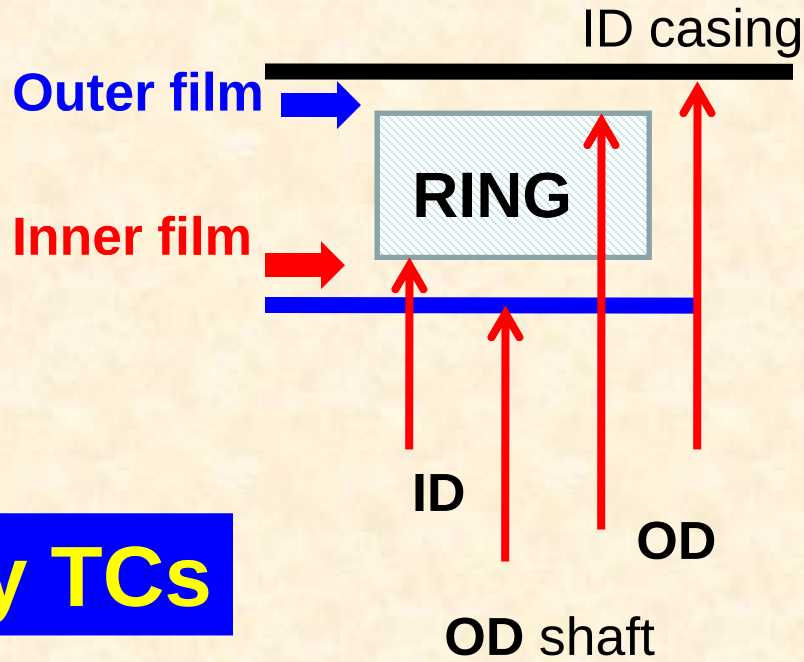
If successful,

a) Ready tool for PRODUCTION
b) Demonstrate savings
c) Install tool at all TC core engineering centers

KEY OBJECTIVE # 4

Variations in manufactured RING dimensions

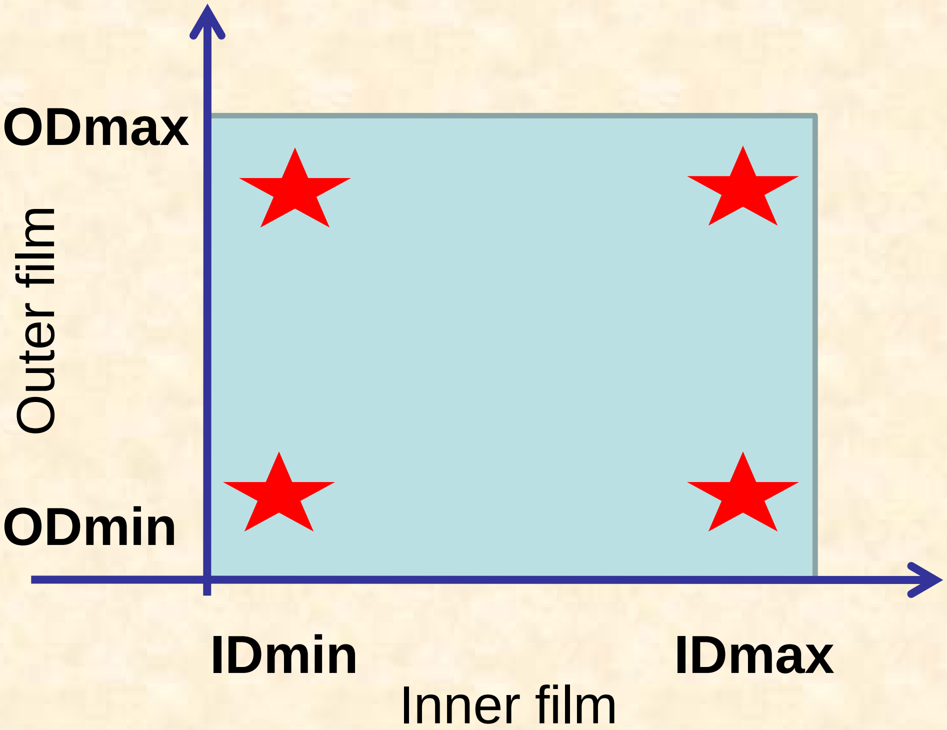


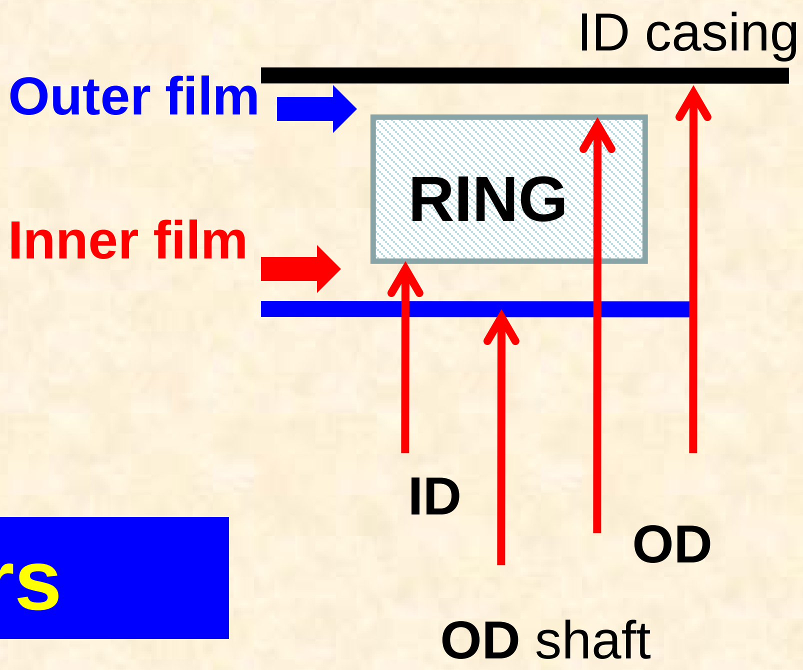


Costly procedure to qualify TCs

Four corners clearance limits

Costly TC qualification certification

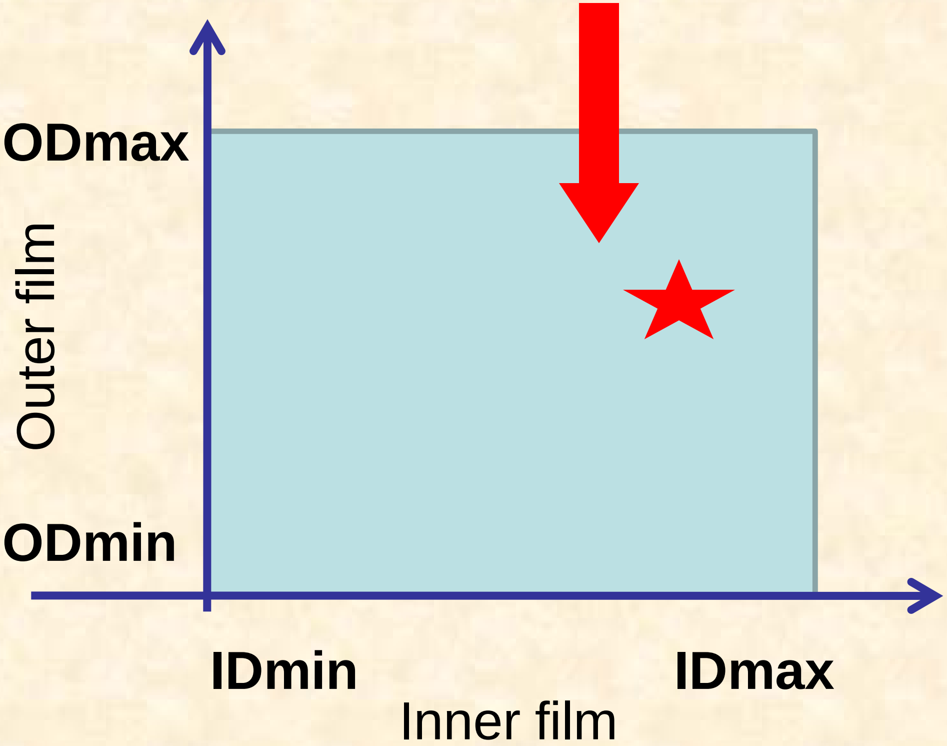


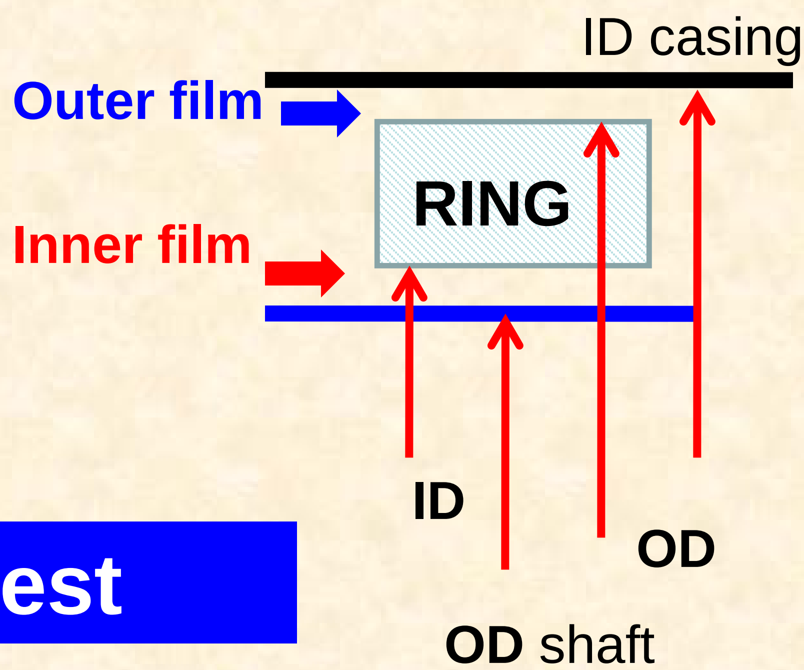


Past: NHS tests at 4 corners

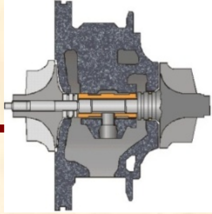
Savings in TC qualification certification

Determined from Virtual Tool

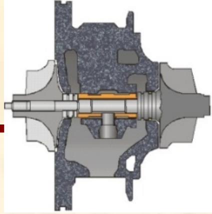




Current: One (or no) NHS test

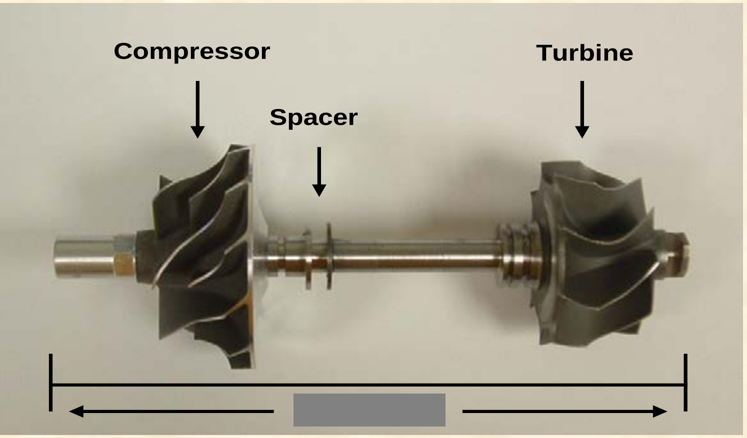


Validation: shaft motion for PV TC



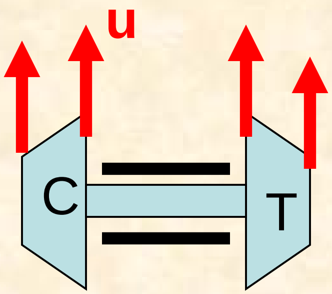
TC rotor & bearing system

2 shaft model



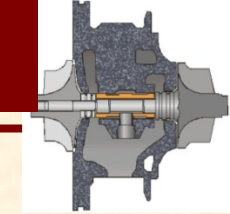
Example: RBS with Semi Floating Bearing

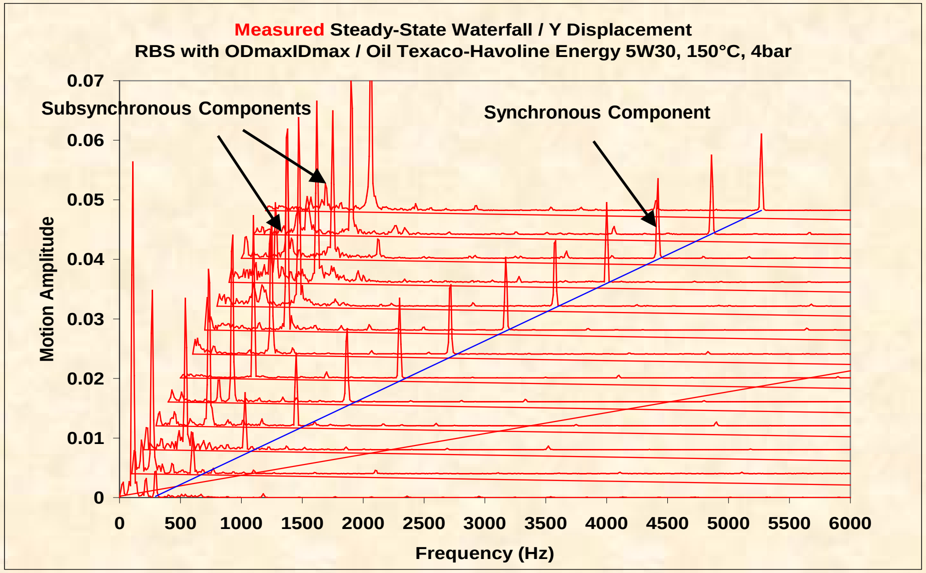
shaft speed 18 - 240 krpm
Oil 5W-30, 100 C inlet temperature, feed pressure 2,4 bar



ASME DETC2007-34136

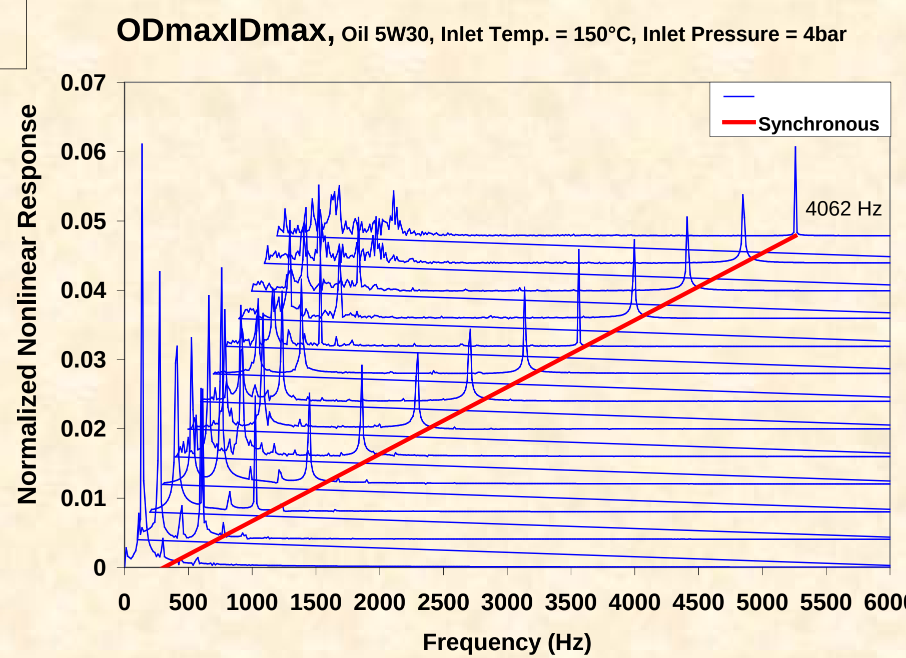
ODmax-IDmax - compare





Measured at compressor end

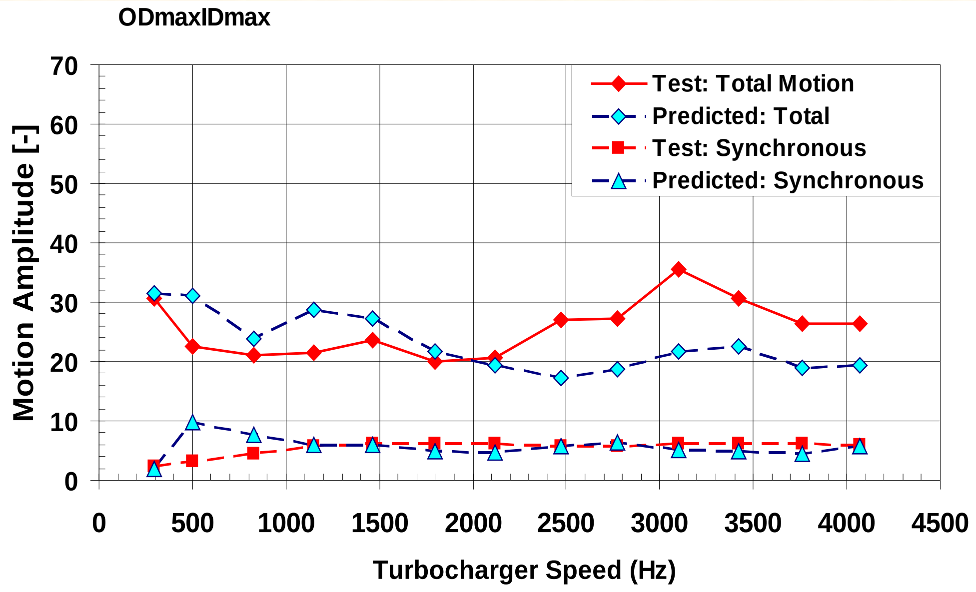
Predicted at compressor end



WATERFALLs of SHAFT MOTION

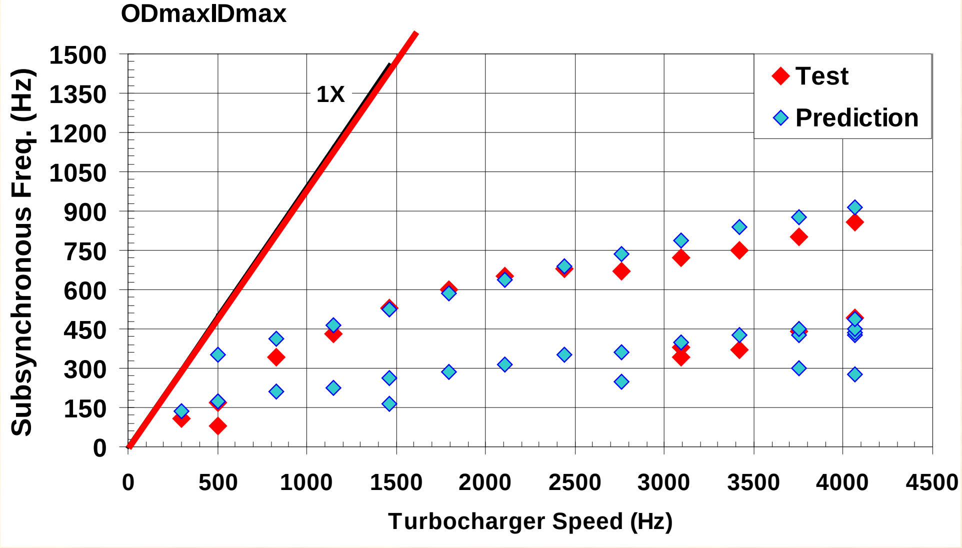
ASME DETC2007-34136

ODmax-IDmax - compare

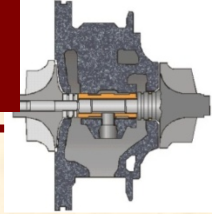


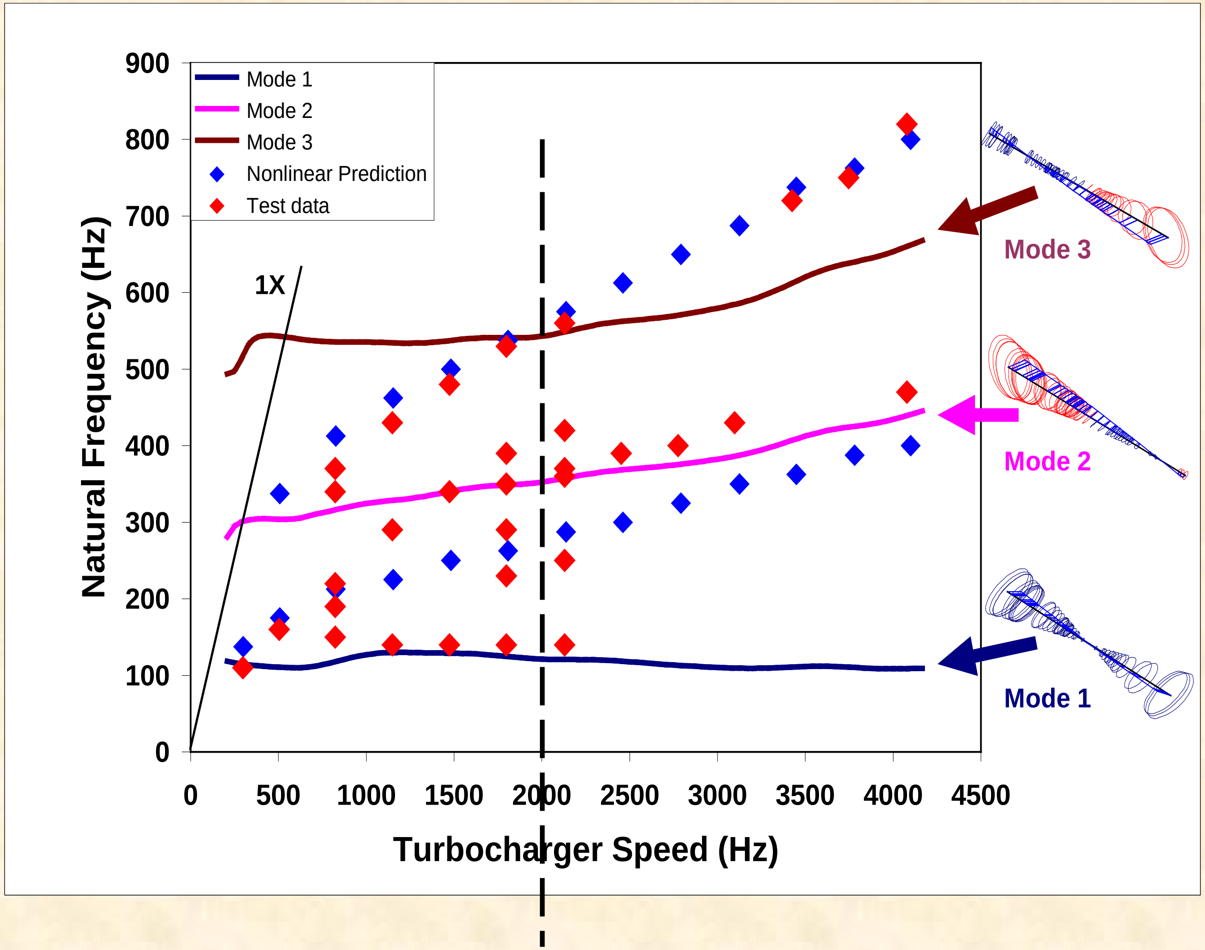
Total motion & 1X motion

Whirl frequency



ODmin-IDmax - compare





Cylindrical - Deformed Mode Shape

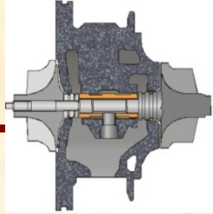
Compressor - End Ring Mode

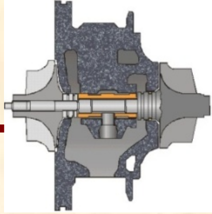
Conical Mode Shape

Nonlinear predictions reproduce test data – Linear eigenvalue analysis is limited in accuracy

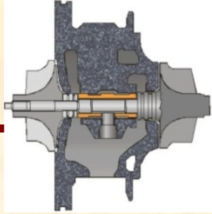
ASME DETC2007-34136

TC shaft motions virtual tool





Validation: shaft motion for CV TC

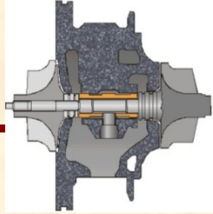


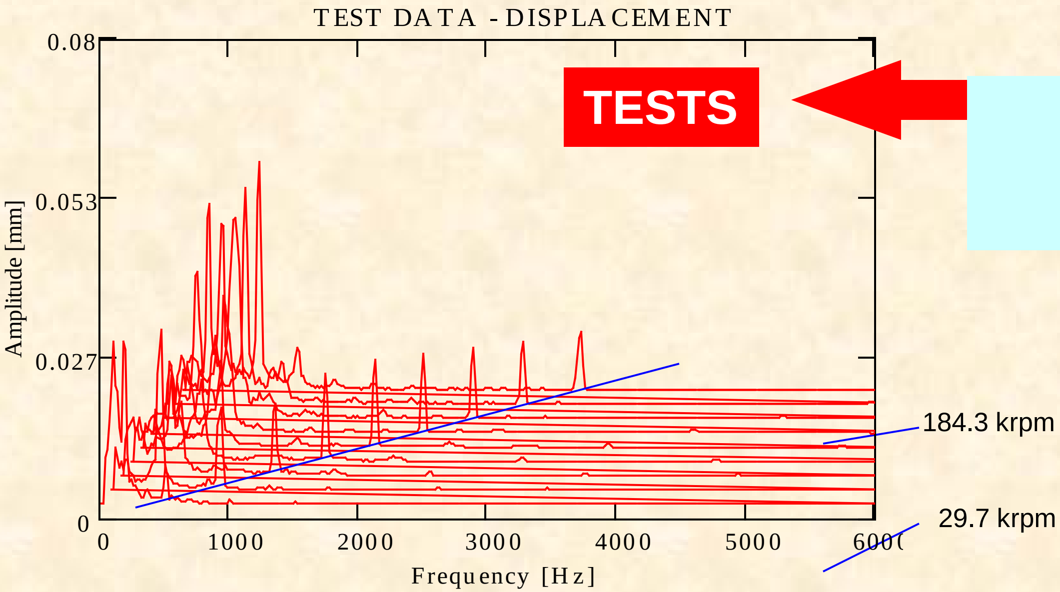
TC rotor & bearing system

3 shaft model

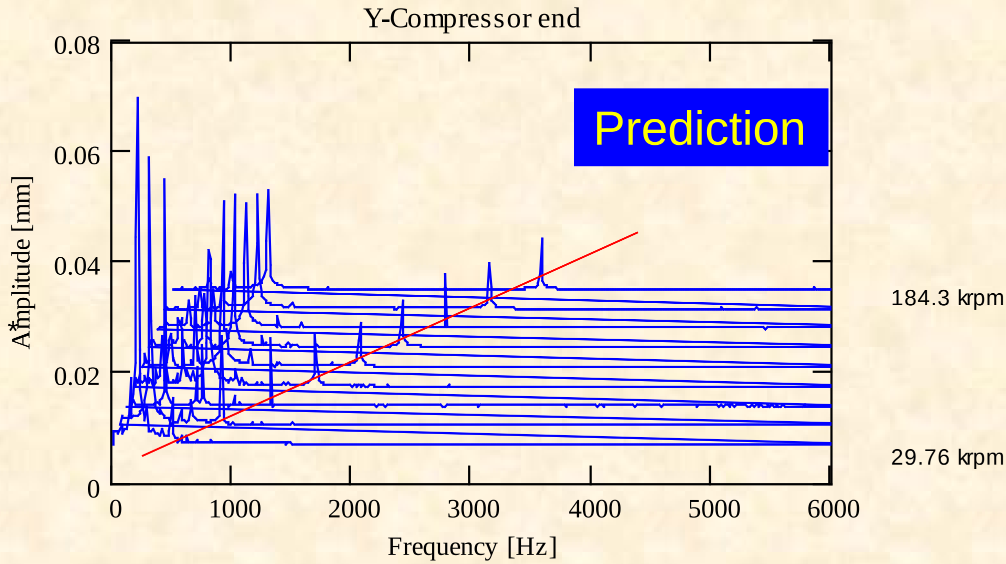
shaft speeds 30 - 180 krpm
Oil 0W-30, 92 C inlet temperature, feed pressure 4 bar

Validation CV TC





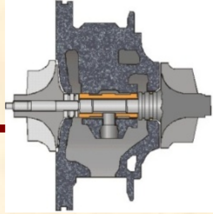
Test data shows broad bands in sub synchronous frequency regions.
Whirl motions persist at all speeds.

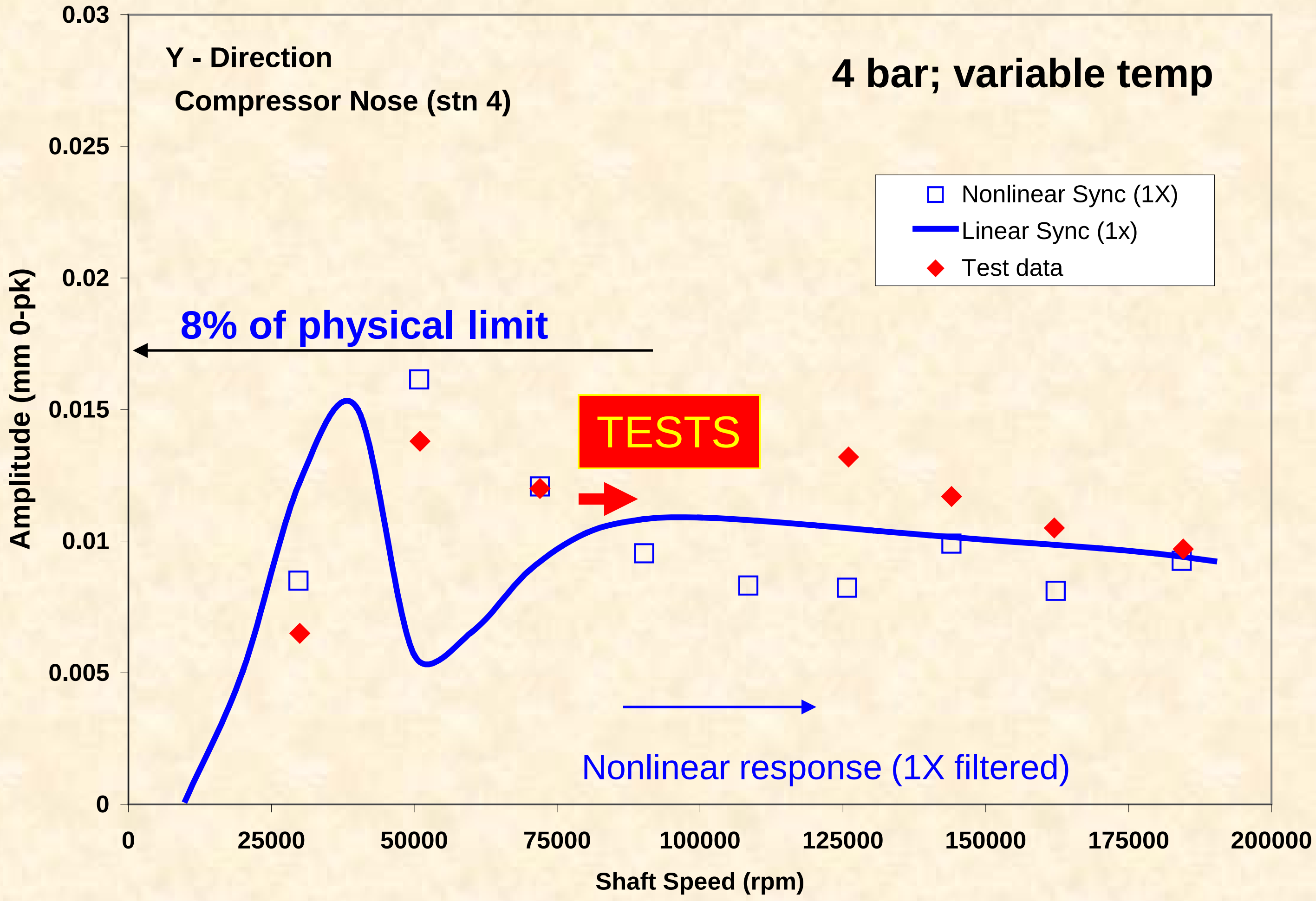


Predictions show sub synchronous frequencies to 184 krpm. More severe than test data at low shaft speeds.

TC – Waterfalls: Test data and Nonlinear predictions

TC shaft motions virtual tool

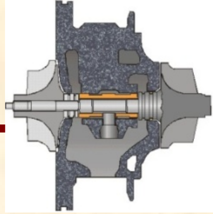




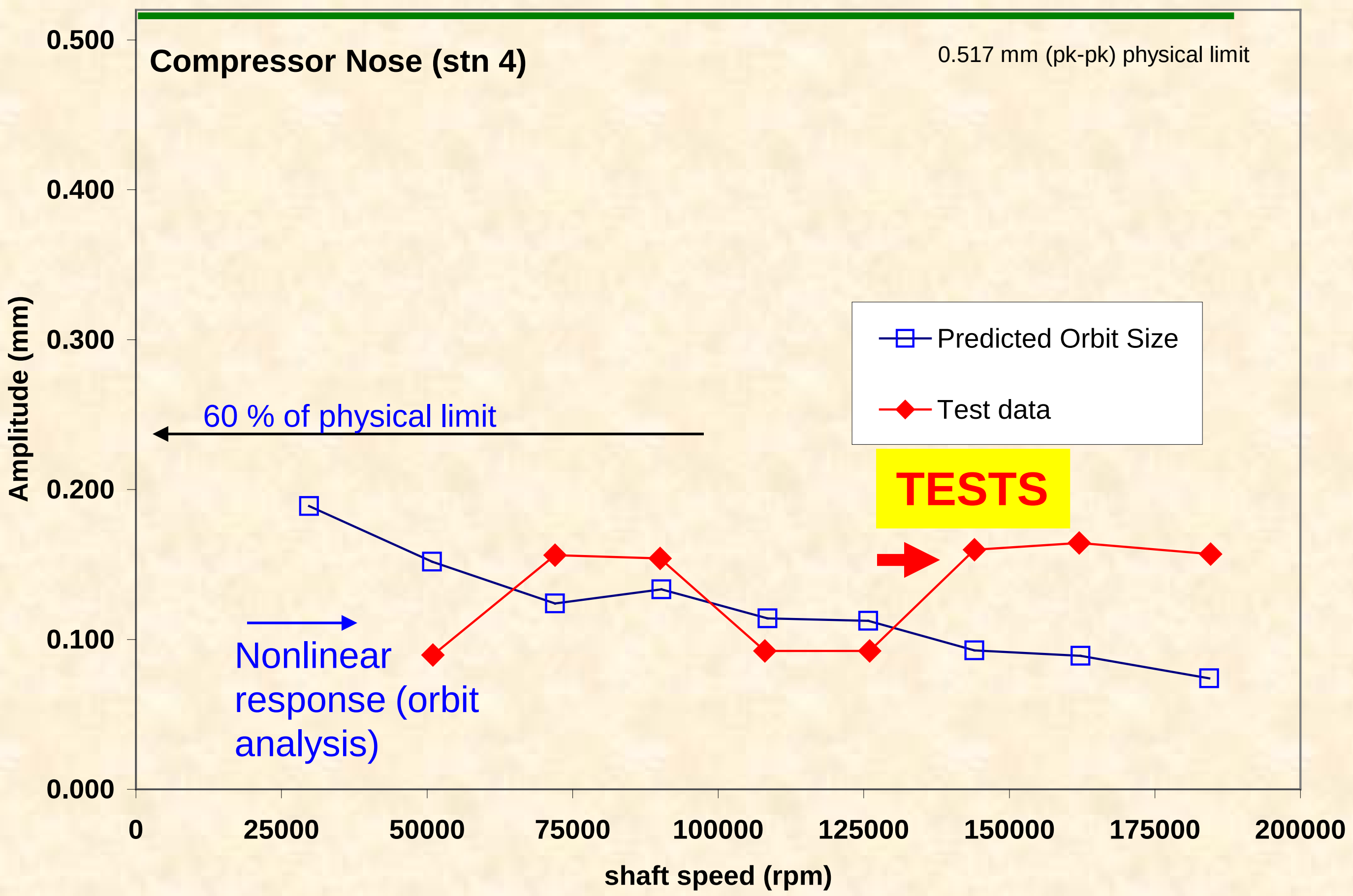
Nonlinear response predictions (1X filtered) compares best with test data at low shaft speeds

Imbalance response (linear and nonlinear) vs test data

TC shaft motions virtual tool



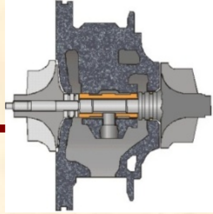
4 bar; variable temp



Good correlation with test data, in particular at mid shaft speed range (70-130 kprm).

Test data & predictions show persistent sub sync motions

Total Motion: test data and predictions



Validation: engine induced excitations

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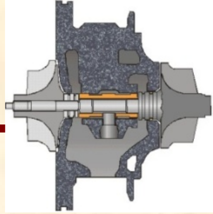
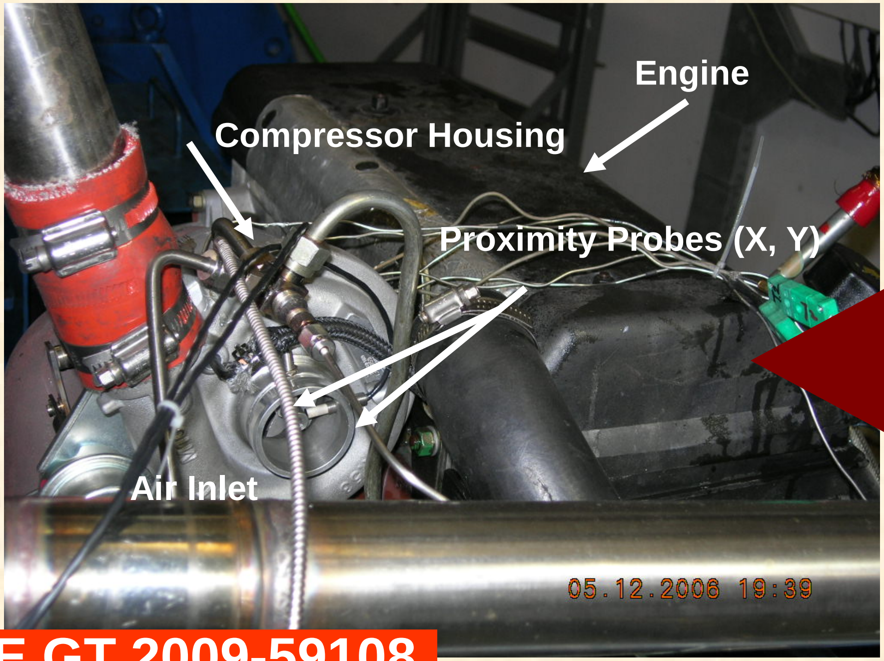


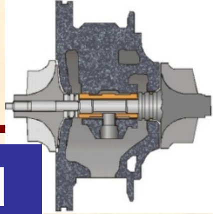
Operating conditions from test data:

- TC speed ranges from 48 krpm – 158 krpm
- Engine speed ranges from 1,000 rpm – 3,600 rpm
- 25%, 50%, 100% of full engine load
- Nominal oil feed pressure & temperature: 2 bar, 100°C



TC Engine Test Facility Stand

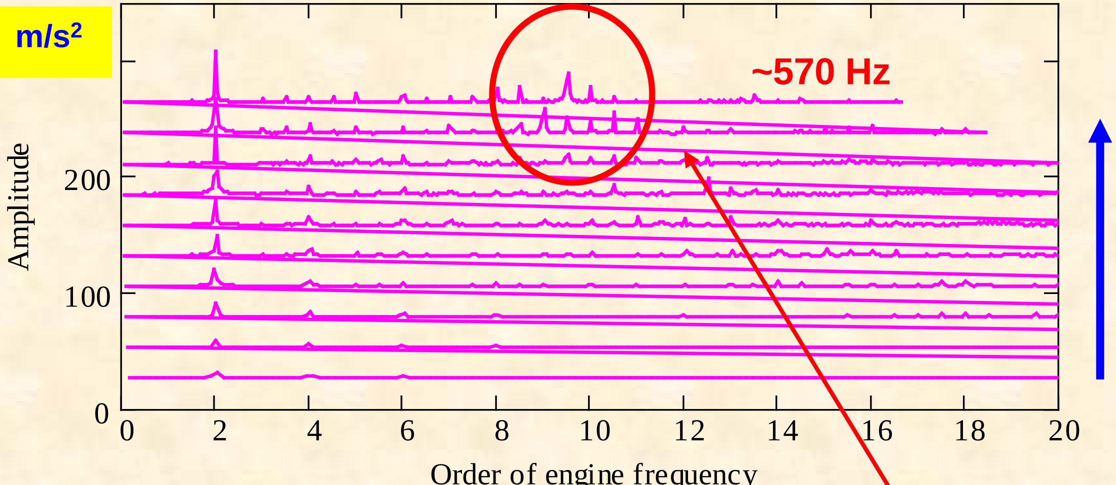
IC engine induced excitations



TC housing acceleration analysis

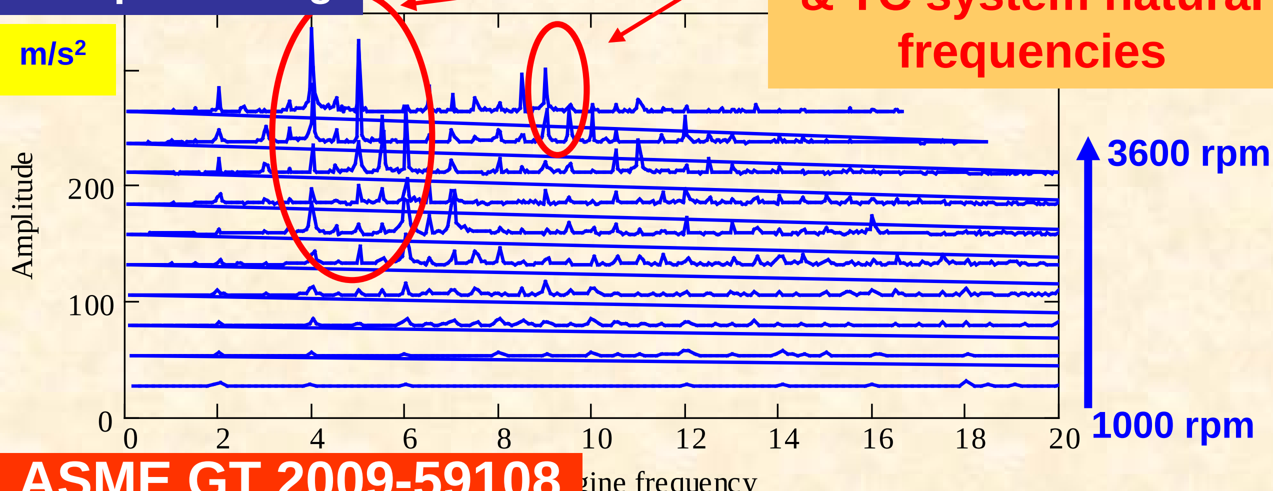
100% engine load

Center Housing



Combined manifold & TC system natural frequencies

Comp. Housing



2, 4, and 6 times engine (*e*) main frequency contribute significantly

***1e* order frequency does not appear**

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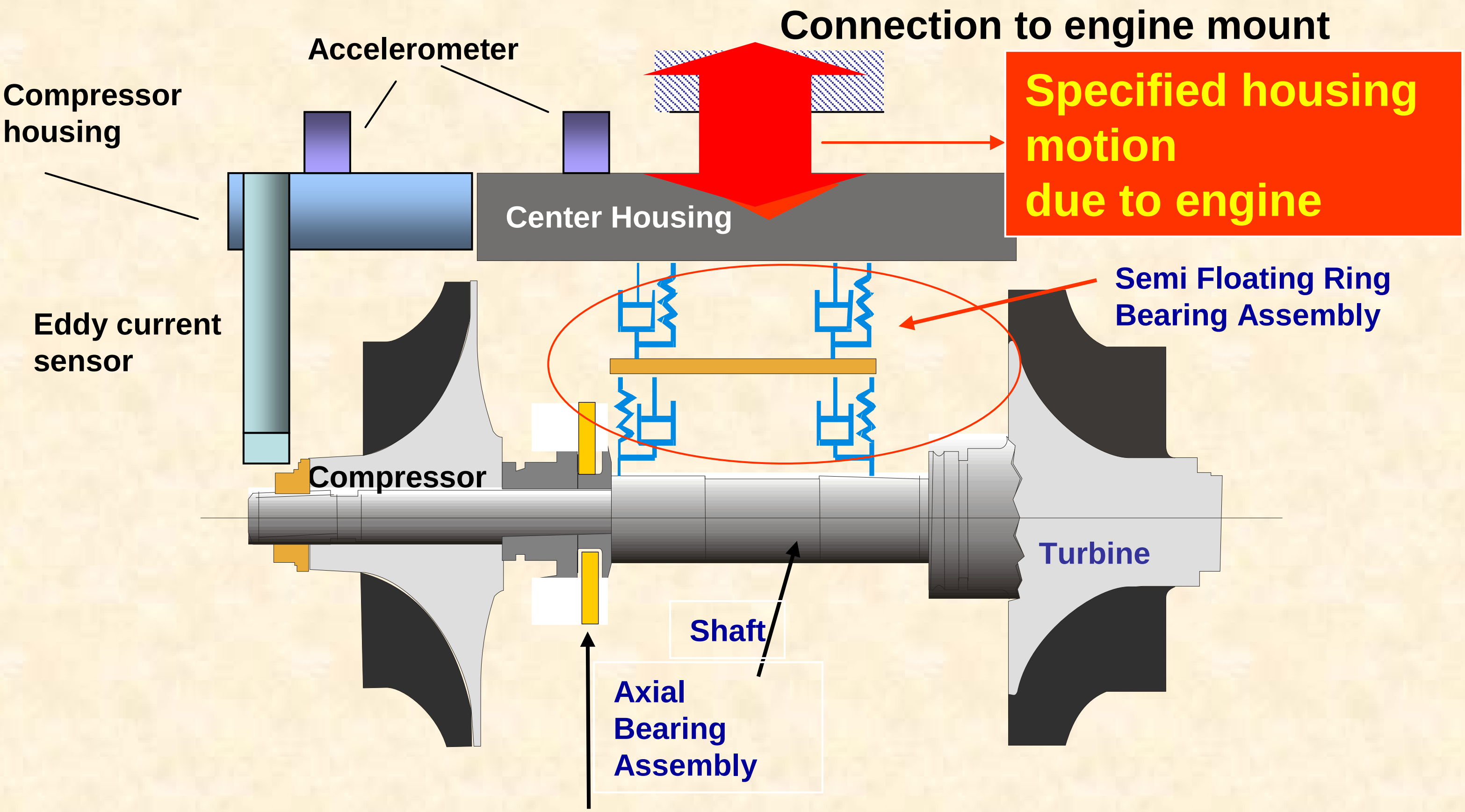
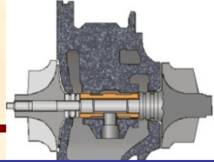
IC engine induced excitations

Housing accelerations into model

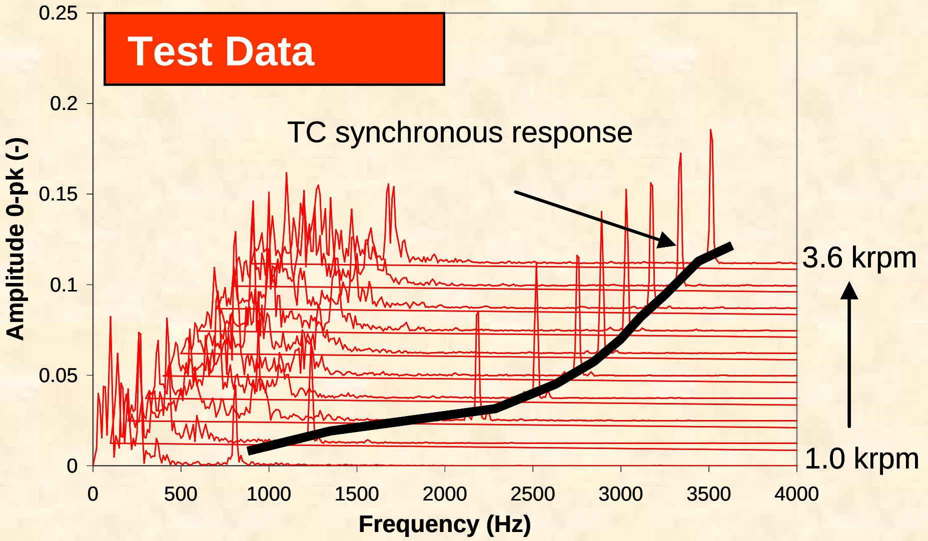


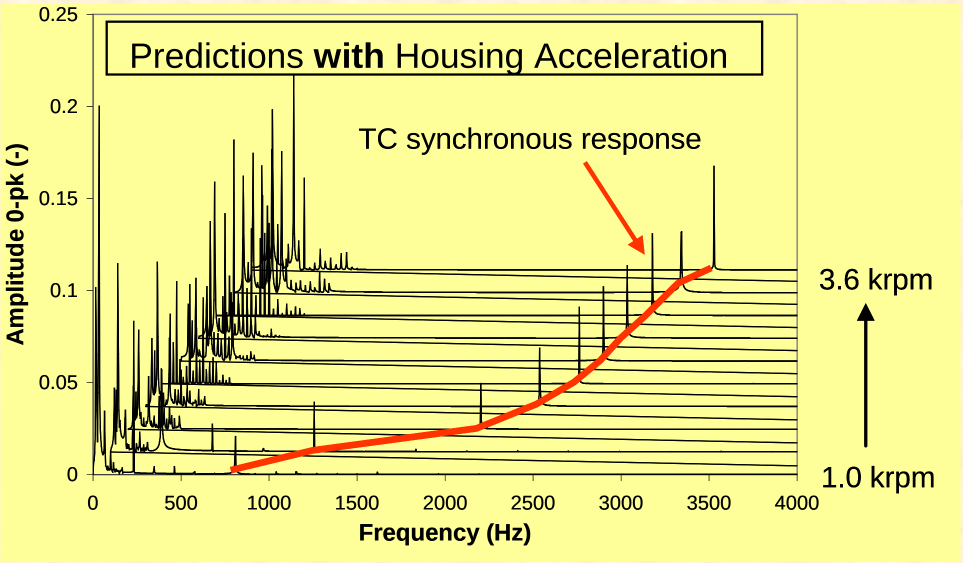
IC engine induced excitations

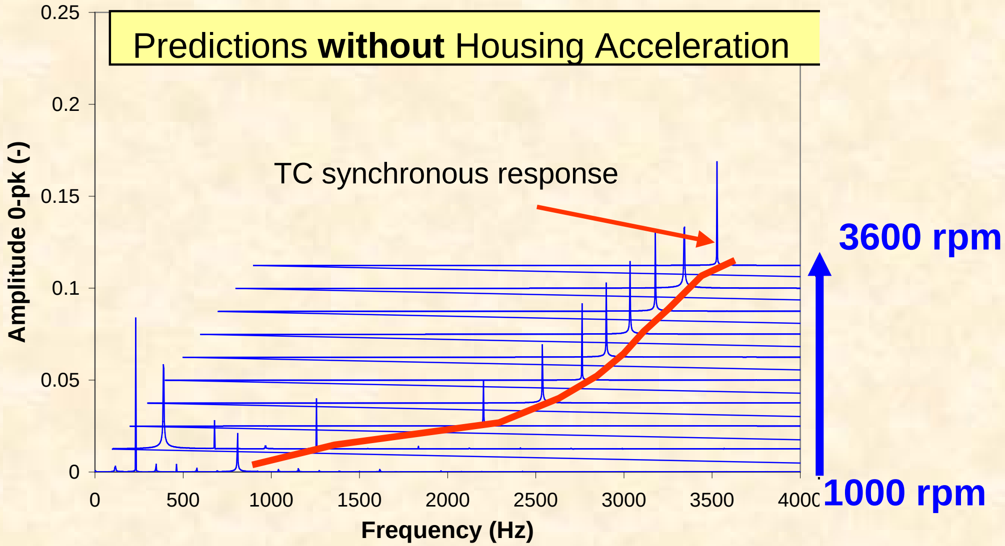


Waterfalls of shaft motion at compressor end

100% engine load



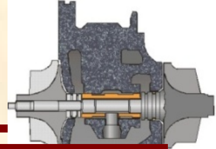




Housing accelerations induce broad range, low frequency whirl motions

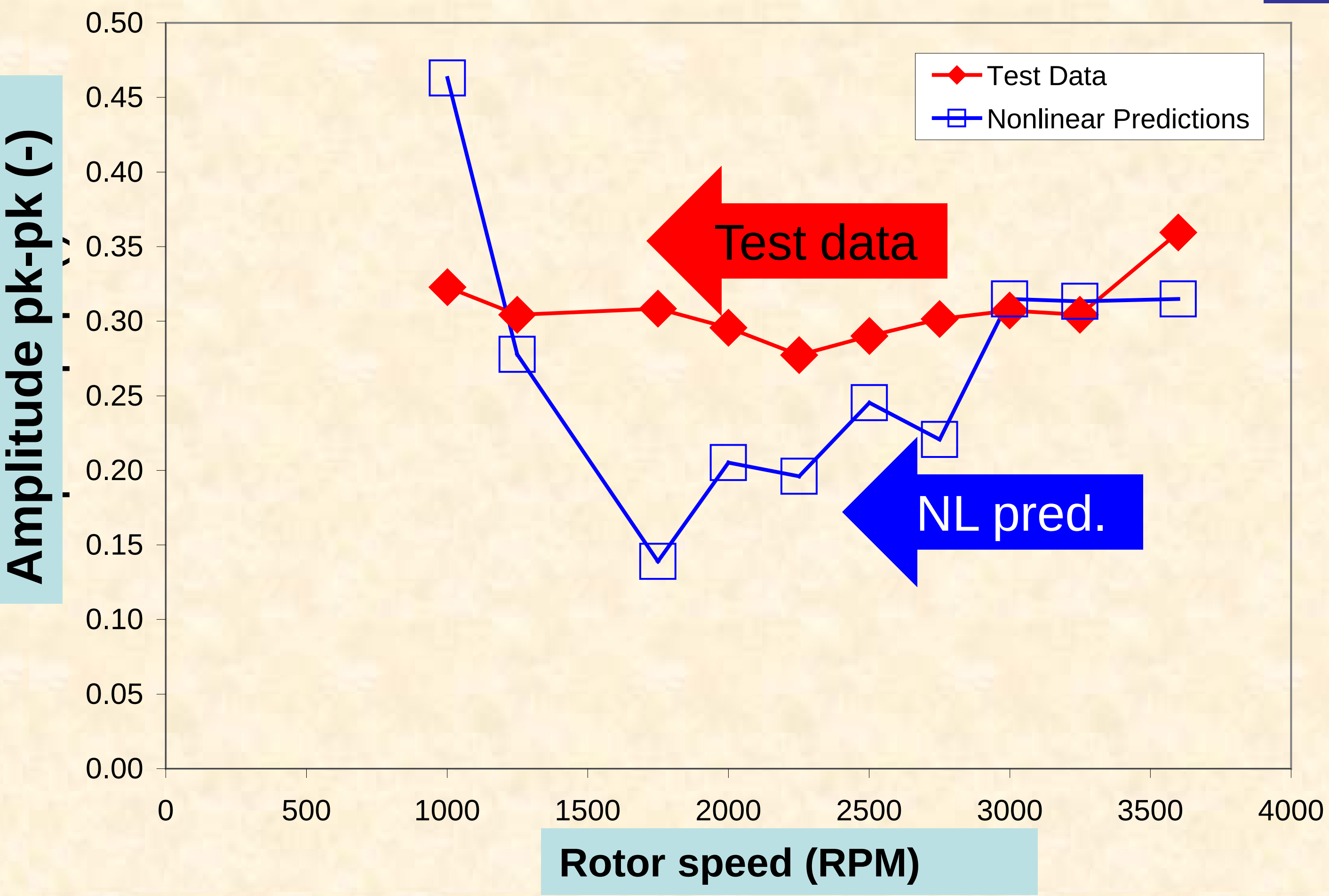
Test data shows broad frequency response at low frequencies (engine speeds)

IC engine induced excitations



Total shaft motion at compressor end (amplitude)

100% engine load



Good correlation with test data for all shaft speeds

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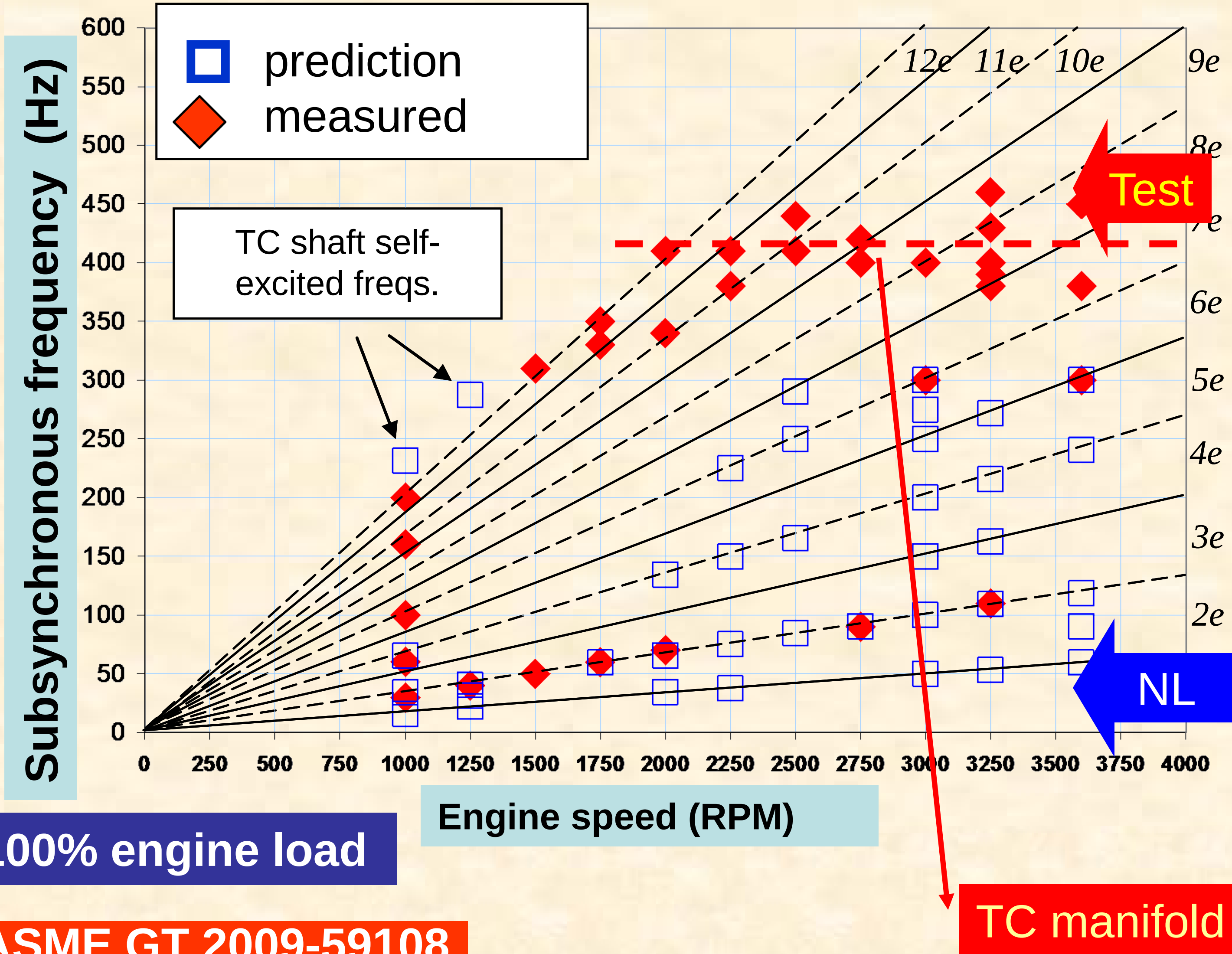
Subsynchronous freq. vs. IC engine speed



Subsynch. freqs. are multiples of IC engine frequency

Higher engine order frequencies not predicted

100% engine load

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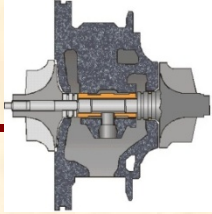
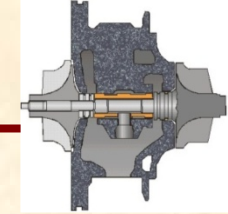


Validation: noise generation & frequency jump

IFToMM 2010

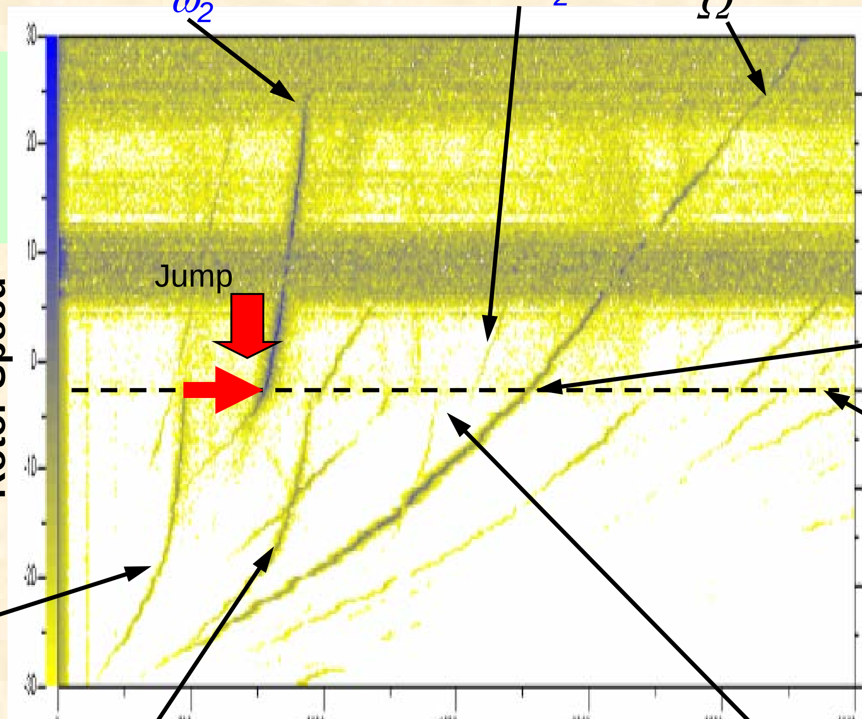
Frequency jumps: test data



center housing acceleration (test data)

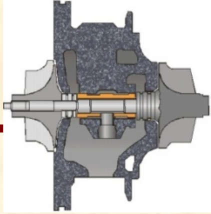
Jump from 1st to 2nd whirl frequency increases noise

Shaft accelerates
Top speed ~180 krpm (3 kHz)
Oil inlet temp= 30°C
Oil inlet pressure = 4 bar

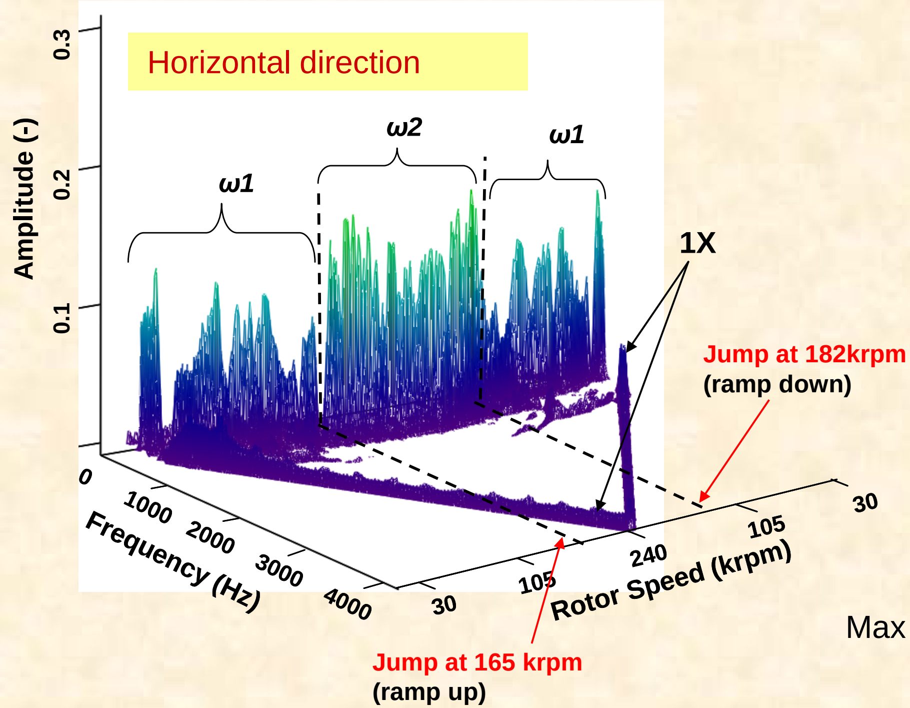


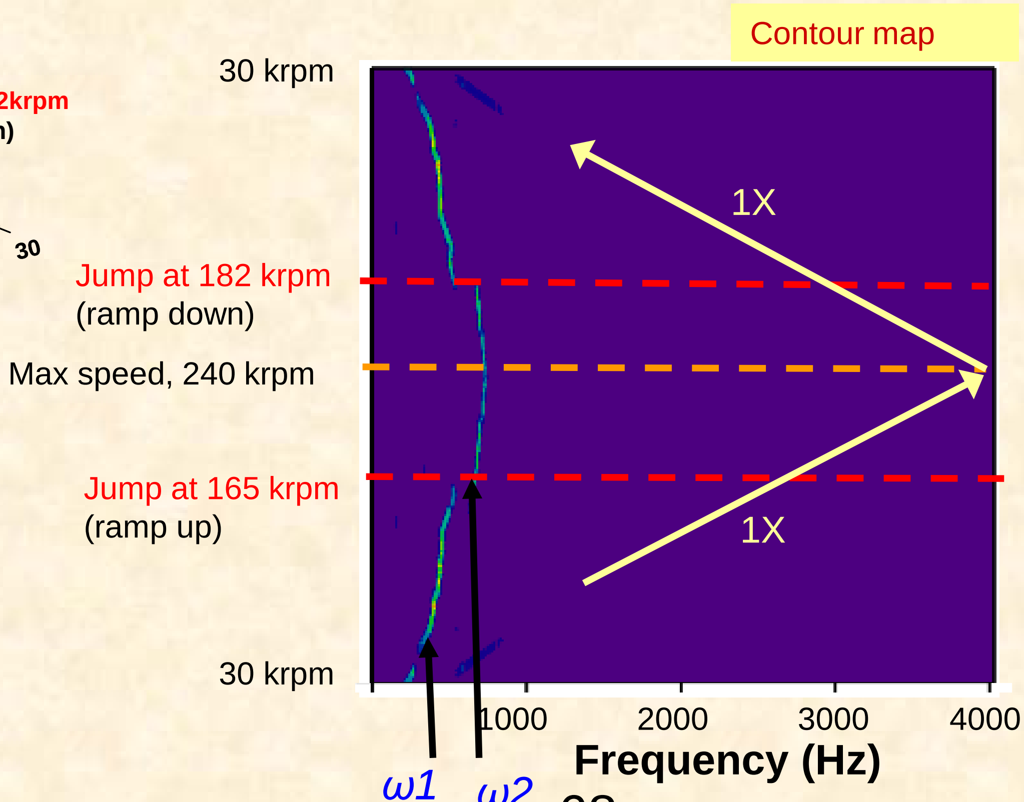
Objective: study bearing parameters and rotor characteristics affecting frequency jump

NL predictions: frequency jumps

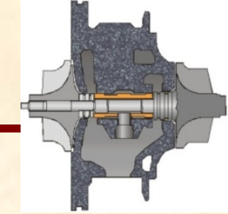


Waterfalls of shaft motion (compressor end)



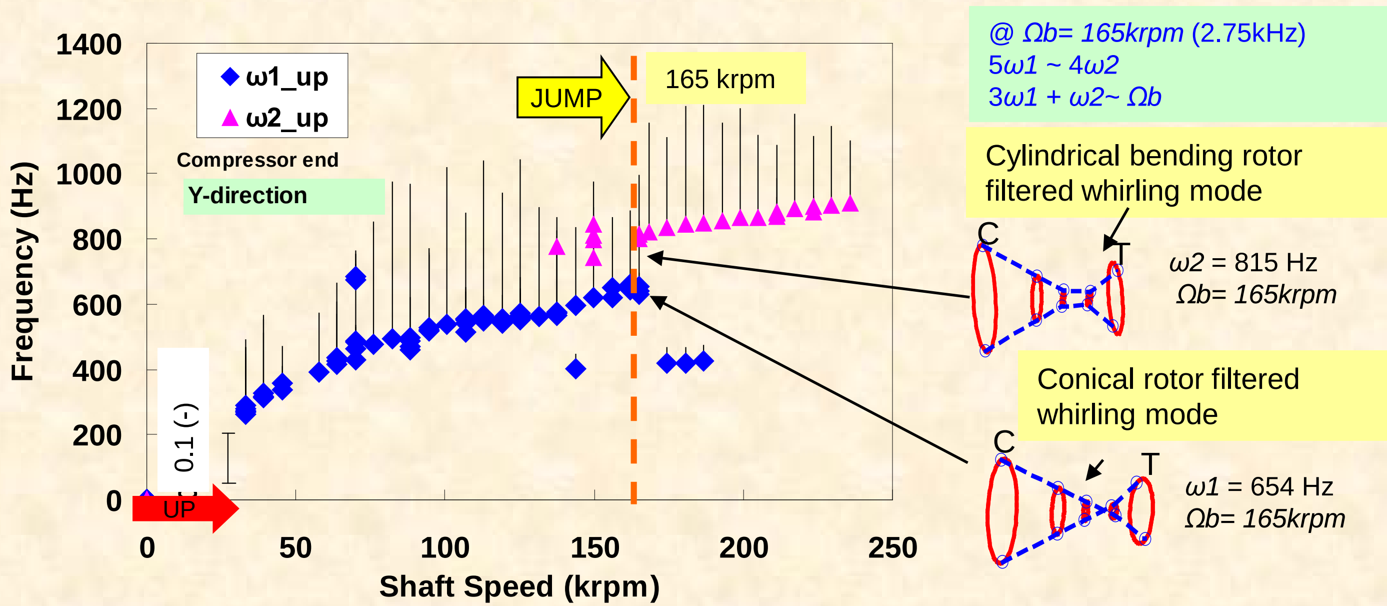


NL predictions: frequency jumps

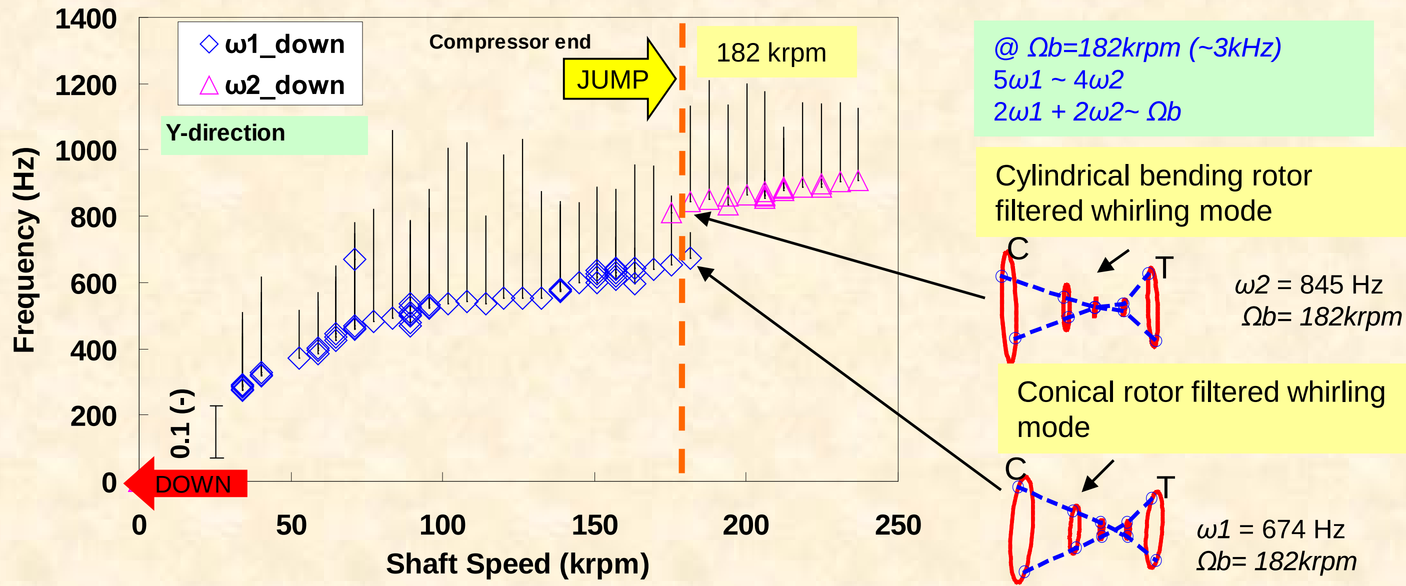


Rotor subsynchronous frequency (and amplitude) versus shaft speed (compressor end)

Rotor accelerates

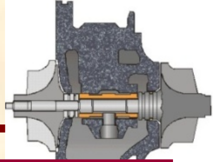


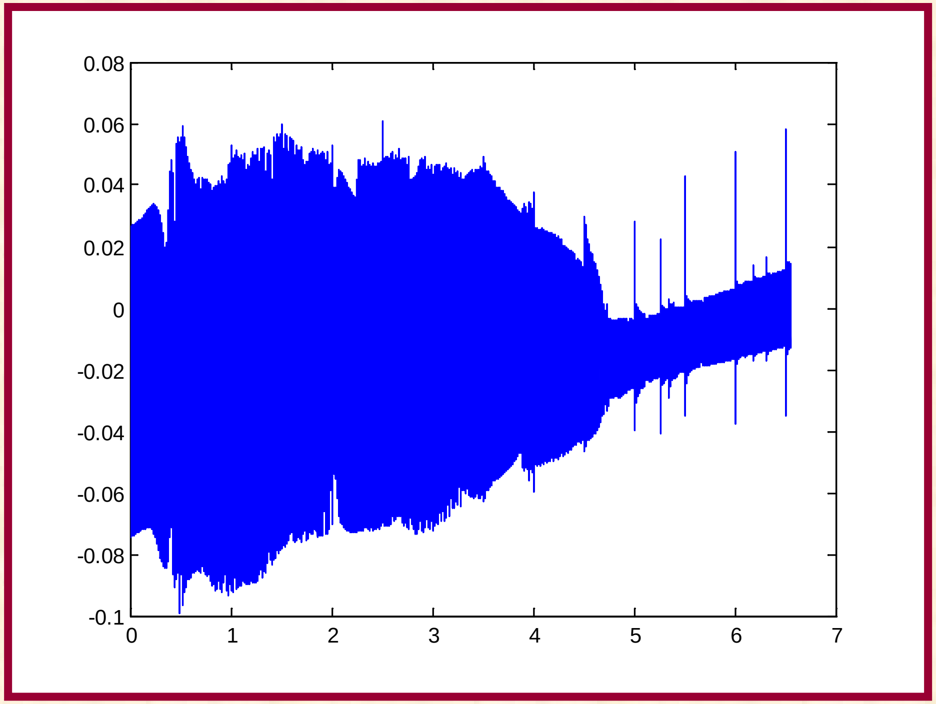
Rotor decelerates

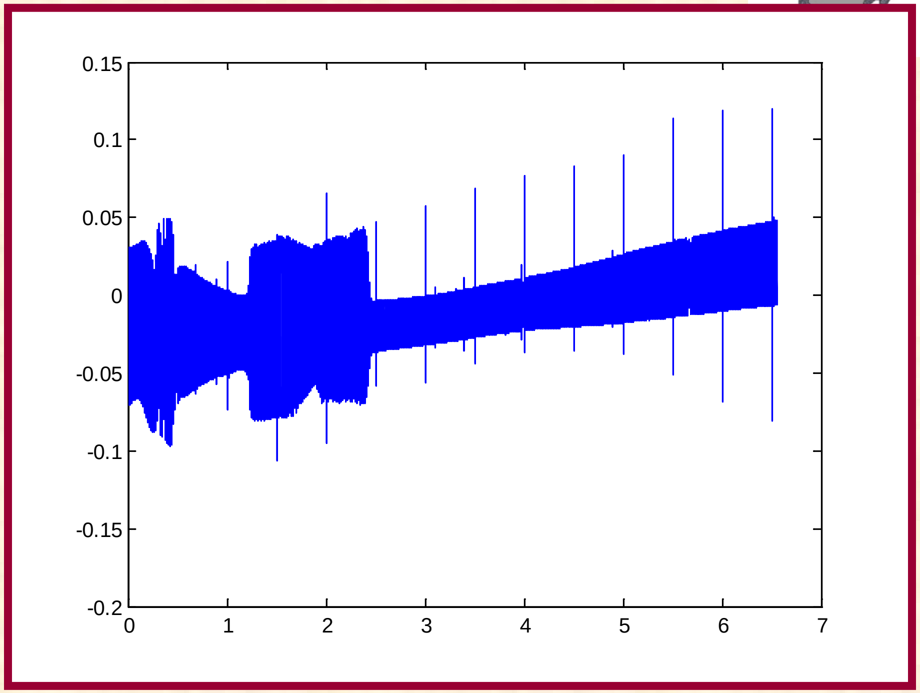


IFToMM 2010

NL predictions: noise





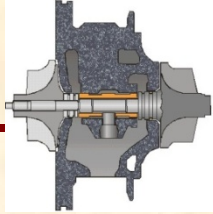


18 krpm → **240 krpm**　**18 krpm** → **240 krpm**

Predictions of TC shaft motion response – displacement versus time: rotor acceleration

TC shaft motions virtual tool

TC shaft motions virtual tool



1. Tests SHOW dominance of SUB SYNCHRONOUS MOTIONS on rotordynamic response of PV TCs

TAMU & HTT

2. TOOL for prediction of fully floating and semi-floating ring bearing (SFRB) static and dynamic forced response is ACCURATE

XLBRG

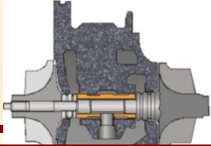
XLTRC2

3. VIRTUAL TOOL: Seamless Integration of FRB and SFRB codes into nonlinear rotordynamics program

Test vs. predictions

Substantial savings in product development/prototype testing

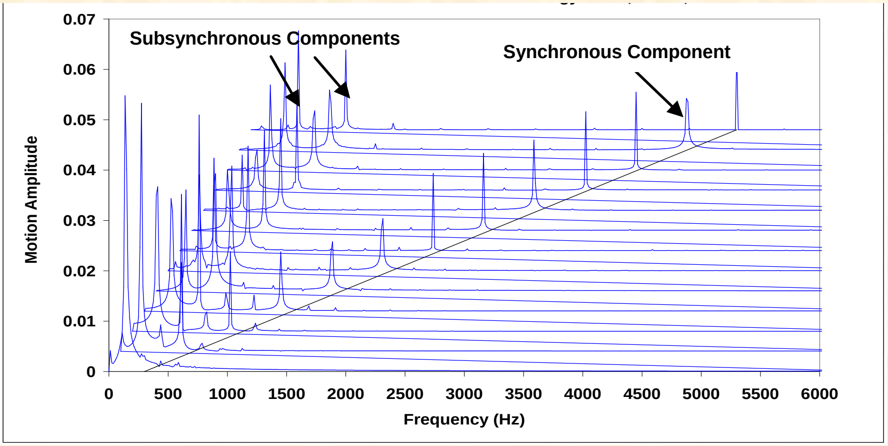
Major benefit to industry



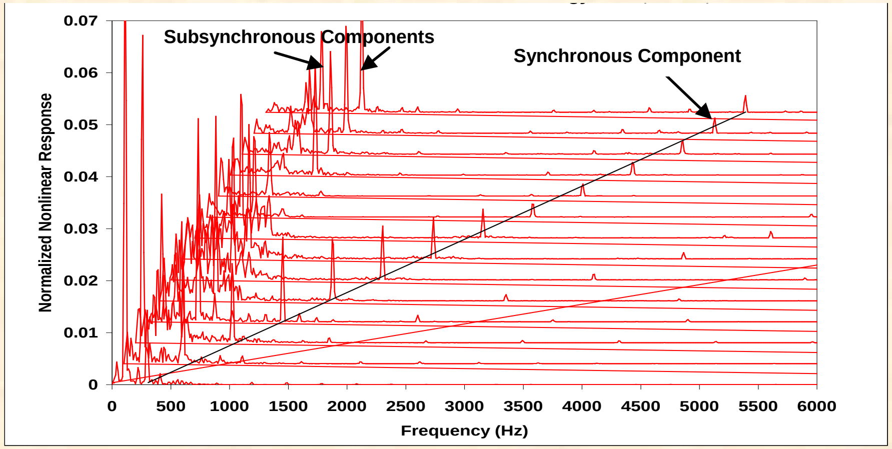
TAMU-HTT VIRTUAL TOOL for Turbocharger NL Shaft Motion Predictions

XLTRC^{2}® & XLBRG® have a demonstrated 70% cycle time reduction in the development of new *CV TCs*. Since 2006, code aids to developing *PV TCs* with savings up to $150k/year in qualification test time

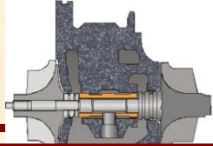
Predicted shaft motion



Measured shaft motion



ASME DETC2007-34136



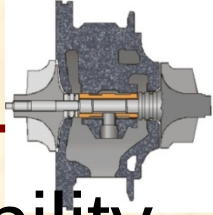
HTT 2011-12 Project

Complete thermal analysis of FRBs and S-FRBs for TCs

- **Prediction of thermal fields in entire TC system**
- **Quantification of power losses and prediction of bearing seizure & oil coking**
- **Analysis of frequency jump phenomena and multiple internal and combined resonances**

- **$ 350 k (2 years)**

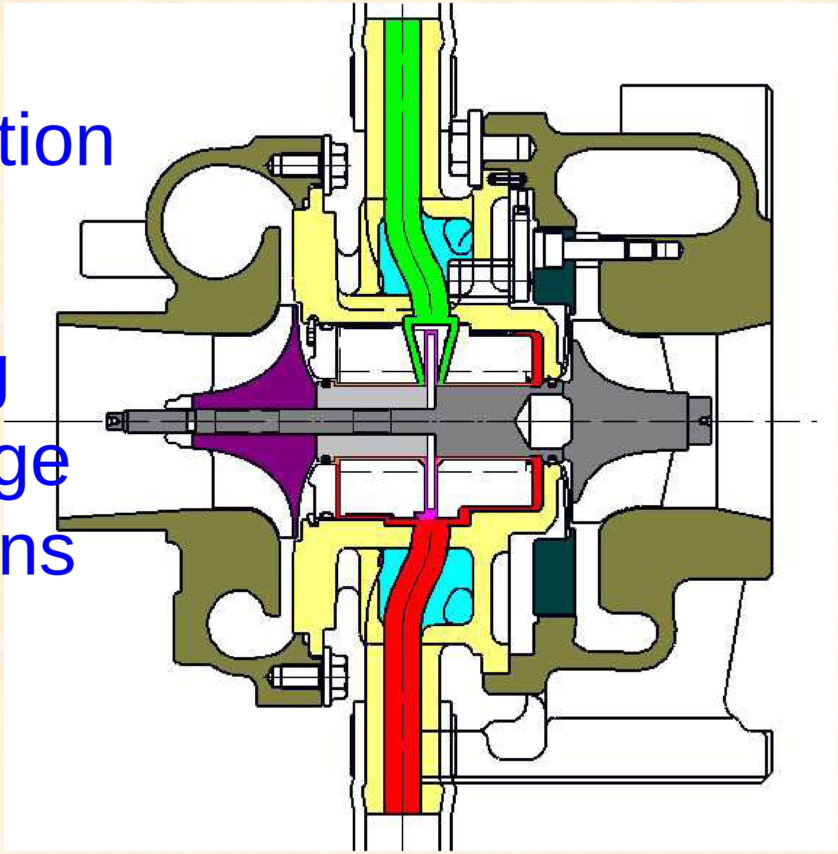
Oil-less turbochargers



Driver: HT ceramic ICEs with improved reliability

Advantages:

+ TH efficiency, HT limited by materials only, less contamination



Disadvantages:

+ cost, more parts & balancing

Unknown performance for large dynamic loads & road conditions

Unknown thermal soaking

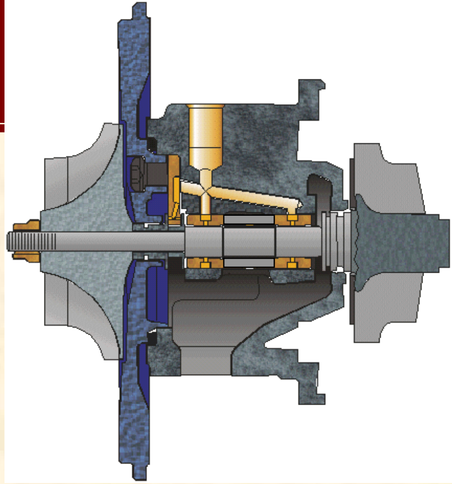
Cheap solution sought: metal wire mesh bearings!

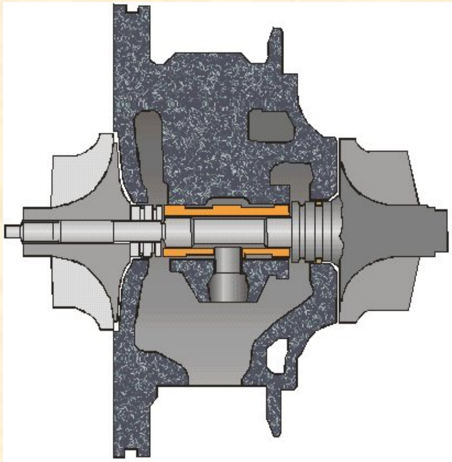
Other forces and issues

Thrust bearings:
Tools available
Issues: thermal & coupling to lateral RD in PV TCs

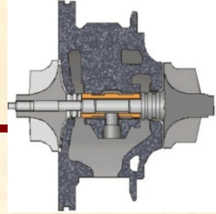
Aerodynamic forces:
Tools available
Issue: At + high speeds, turbine develops a destabilizing force

Piston ring seal:
Unknown forces.
Issue: oil coking locks ring

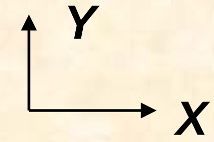

CV TC

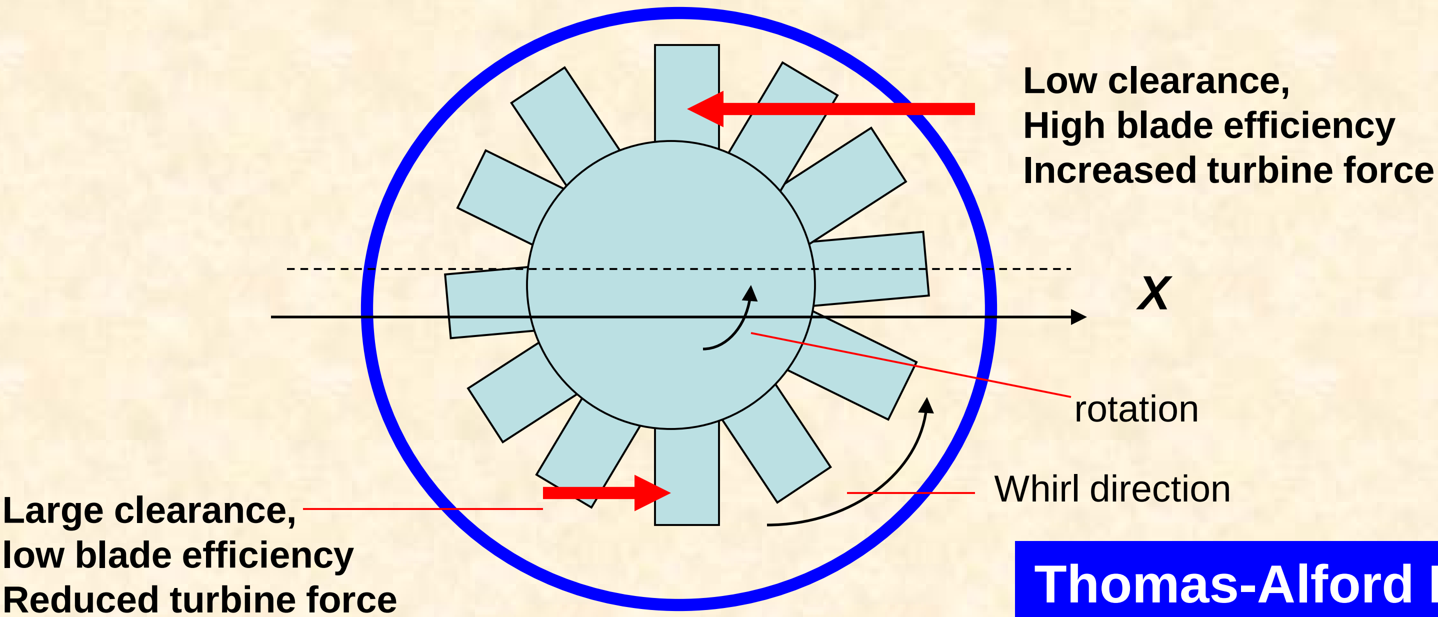

PV TC

Aerodynamic force in turbines



As rotor whirls, regions of low clearance improve efficiency of blades and generate a force (from torque)



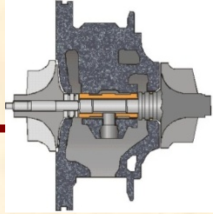


Thomas-Alford Force Model

$$-F_X = K_{XY}\,\Delta Y, \; -F_Y = -K_{YX}\,\Delta X$$

$$K_{xy} = -K_{yx} = \frac{\beta T}{DH}$$

T: torque
D: tip diameter
H: blade height
β: efficiency parameter (empirical) =1-1.5



Acknowledgments

Honeywell Turbocharging Technologies (2002-2011)

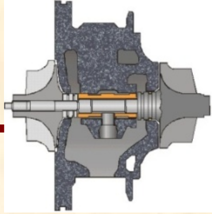
TAMU Turbomachinery Laboratory

Turbomachinery Research Consortium (XLTRC$^{2®}$)

Luis San Andres

Learn more at
http://rotorlab.tamu.edu

TC shaft motions virtual tool



	San Andrés, L., and Vistamehr, A**.,** 2010, **“**Nonlinear Rotordynamics of Vehicle Turbochargers: Parameters Affecting Sub Harmonic Whirl frequencies and Their Jump,” Proc. of the 8th IFToMM International Conference on Rotordynamics, September, Seoul, Korea, Paper P-1115
	Gjika, K., C. Groves, L. San Andrés, and LaRue, G., 2010, “Nonlinear Dynamic Behavior of Turbocharger Rotor-Bearing Systems with Hydrodynamic Oil Film and Squeeze Film Damper in Series: Prediction and Experiment,” ASME Journal of Computational and Nonlinear Dynamics, Vol. **5** (October), p. 041006-(1-8).
	San Andrés, L., Maruyama, A., Gjika, K., and Xia, S., 2010, “Turbocharger Nonlinear Response with Engine-Induced Excitations: Predictions and Test Data,” ASME J. Eng. Gas Turbines Power, Vol. 132(March), p. **032502** (ASME Paper No. GT2009-59108)
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	San Andrés, L**., J.C. Rivadeneira,** K. Gjika, C. Groves, and G. LaRue, 2007, “Rotordynamics of Small Turbochargers Supported on Floating Ring Bearings – Highlights in Bearing Analysis and Experimental Validation,” ASME Journal of Tribology, Vol. 129, pp. 391-397.
	San Andrés, L**.,** J.C. Rivadeneira**,** M. Chinta, K. Gjika, G. LaRue, 2007,”Nonlinear Rotordynamics of Automotive Turbochargers – Predictions and Comparisons to Test Data,” ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 488-493 (ASME Paper GT 2005-68177)
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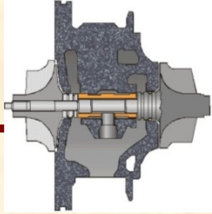
References

TC shaft motions virtual tool



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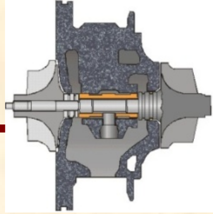
	Naranjo, J., C. Holt, and L. San Andrés, 2001, “Dynamic Response of a Rotor Supported in a Floating Ring Bearing,. 1st International Conference in Rotordynamics of Machinery, ISCORMA1, Paper 2005, August 2001 (CD only).
	Over 80 proprietary monthly progress reports to sponsor (Honeywell Turbocharging Systems), 2002-2011.

References



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