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Case Studies on Vibration Problems in Oil-free Microturbomachinery

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Abstract

Eco-friendly technologies are becoming more popular and important. High speed gas foil bearings enable oil-free turbomachinery, compact and with a low footprint. The lecture introduces oil-free micro-turbomachinery (<250 kW) for industrial use and details three case studies of troubleshooting rotordynamic problems. The study includes vibration measurements, rotordynamic analysis for problem identification, and simple solution techniques to reduce unfavorable vibrations in turbo blowers for wastewater treatment plants and in a turbocompressor-electric motor for eco-friendly passenger vehicles.

AGENDA

Lecturer Bio

Tae Ho Kim (aggie class of 2007) joined the School of Mechanical Engineering in Kookmin University, Seoul, Korea in 2012. Previously, he worked for the Korea Institute of Science and Technology (KIST) as a Senior Research Scientist. He received B.S. and M.S. degrees in mechanical engineering from Hanyang University (Korea) in 2000 and 2002, respectively, and a Ph.D. degree in mechanical engineering from Texas A&M University in 2007.

Prof. Kim has won multiple awards from ASME: 2013 Tribology Division Burt L. Newkirk Award for young investigator and Journal of Tribology 2010 & 2012 Best Paper Award. Dr Kim is an Associate Editor for the ASME Journal of Engineering for Gas Turbines and Power. His main research fields are gas/fluid film bearings, analysis and experimental evaluation, and structural/rotordynamic analysis of high speed rotating machinery.

Tae-Ho is a former TurboLab student and presently is a visiting Scholar at ME- TAMU

Kookmin University

Bukhansan National Park

111,155
Alumni

18,182
Enrolled Students

2,278
International Students

1,715
Faculty Members

440
Administrative Staffs

13
Colleges

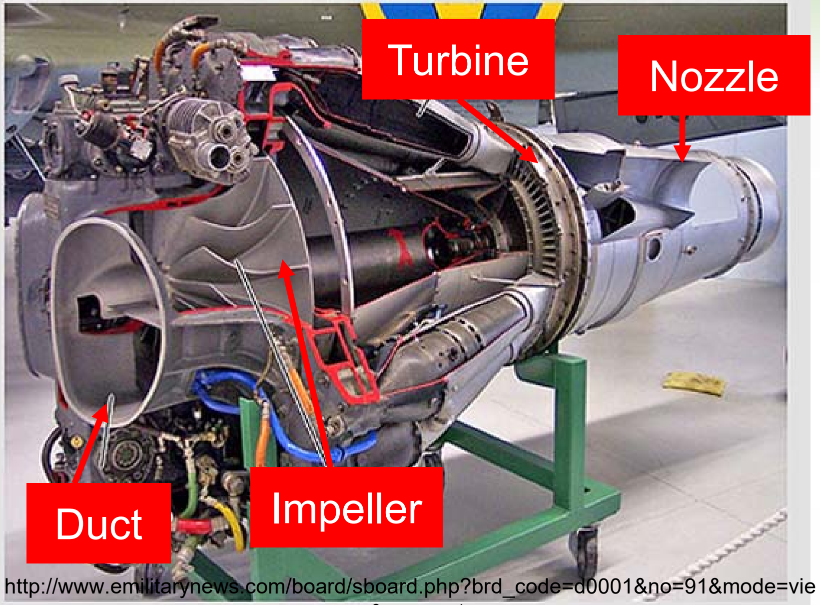
Private university established in Seoul, Korea since 1946

Kookmin Univ. consists of 18,182 students (15,162 undergraduate+3,020 graduate students), 1,715 faculty members, and 440 staff members in 13 colleges and 4 graduate schools.

There are 25 faculties in mechanical engineering + 26 faculties in automotive engineering.

Introduction: Micro-turbomachinery?

Macro vs. Micro – turbine engines: example



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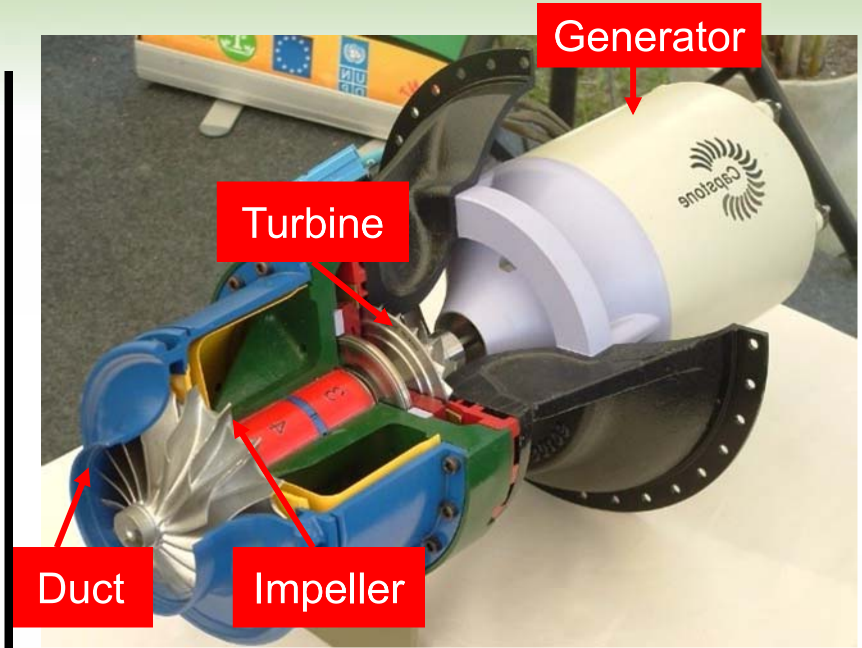


MACRO TURBINE ENGINE

AeroJet Engine with a centrifugal compressor and a turbine

Power range : > 1MW
Cost: High
Power output: Thrust force

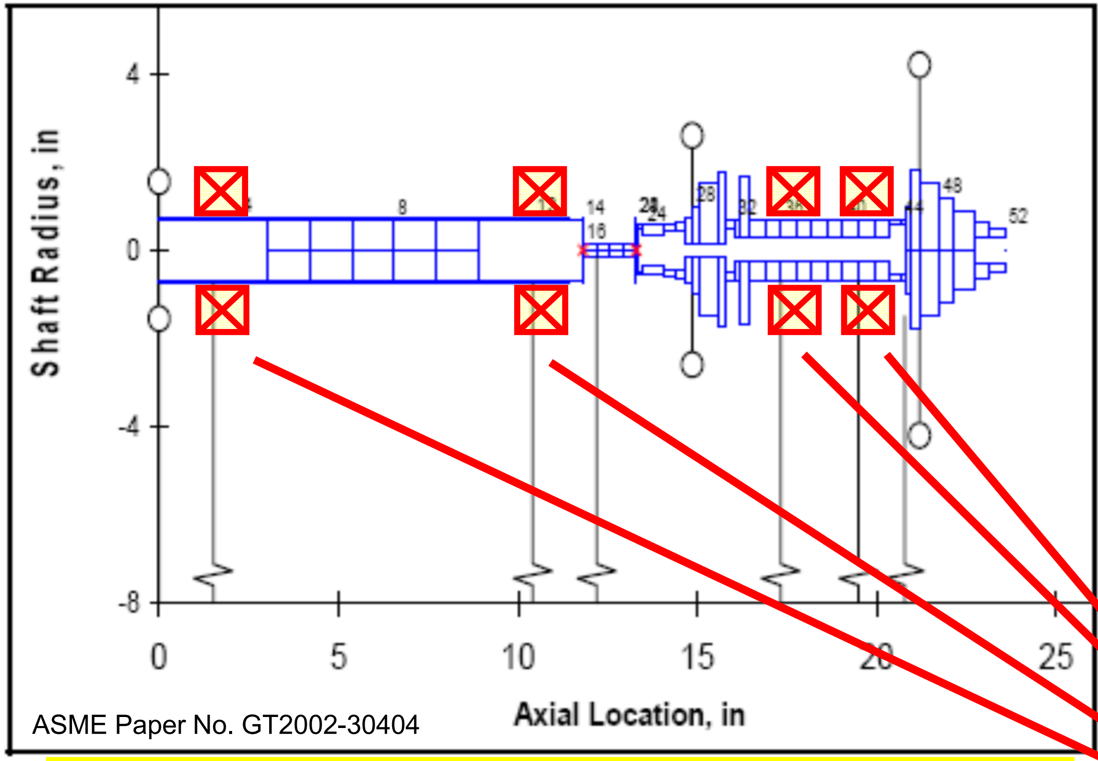
MICRO TURBINE ENGINE

Distributed Power Microturbine with a centrifugal compressor and a turbine

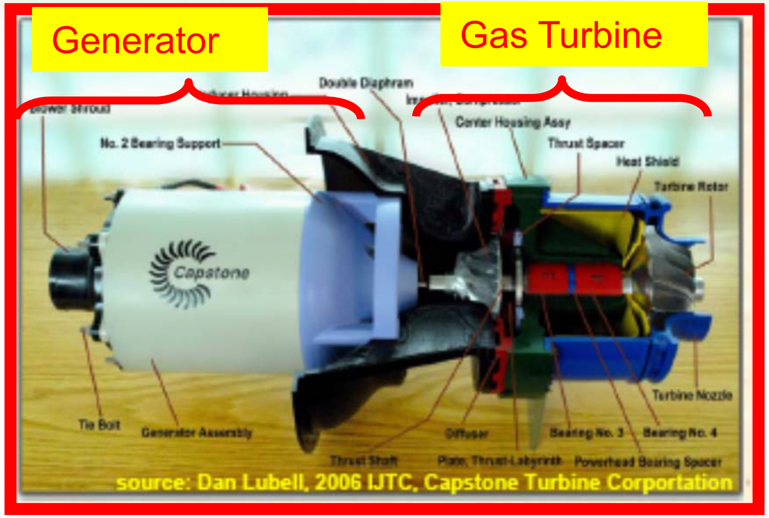
Power range : < 0.3MW
Cost: Low
Power output: Electricity/Heat

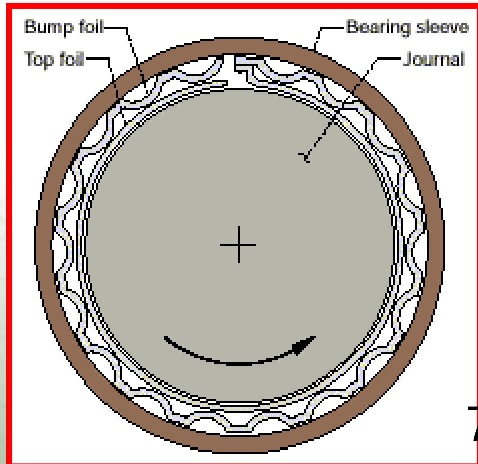
Introduction: Micro-turbomachinery?

Micro-turbomachinery become *Oil-Free* using Gas Foil Bearings!



Finite element rotor - bearing model of microturbine





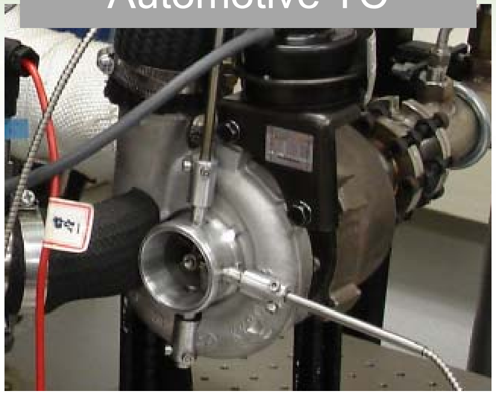
Oil –free (clean), high speed, high temperature
Gas Foil Bearing (GFB)

Gas Foil Bearing- Applications

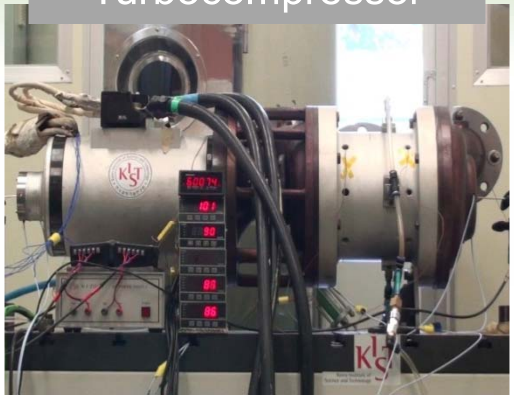
GFB applications: in-use or under-development.

Meso scale rotor

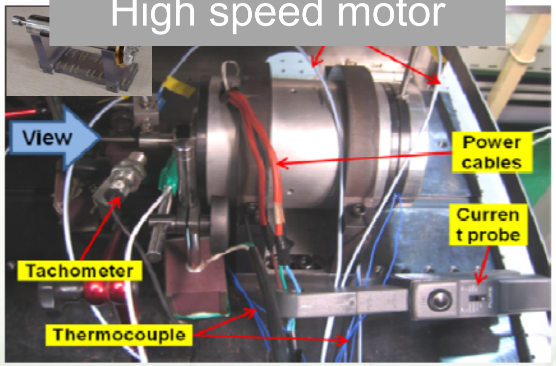
Automotive TC



Turbocompressor

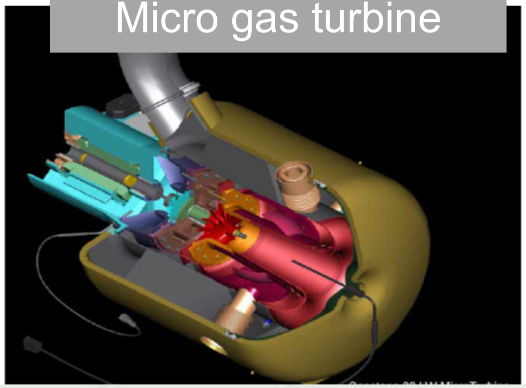


High speed motor



Turboblower

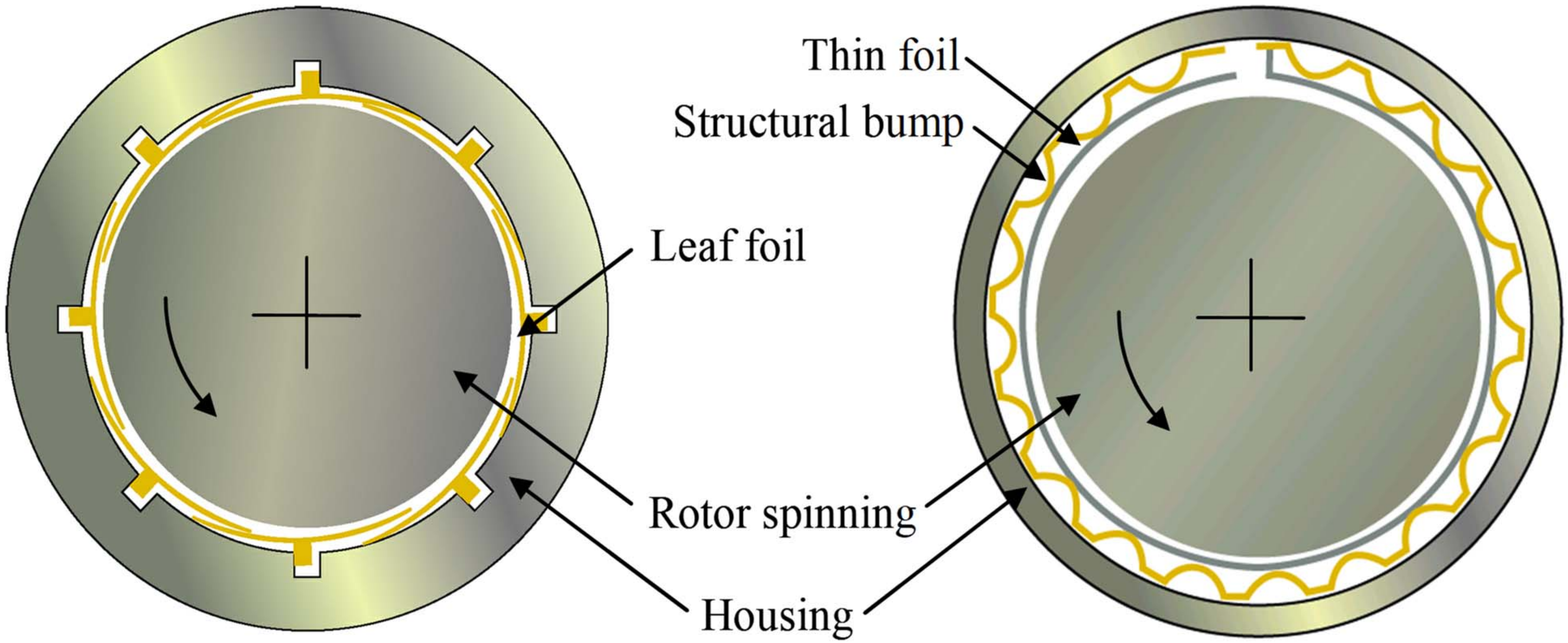
Micro gas turbine



Micro Turbomachinery up to 250 kWatt

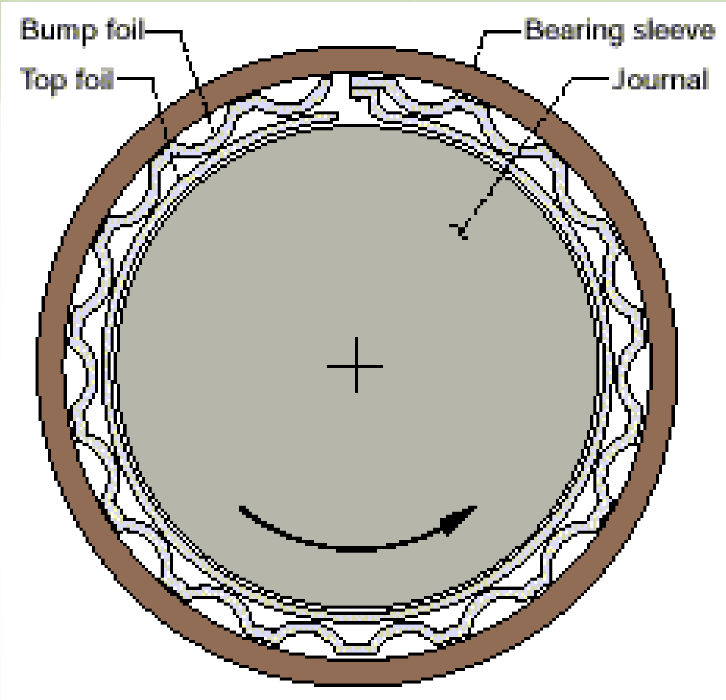
Introduction: *Oil-Free Gas Foil Bearings*

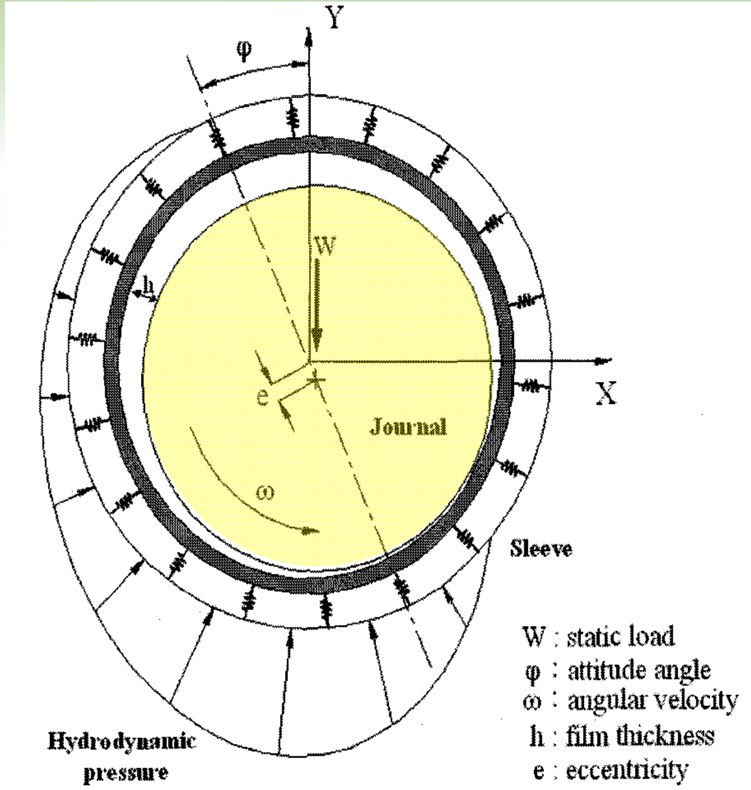
Implementation of GFBs into commercial turbomachinery makes the machines to be compact, light-weight, and oil-free with long life cycles.



(a) Multiple leaf GFB **(b) Corrugated bump GFB**

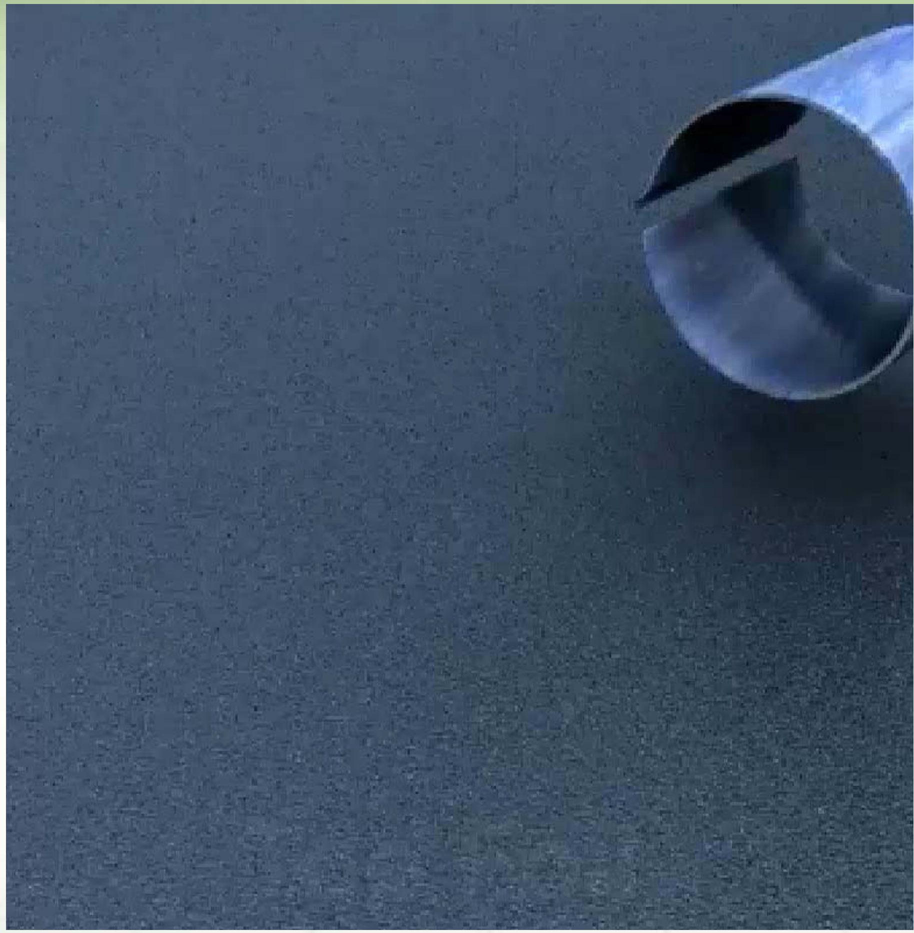
Background





Hydrodynamic gas(or air) pressure generated due to journal spinning between the journal and compliant foil surface. => No oil lubricant and No rolling element!

Background



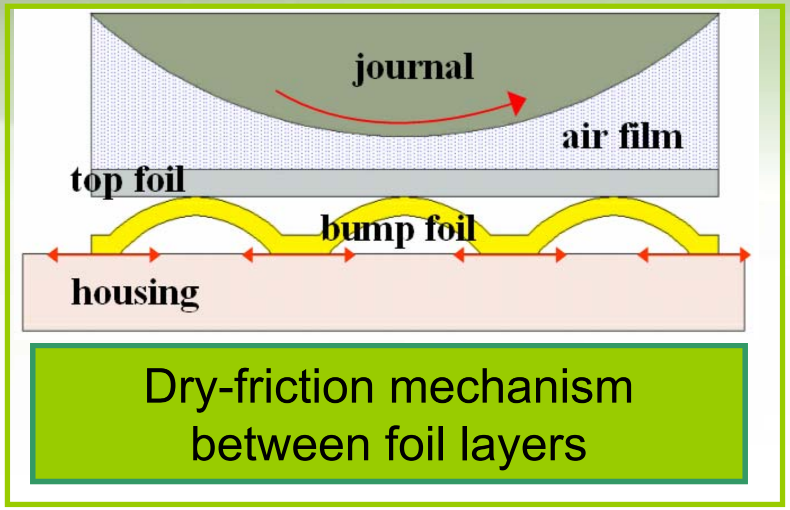
- No actual clearance without rotor spinning

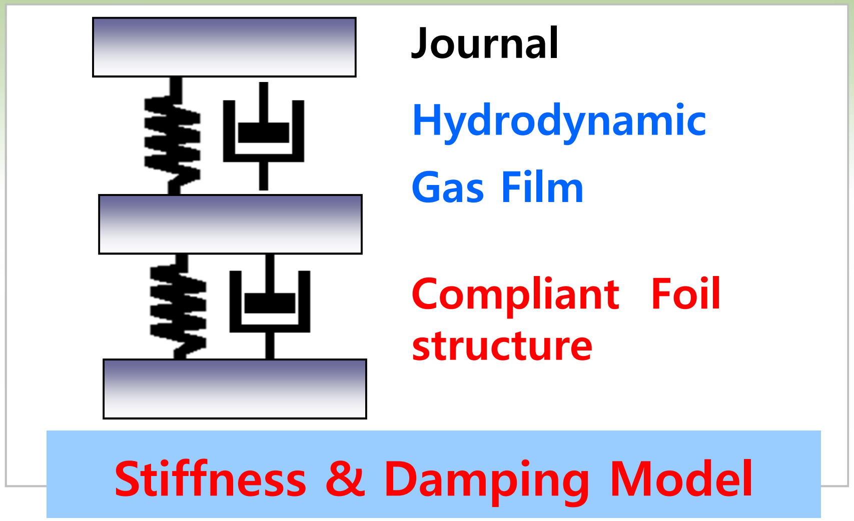
- Hydrodynamic pressure pushes foil outward and creates bearing clearance

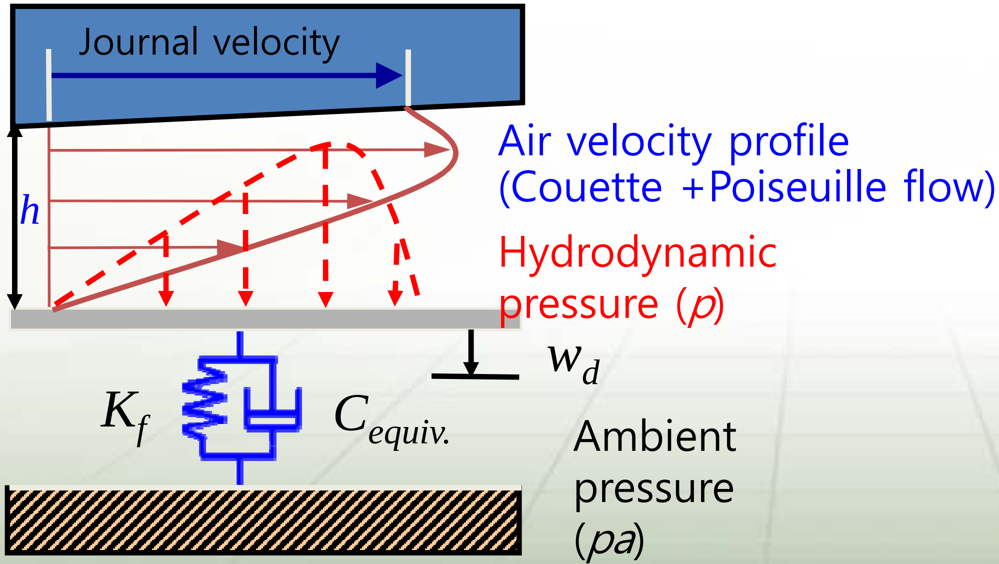
Air foil bearings suspend the shaft by compressing air between the shaft surface and the bearing.

*** Courtesy of NASA Oil-Free Turbomachinery**

Background







- **Integrate hydrodynamic gas film in series with one or more elastic structure.**
- **Provide stiffness and damping to rotordynamic systems**

Background

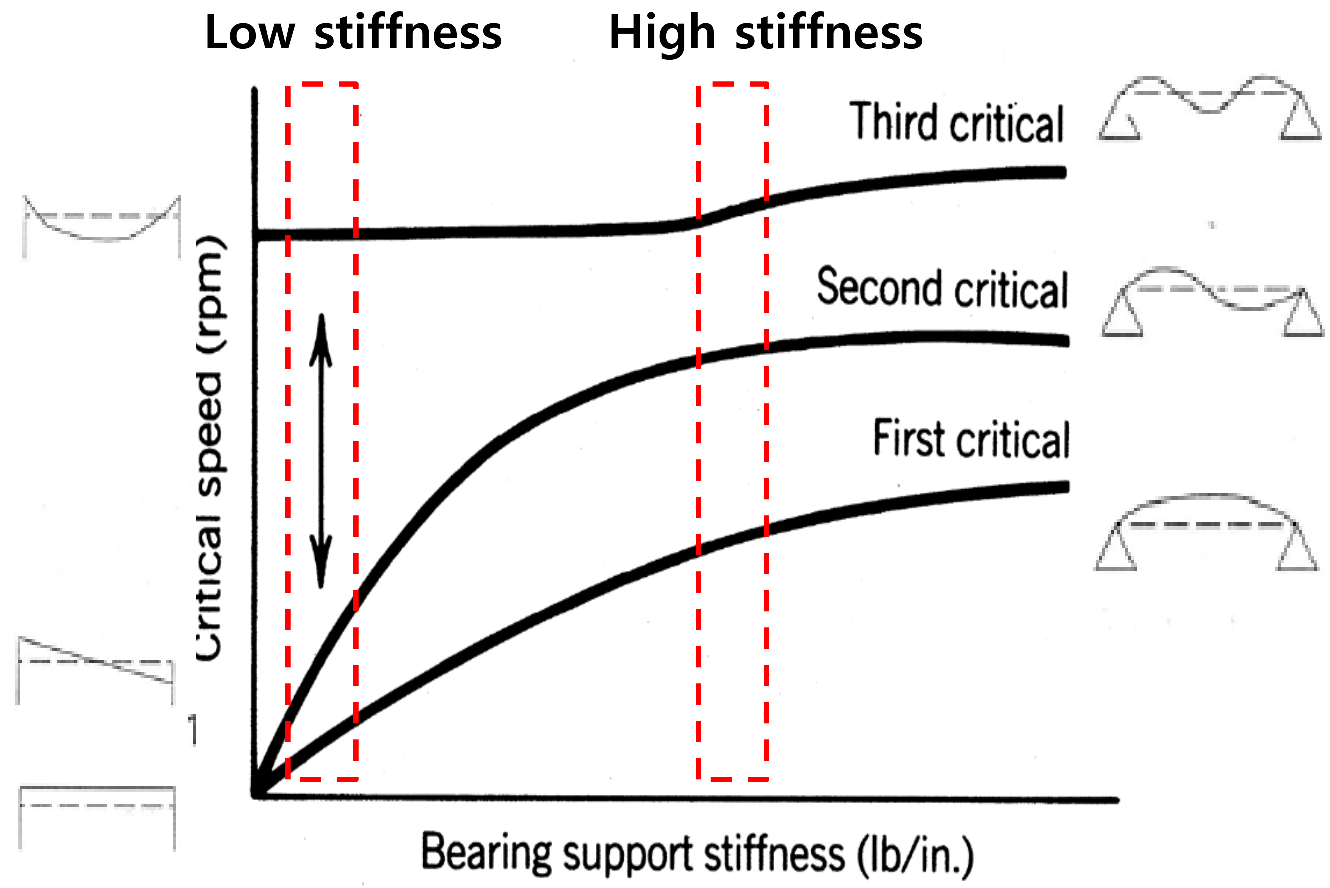
Gas Foil Bearing- Pros and Cons

- Increase in load capacity from compliance surface
- Damping from dry-friction in between foils and bearings
- Tolerant to misalignment and debris, also high temp.
- Ability to sustain high vibration and shock load.

- Less load capacity than rolling or oil bearings
- Need coatings to reduce friction at start-up & shutdown
- Thermal management issues to cool rotor and GFB
- Little test data for benchmarking against model predictions
- Potential for large amplitude subsynchronous motions

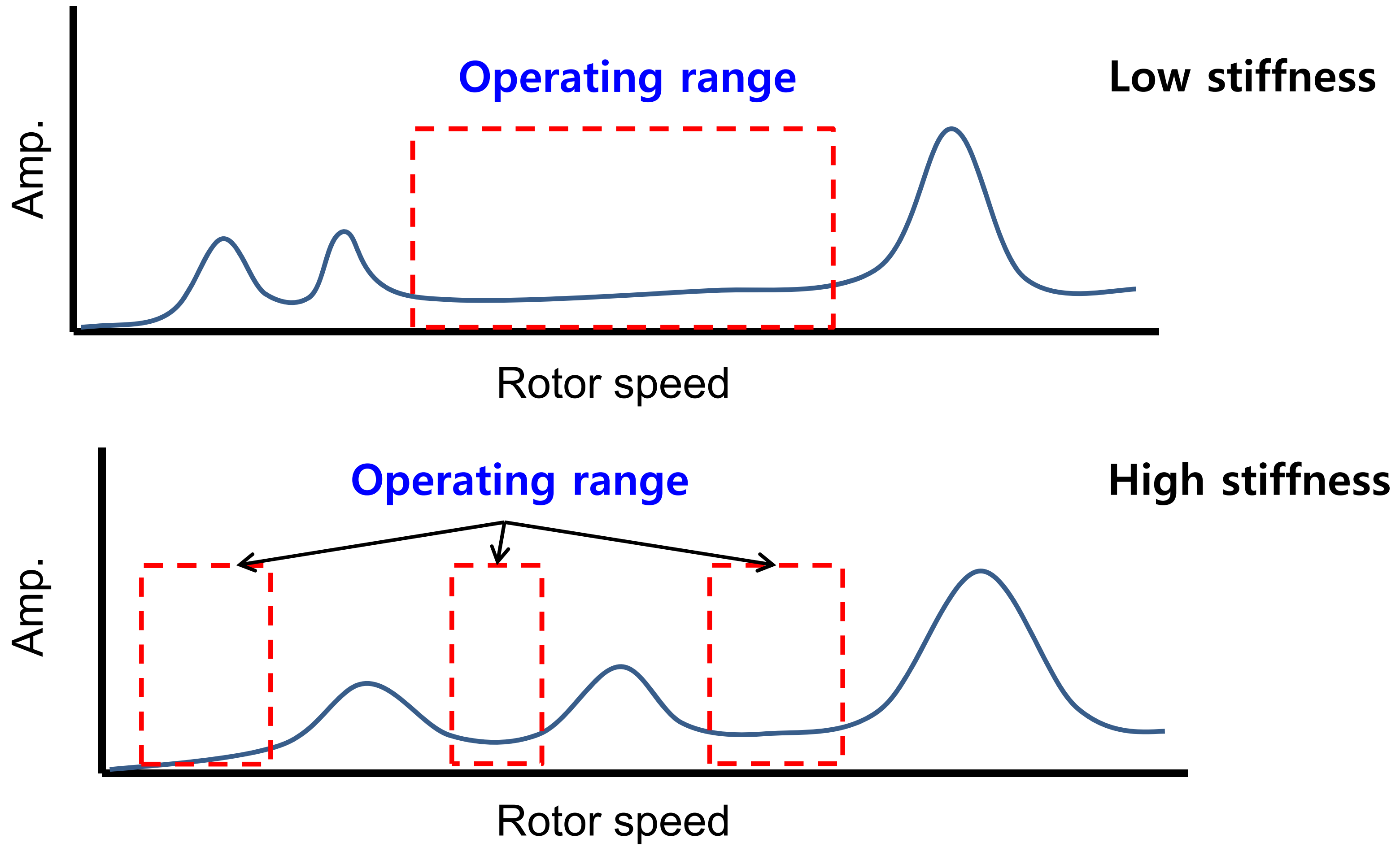
Background

Rotordynamic consideration: selection of bearing stiffness



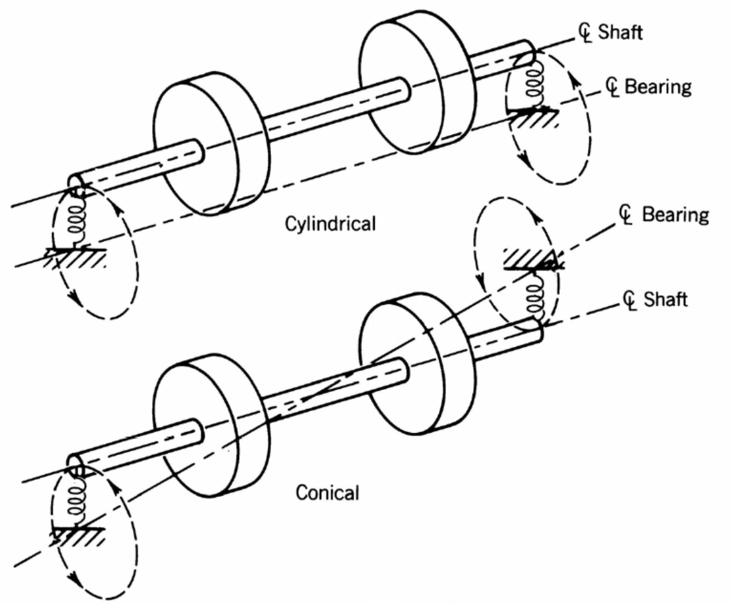
Background

Rotordynamic consideration: selection of operating range

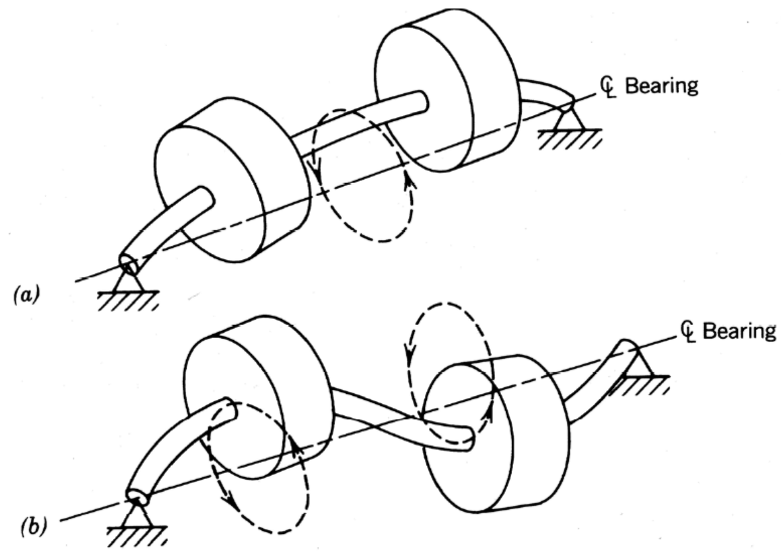


Background

Rotordynamic consideration: Natural mode shapes due to bearing stiffness



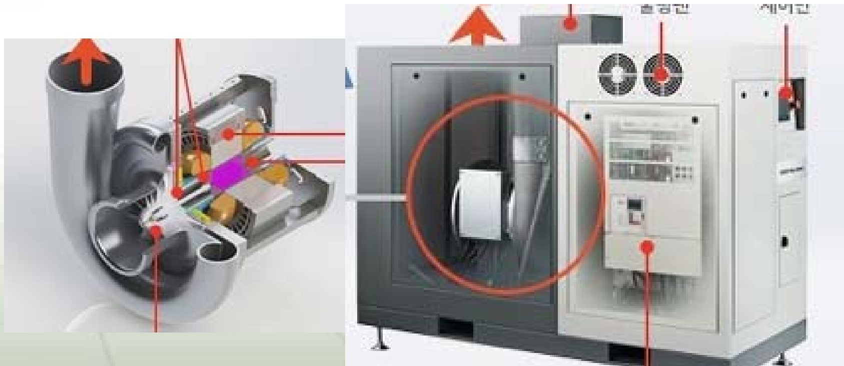
Rigid Shaft Mode Shapes
with soft bearings



Flexible Shaft Mode Shapes
with stiff bearings

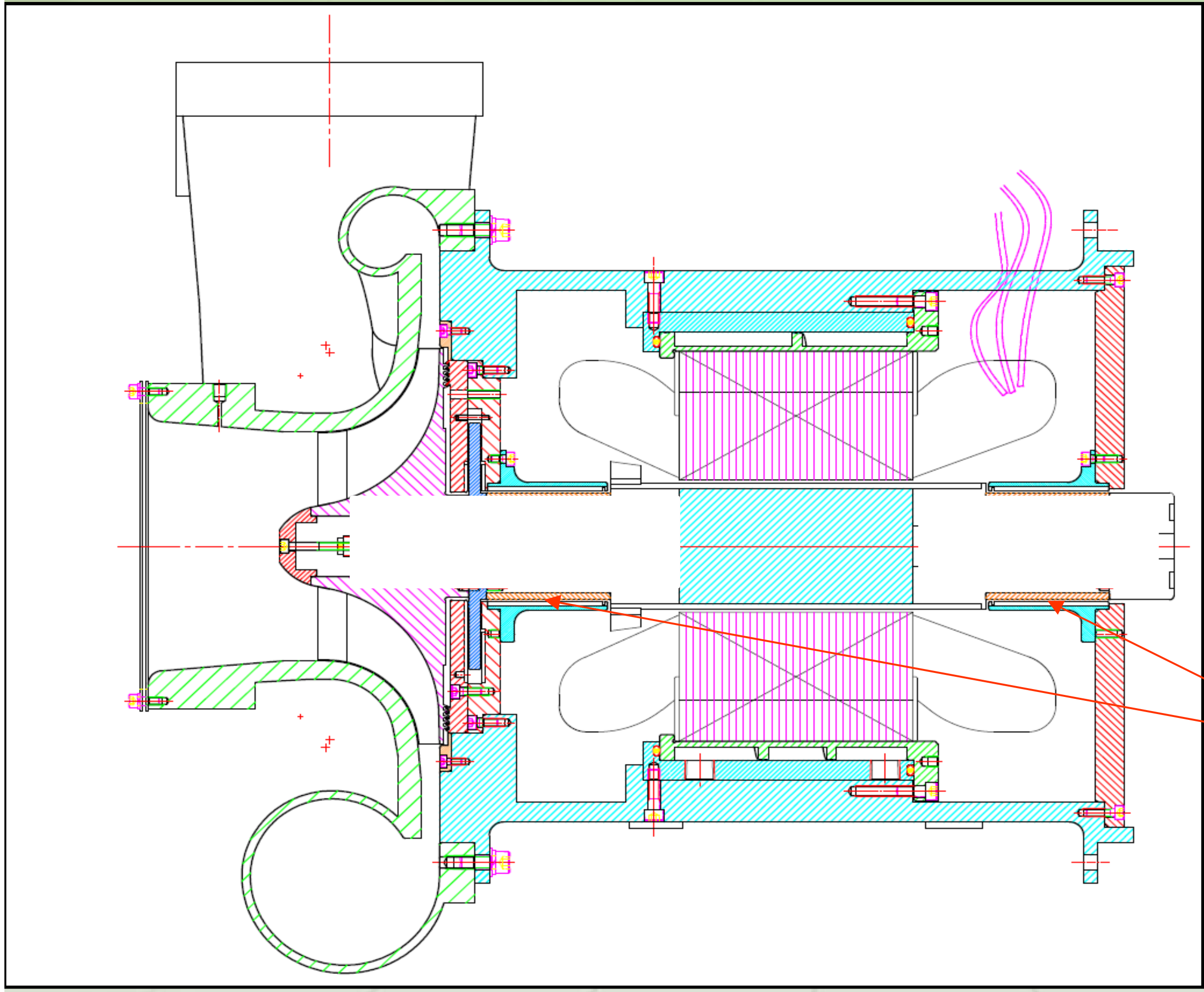
Case study 1

<u>Problem statement</u>: One of three turboblowers for wastewater treatment showed high vibration levels



http://seahcomp1.cafe24.com/product/turbo-blower/01/

Turboblower overview

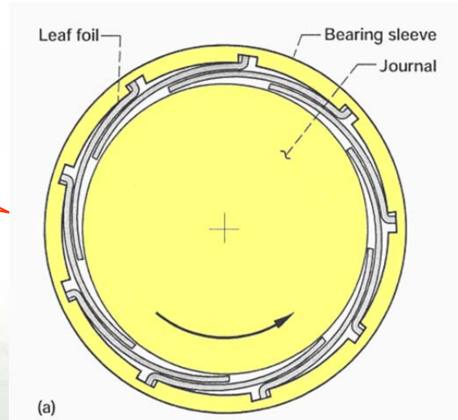


Single impeller blower

Motor power: 200 kW

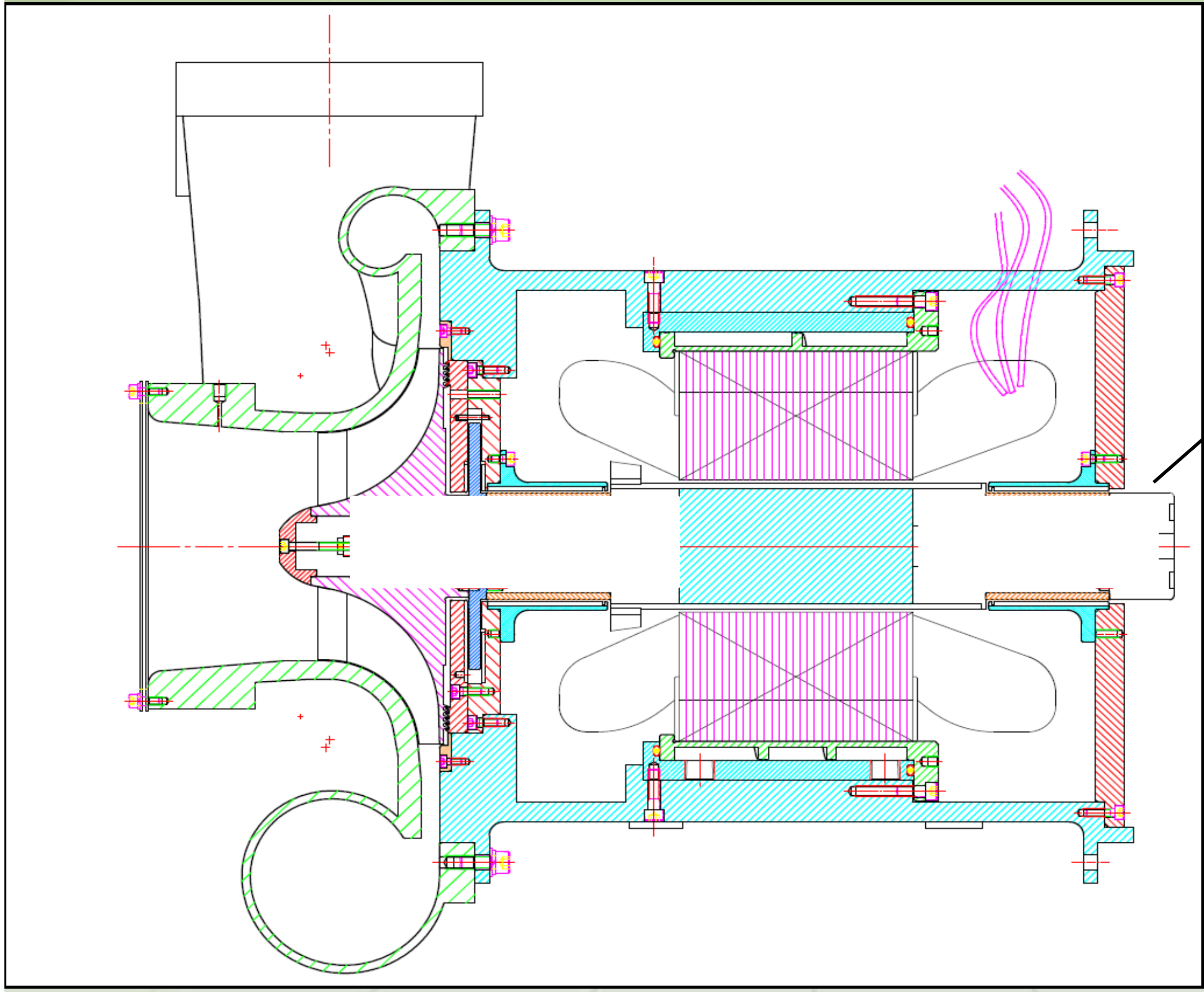
Motor type: Permanent magnetic Synchronous motor (PMSM)

Max. speed: 30,000 rpm

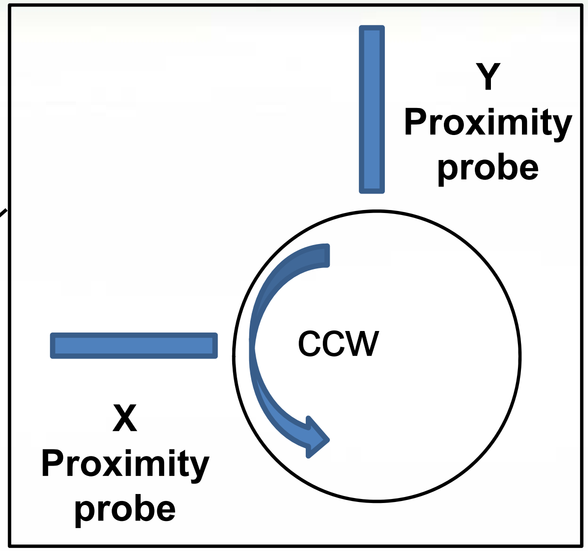


Multiple-leaf type GFBs

Measurement

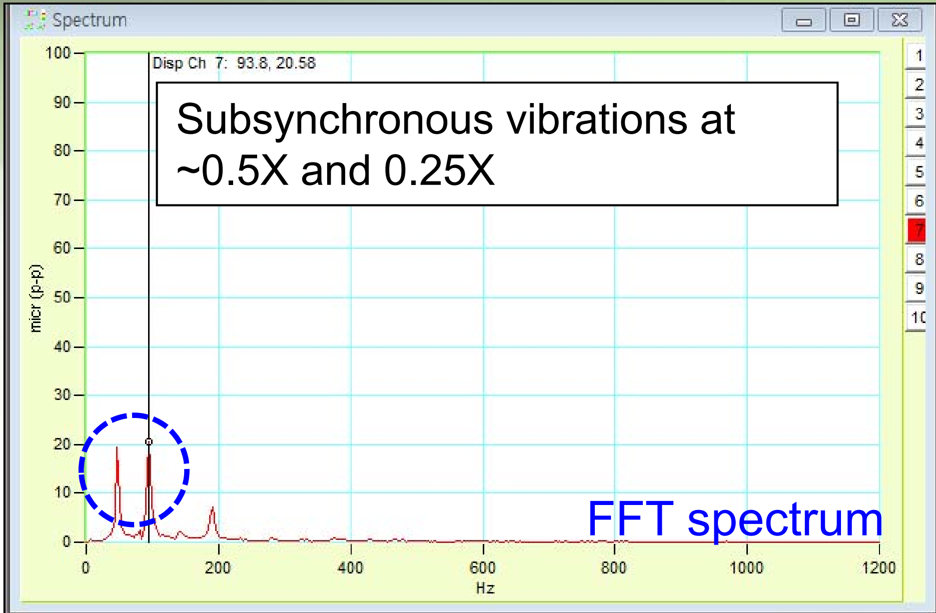


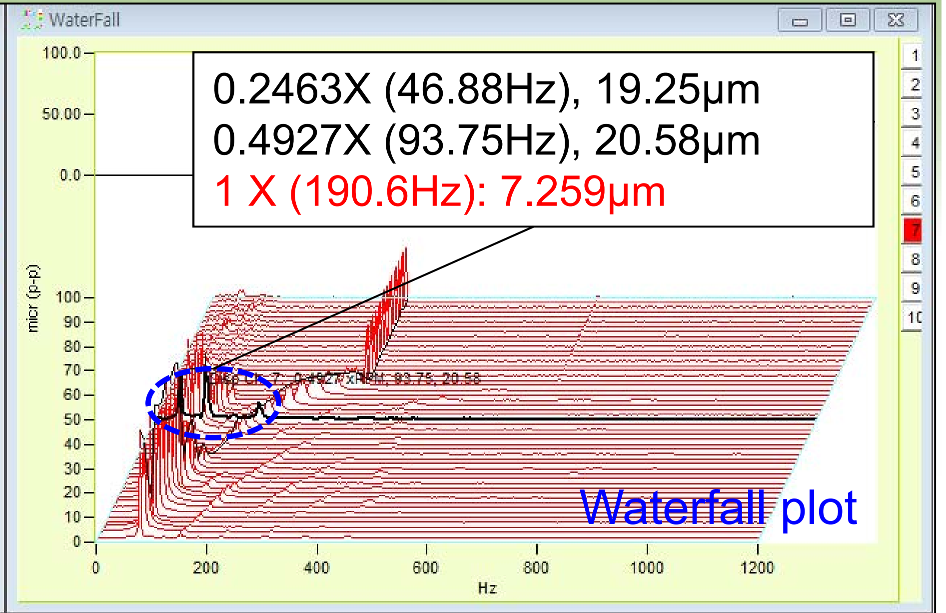
Eddy current type displacement sensor

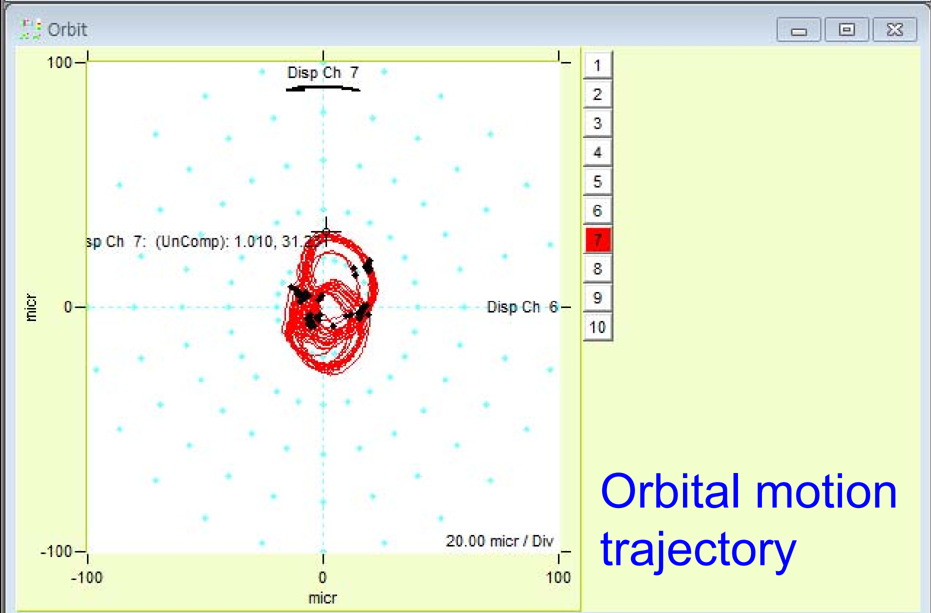


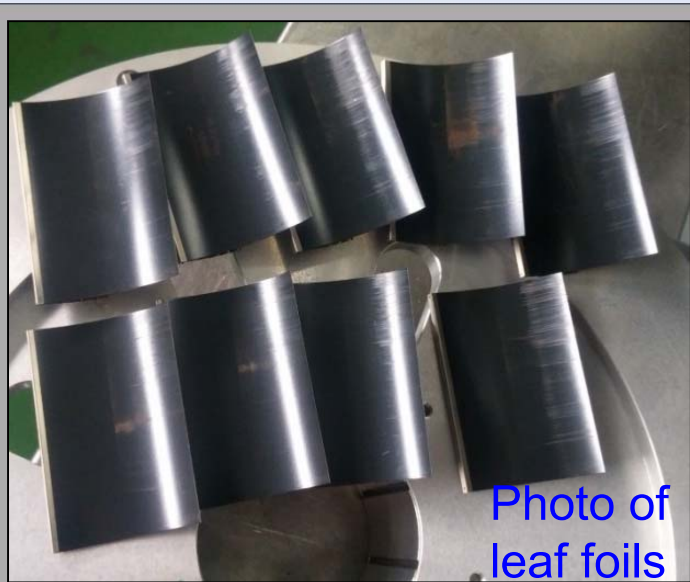
Tachometer for key phasor and speed measurement

Event: vibration data



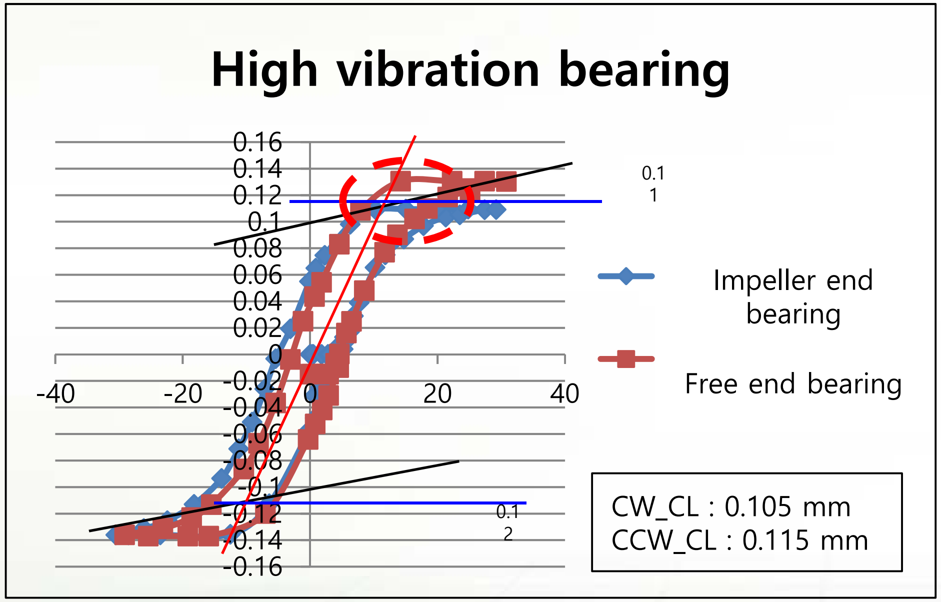


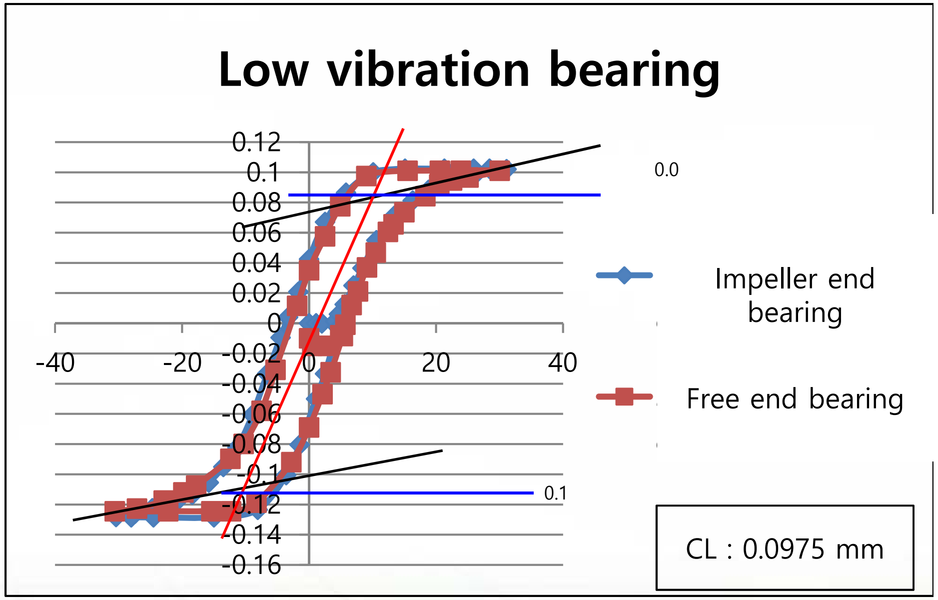




Root cause identification

Based on vibration data, it is decided to compare the bearing (nominal) clearances of three turboblowers with and without high subsynchronous vibrations



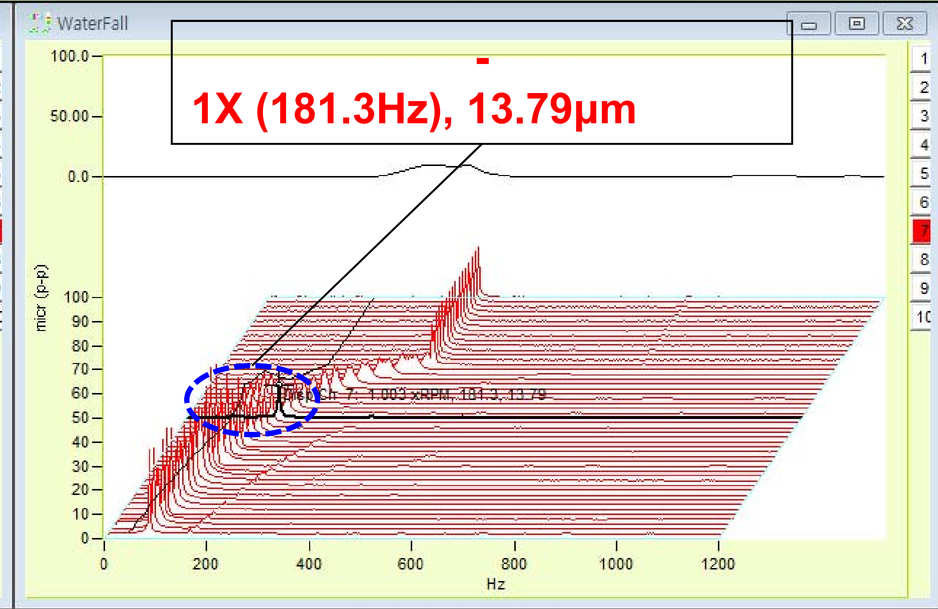


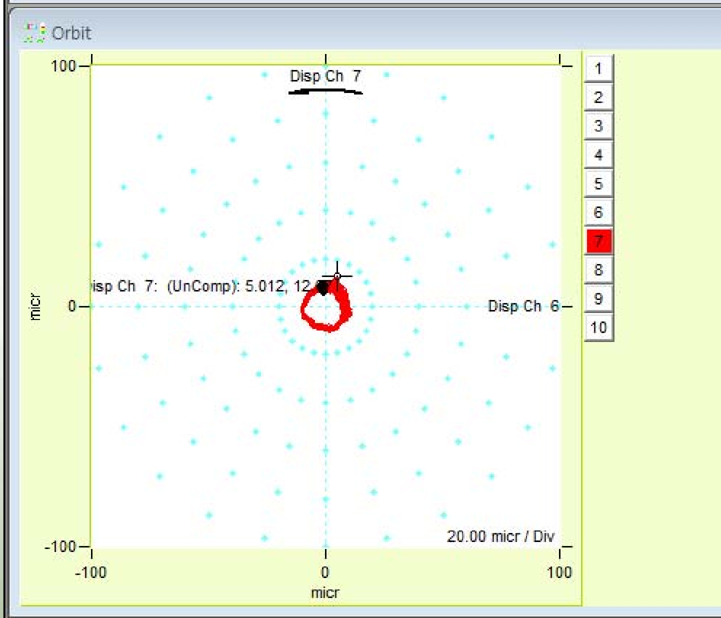
Data analysis and solution technique

- Free end bearing of the turboblower with high subsynchronous vibrations has larger clearance than recommended design clearance.

- Replacement of the used bearing with new one that has the recommended bearing clearance.

Vibration data after clearance revision

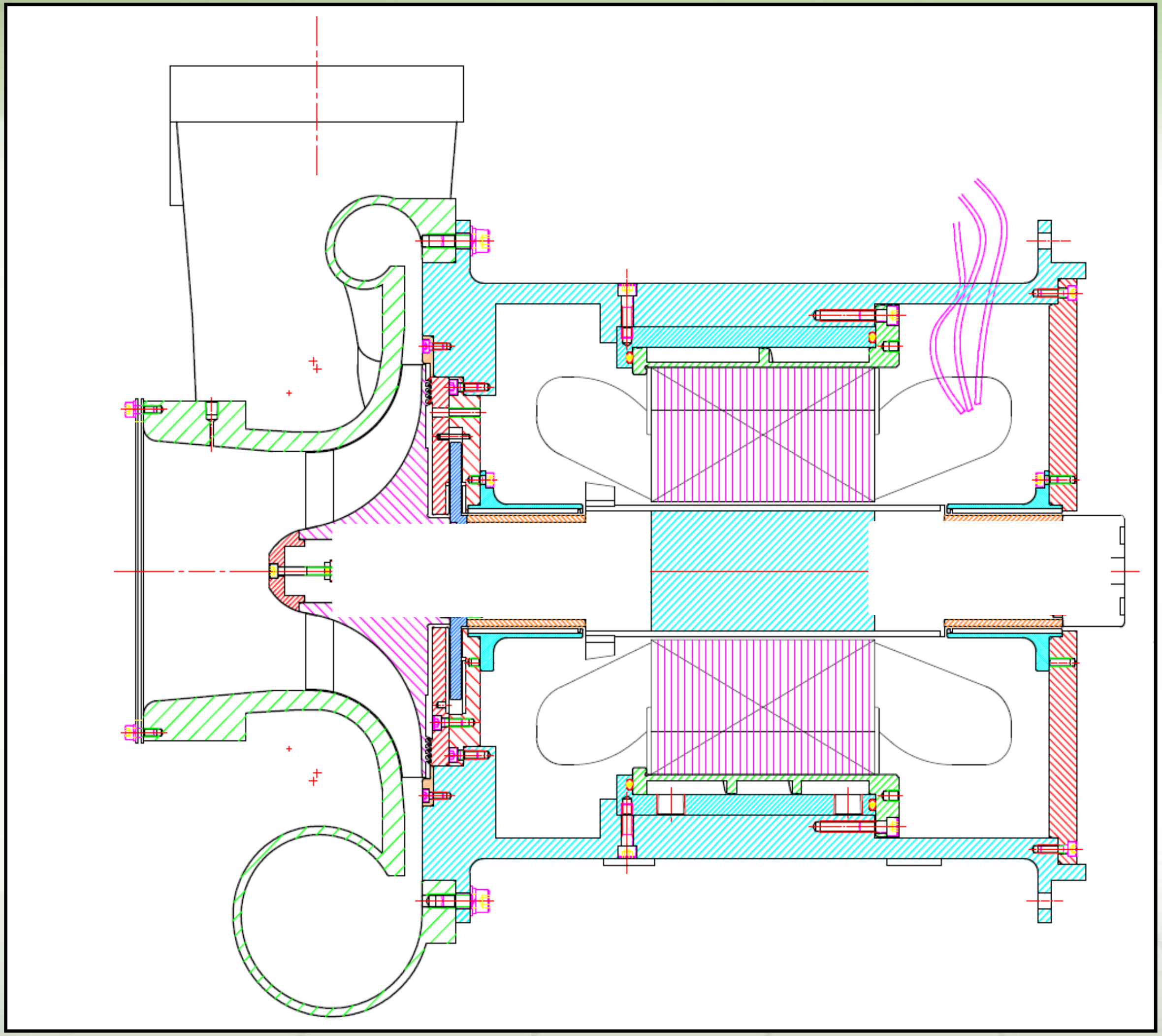




<sample B>

RESULT: Subsynchronous vibrations disappear and the overall vibration level is acceptable.

Turboblower under development

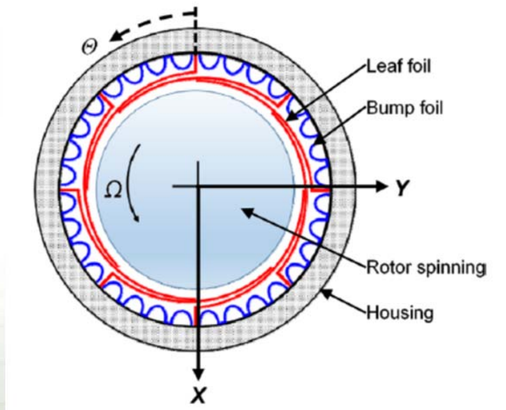


Single impeller blower

Motor power: 250 kW

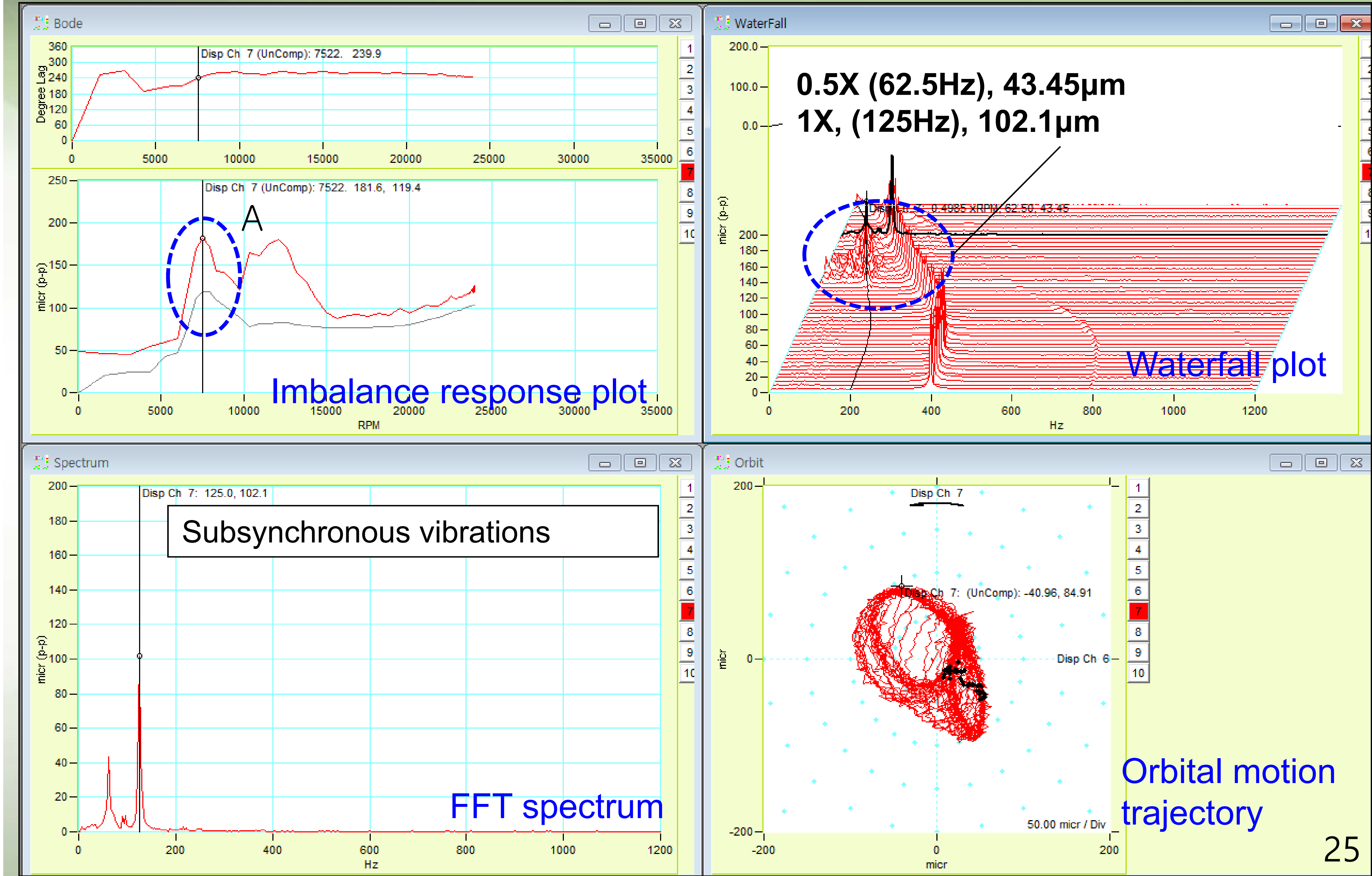
Motor type: Permanent magnetic Synchronous motor (PMSM)

Max. speed: 25,000 rpm



Multiple-leaf with backup bump GFBs

Measurement

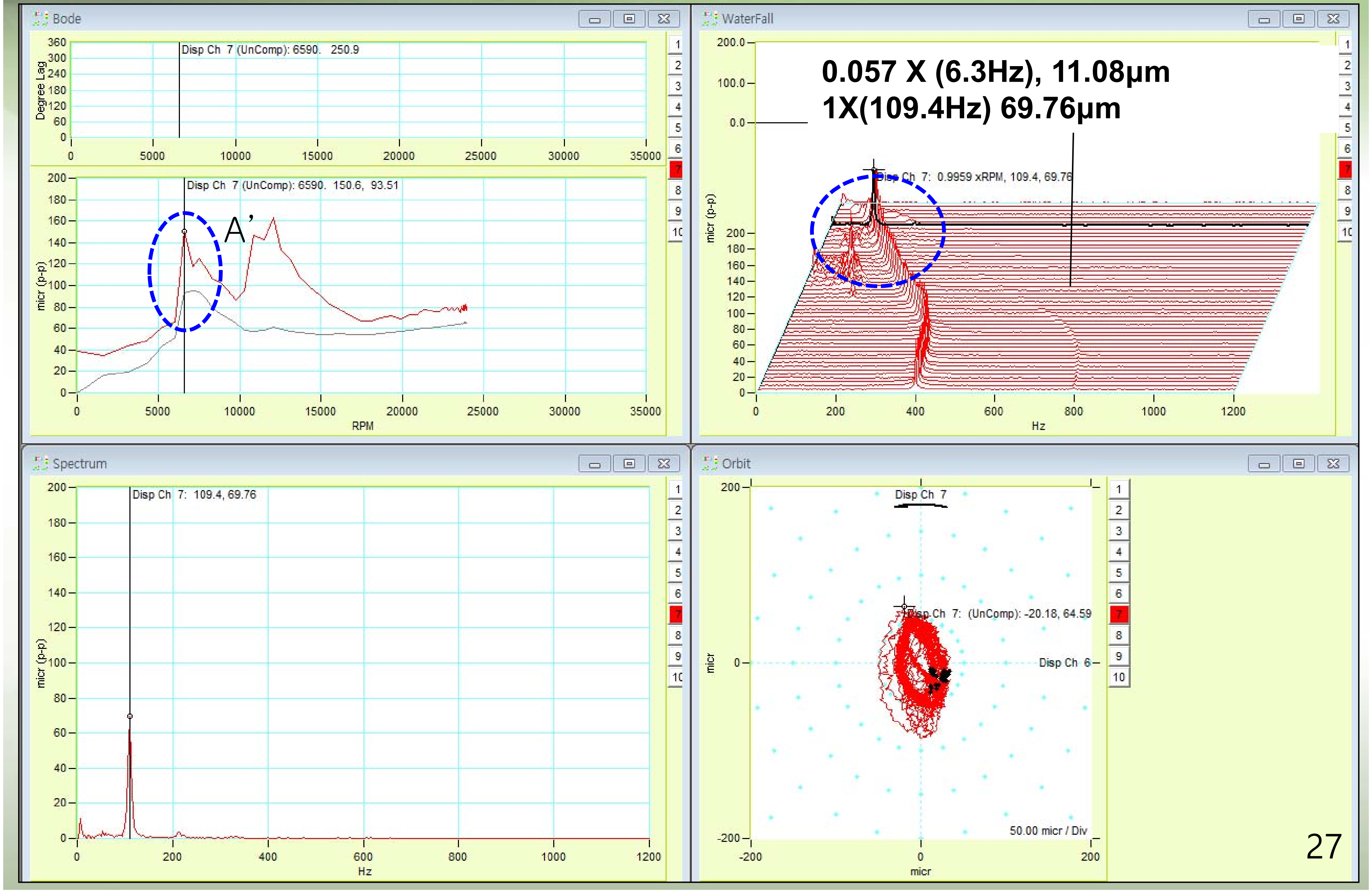


Data analysis and solution technique

- Based on vibration data, it was thought that subsynchronous vibrations are attributed to rotor rubbings caused by large rotor orbital motions.

- Therefore, it is decided to balance the rotor to reduce overall rotor motion amplitudes.

Vibration data after rotor balancing



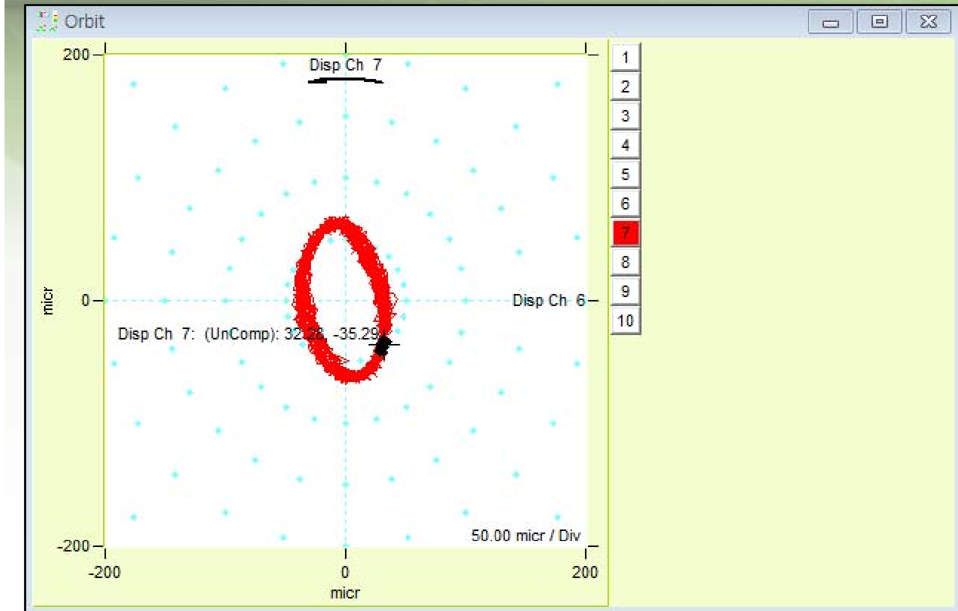
Data analysis and solution technique

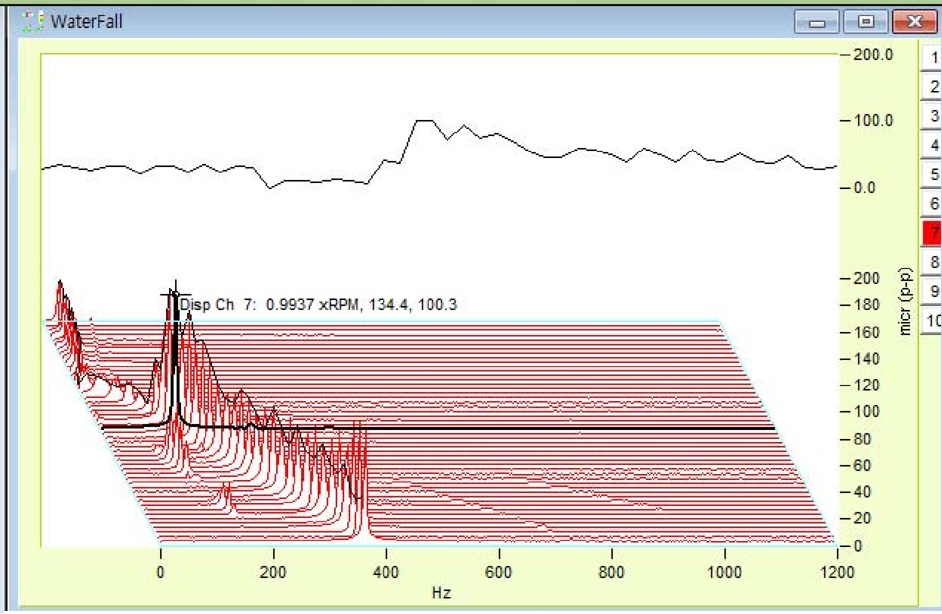
- After rotor balancing, synchronous vibration amplitude decreases from 100 µm to 60 µm at the top speed.

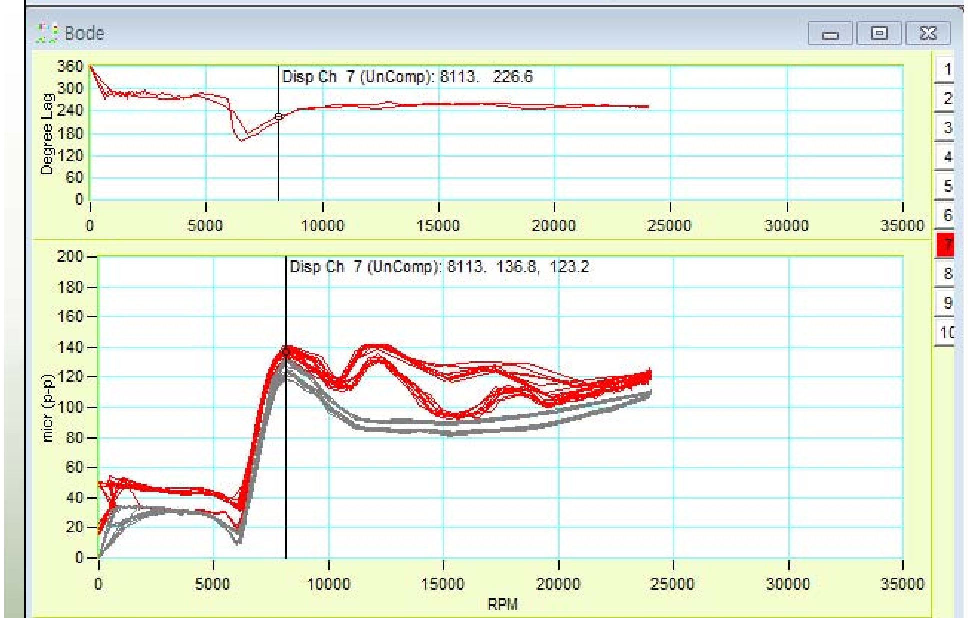
- But there are still subsynchronous vibration while rotor passing twice the critical speed.

- Therefore, it is decided to reduce the bearing clearance to increase its stiffness and the critical speed of the rotordynamic system.

Vibration data after clearance reduction







RESULT: Subsynchronous and overall vibration amplitudes reduce noticeably.

Lessons learned

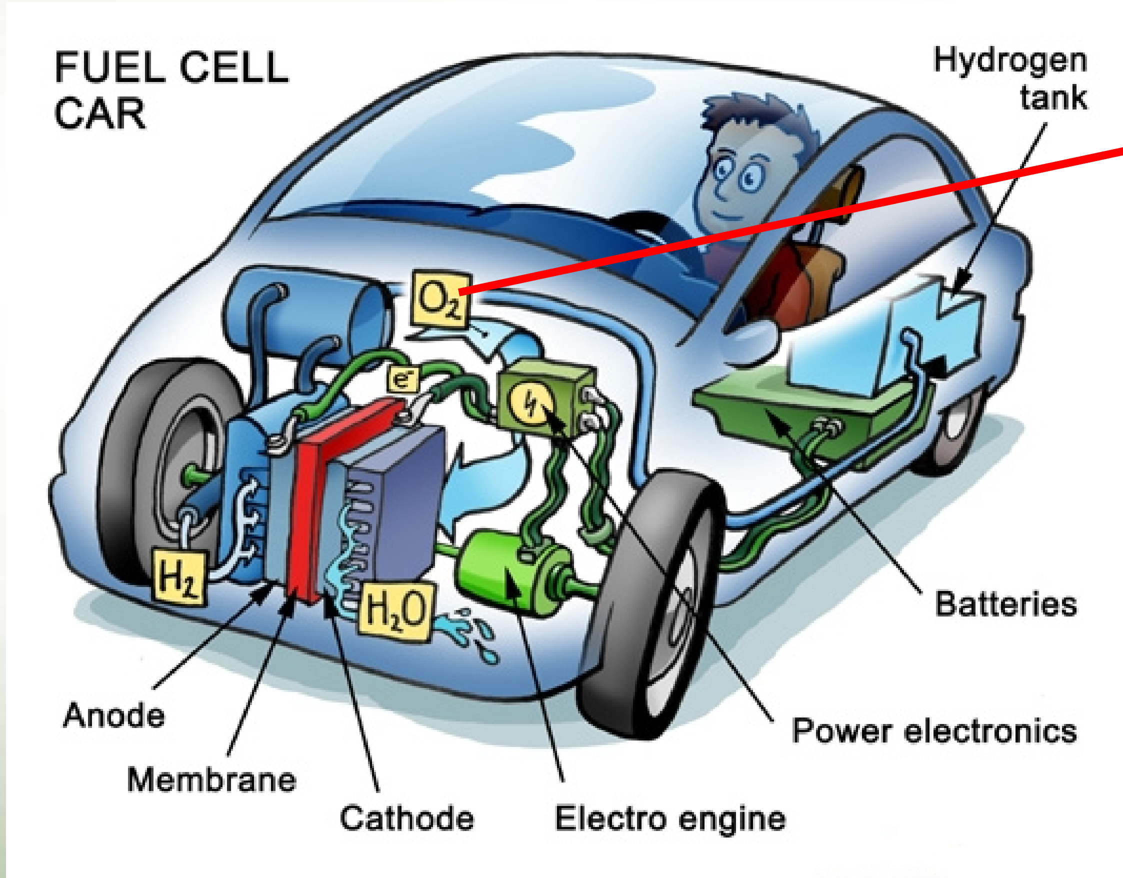
- Simple load vs. deflection test can estimate the nominal radial clearance of gas foil bearings (GFBs).

- Adjustment of radial clearance of GFBs can be a quick remedy to mitigate undesirable subsynchronous rotor vibrations.

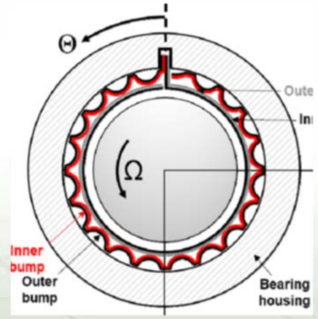
- Rotor balancing reduces synchronous and overall rotor vibrations. But, it may not be enough to remove subsynchronous rotor motions.

Case study 2

<u>Problem statement</u>: Air compressor for use in Fuel Cell Electric Vehicles (FCEVs) showed undesiable subsynchronous rotor vibrations

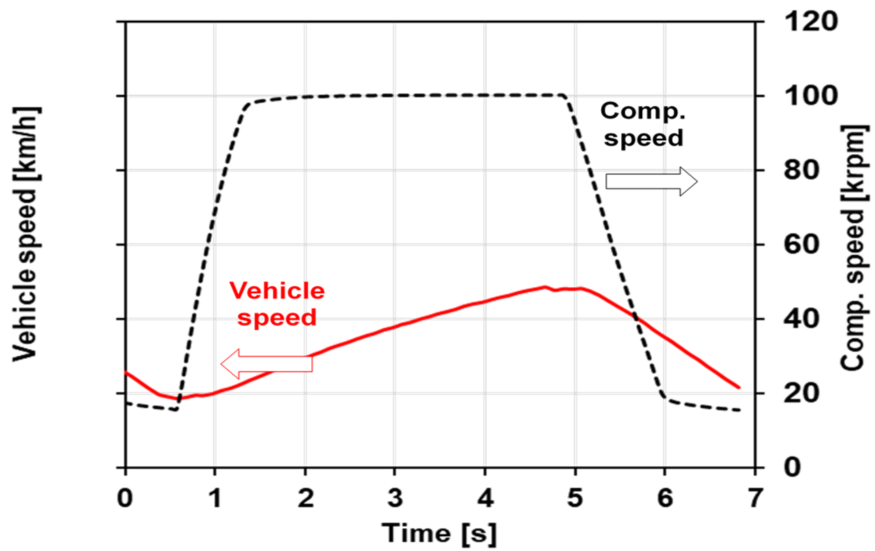


Turbo type air compressor

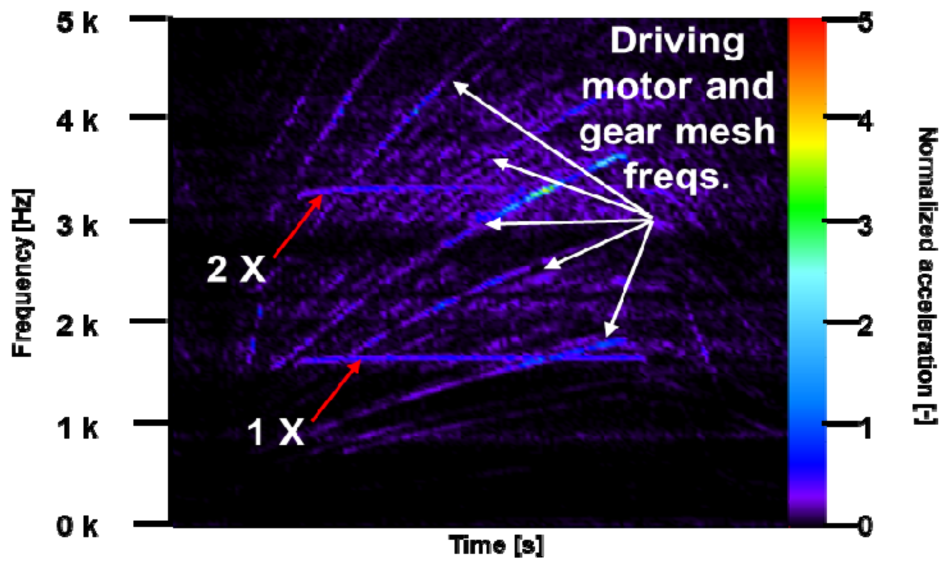


Gas foil bearings for rotordynamic system

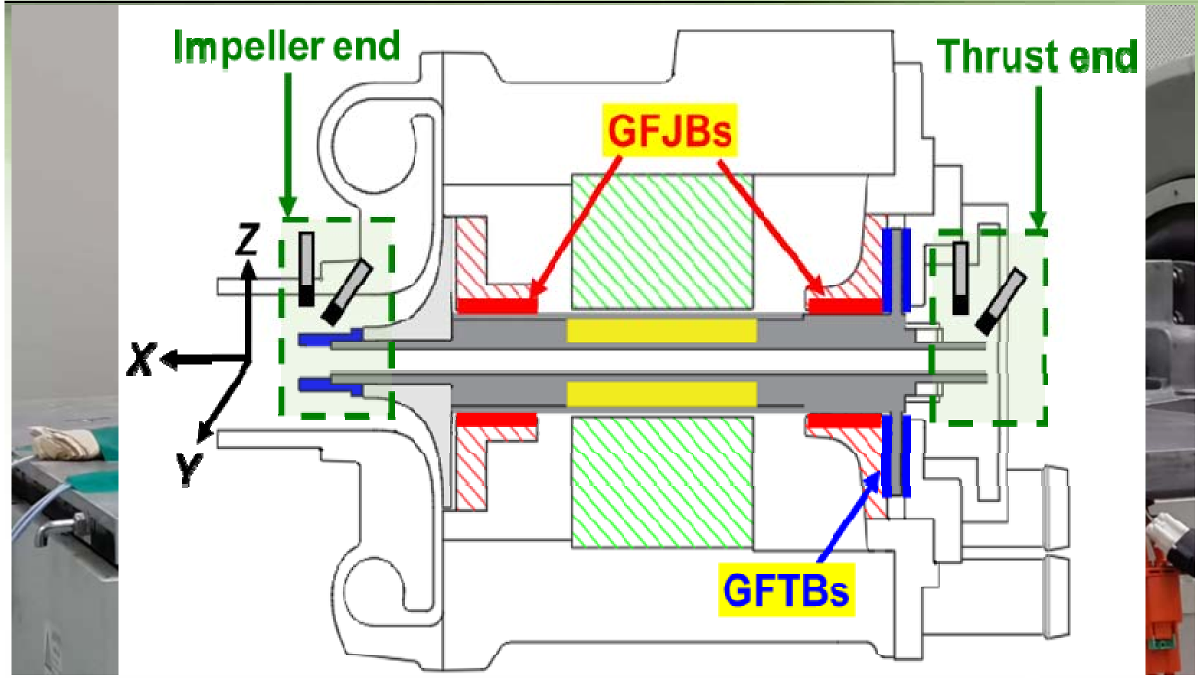
Fuel Cell Electric Vehicle (FCEV)



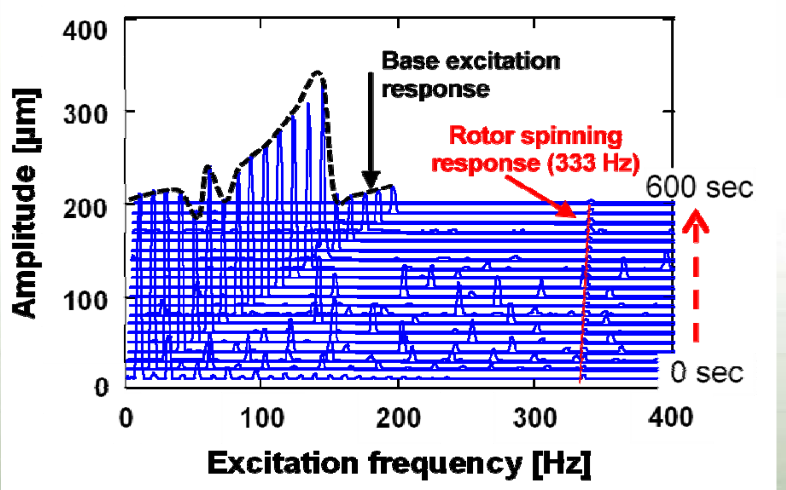
Air compressor is hung underneath fuel cell stack frame



Fuel cell air compressor



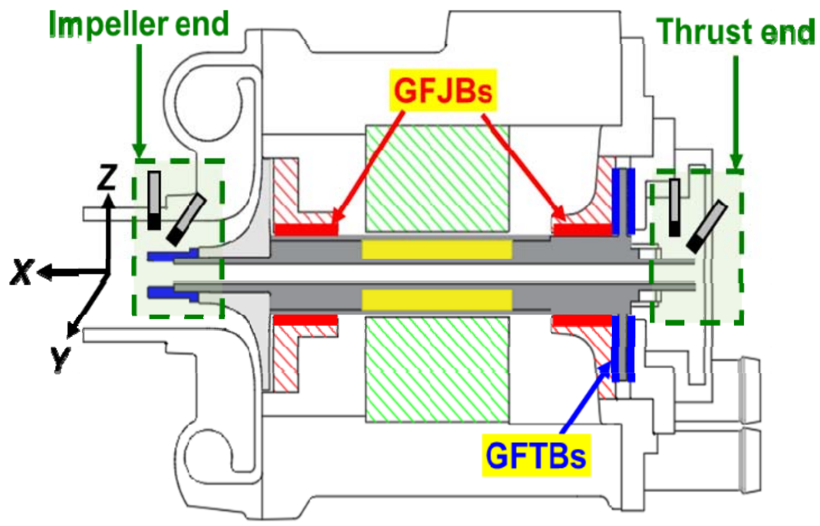
Air compressor test set up for frequency sweep excitation tests (Swept-sine measurement) in laboratory.



Eddy current type displacement sensors measure rotor vibrations and 3 axes accelerometers measure the casing accelerations up to 15 times the gravity.

ASME Paper GT2016-56282

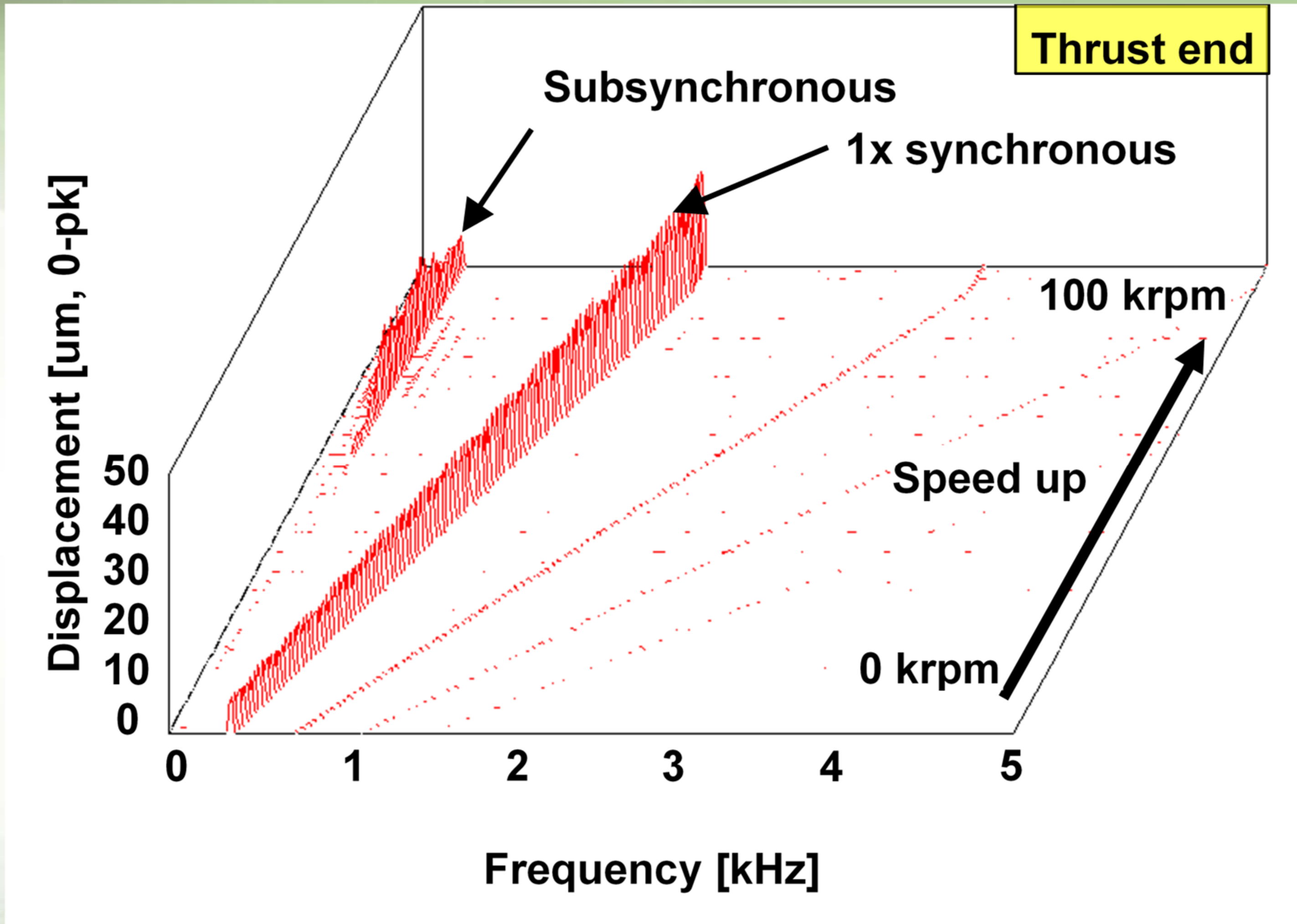
Measurement



Air compressor test set up for speed-up and coast-down laboratory tests.

Eddy current type displacement sensors measure rotor motions and optical tachometer record rotor speed.

Event: vibration data



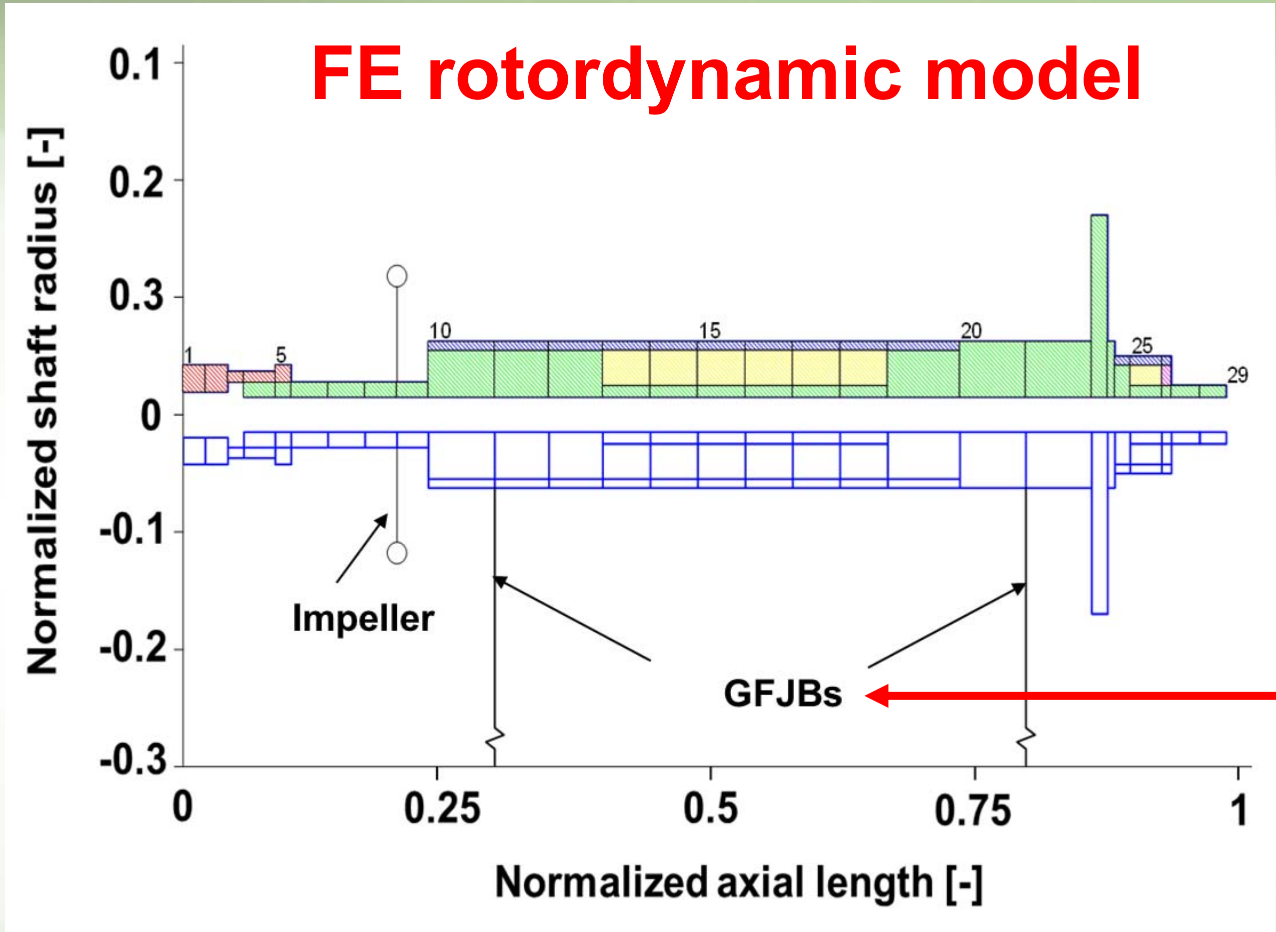
Large subsynchronous rotor motions associated with the natural frequency of rotor-bearing system

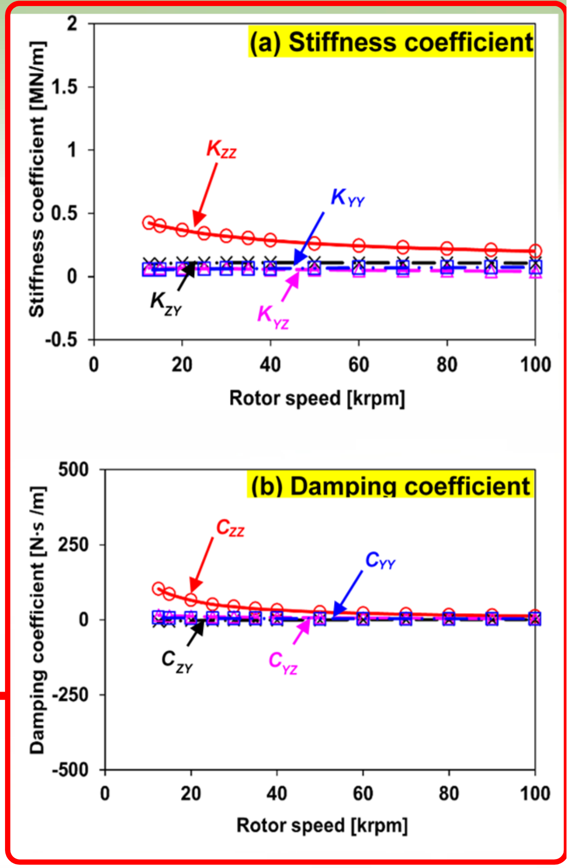
Analysis approach

- Based on the vibration data, it was decided to perform a rotordynamic analysis to find the possible causes of the subsynchronous vibration.

- From the analysis results, solution techniques will be discussed and applied.

Analysis

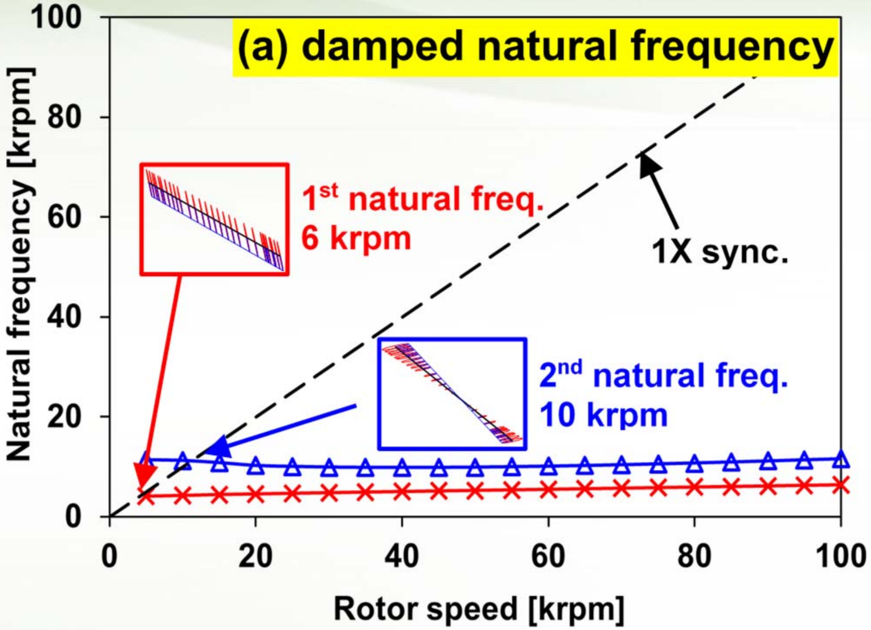


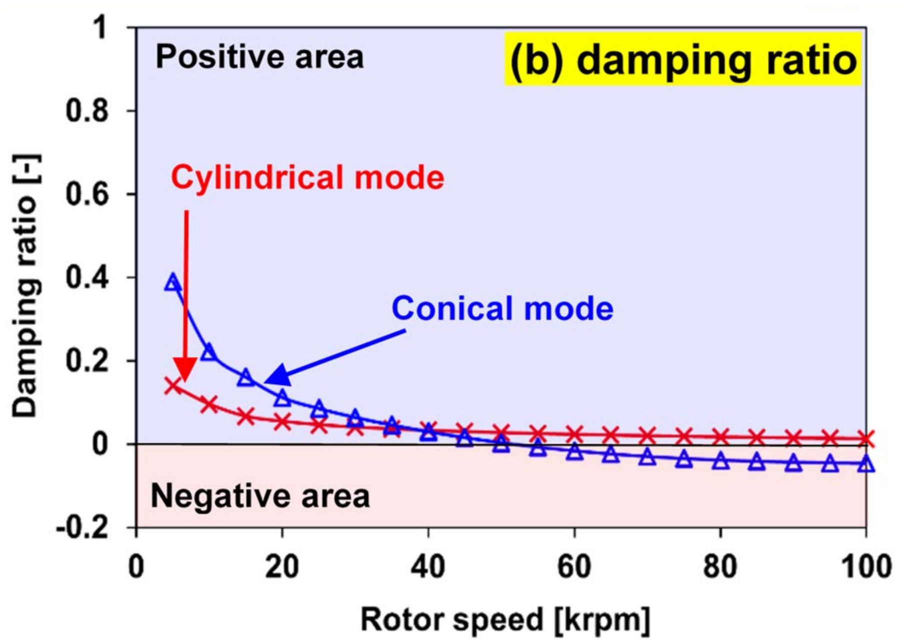


XIrotor (rotordynamic software) aids to develop rotordynamic model integrating gas foil bearing dynamic coefficients.

Analysis results

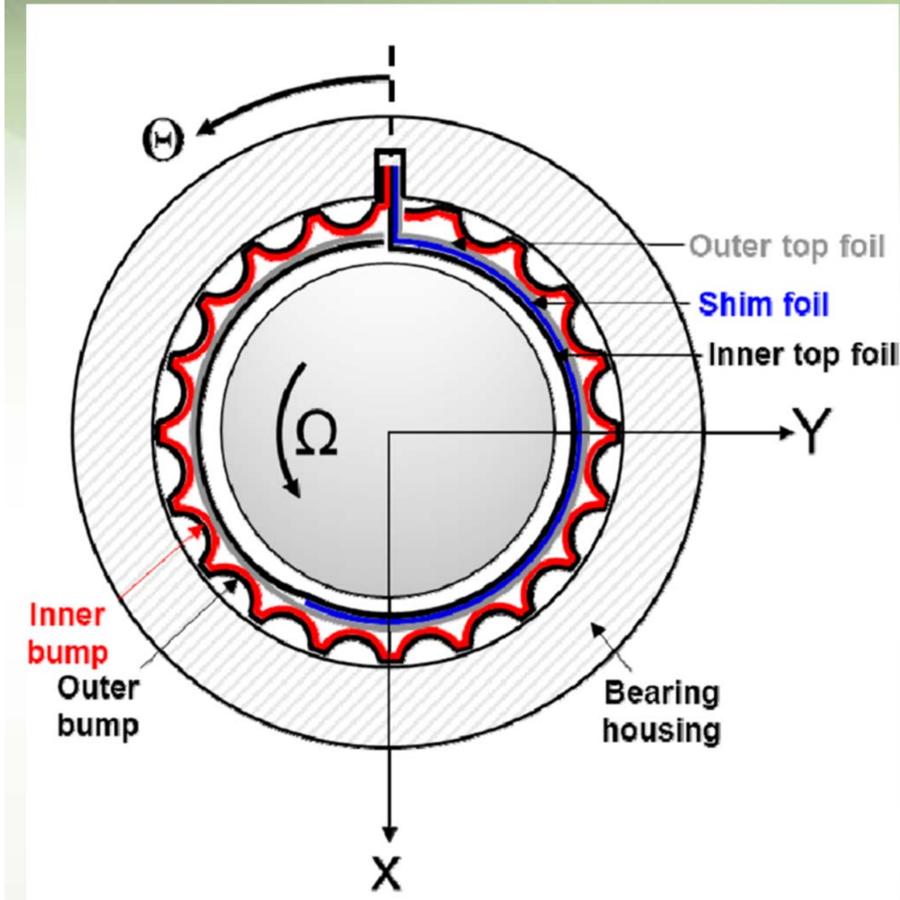
Eigen value analysis

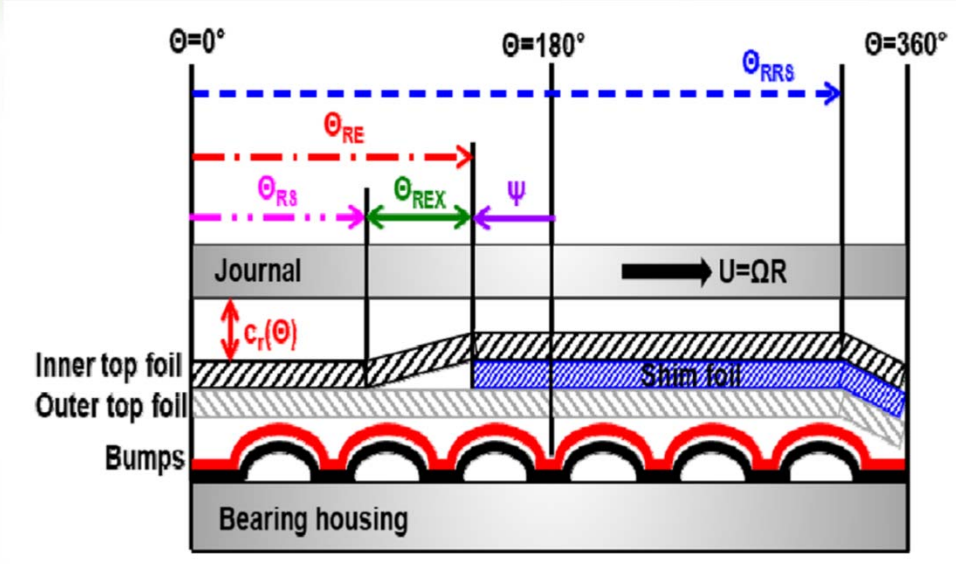




Damping ratio for 2nd natural mode of rotordynamic system becomes negative above 50 krpm.

Solution technique

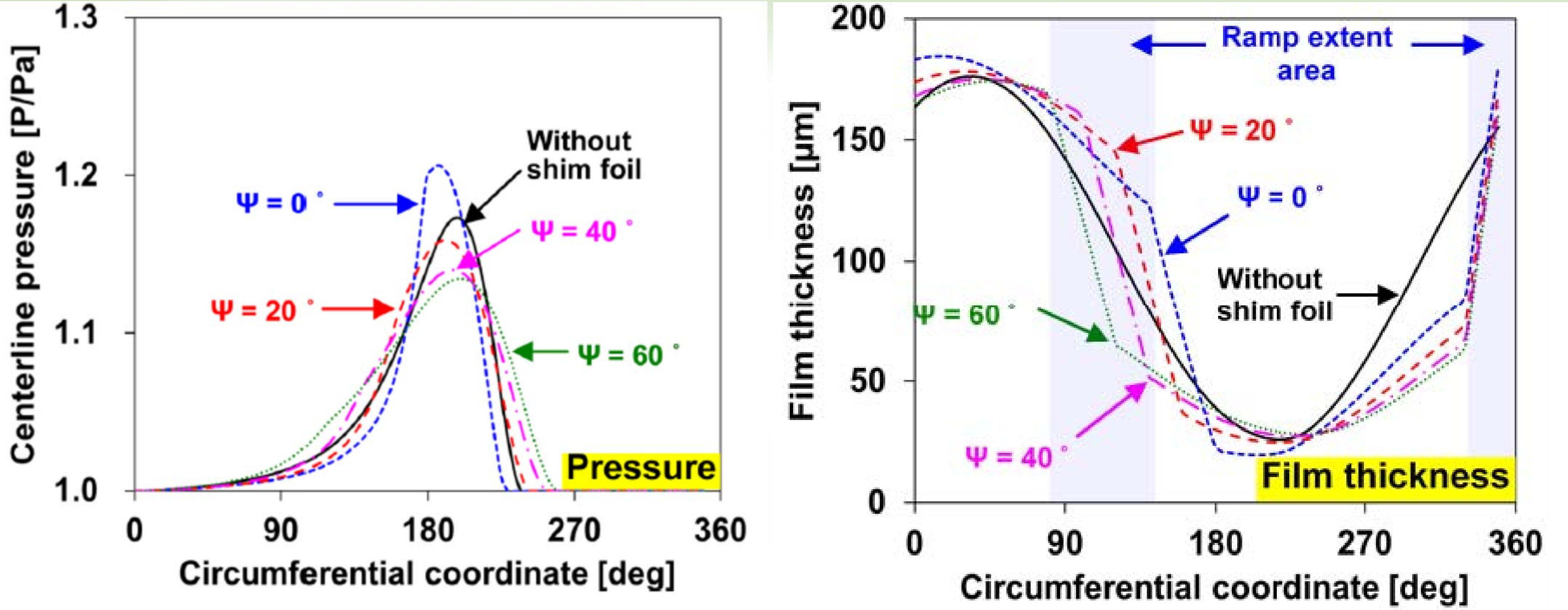




To enhance hydrodynamic pressure, a shim foil with the arc length of a fraction of bearing circumference is inserted between top foil and bump strip layer.

Analysis results

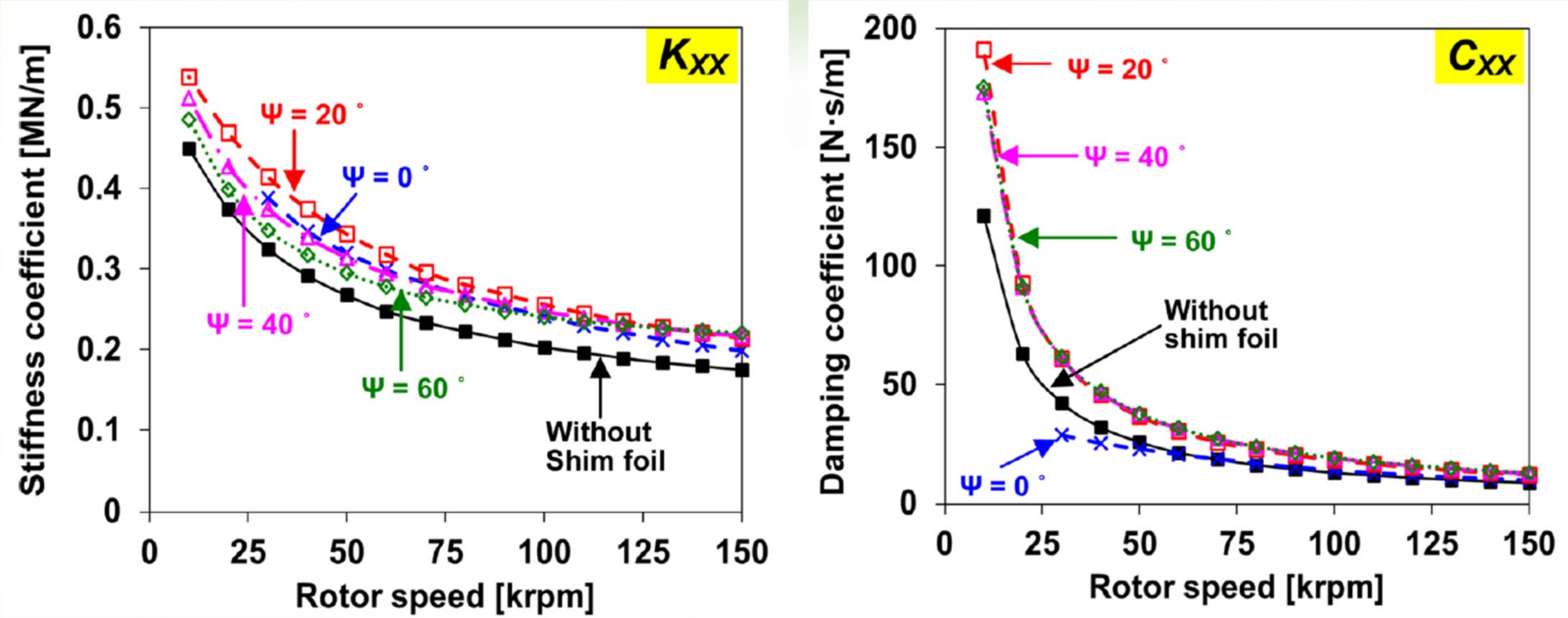
Bearing pressure and film thickness



Predictions show that shim foil generally broaden hydrodynamic pressure as well as min. film thickness zones in circumferential direction.

Analysis results

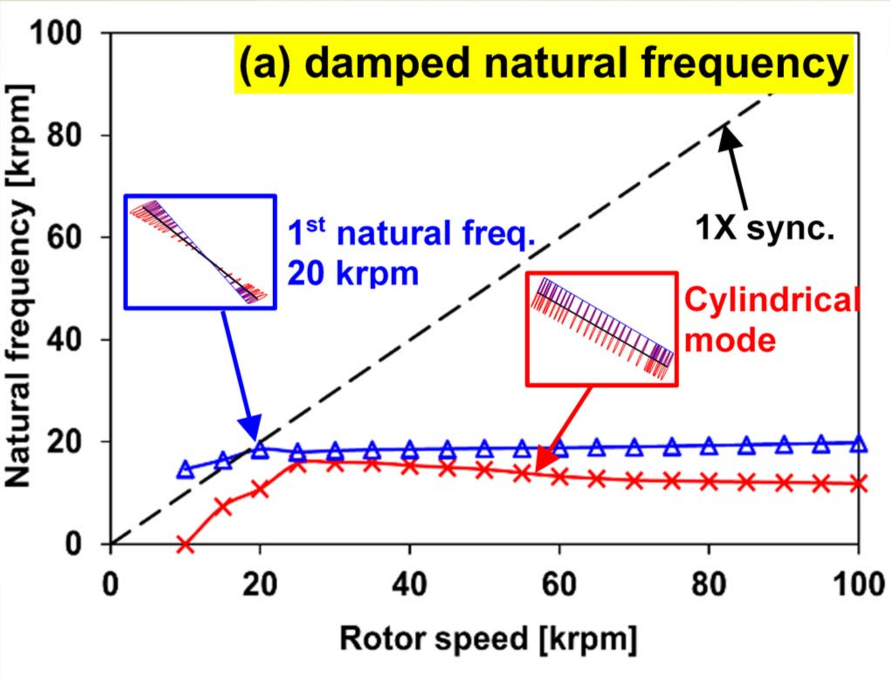
Bearing dynamic coefficients

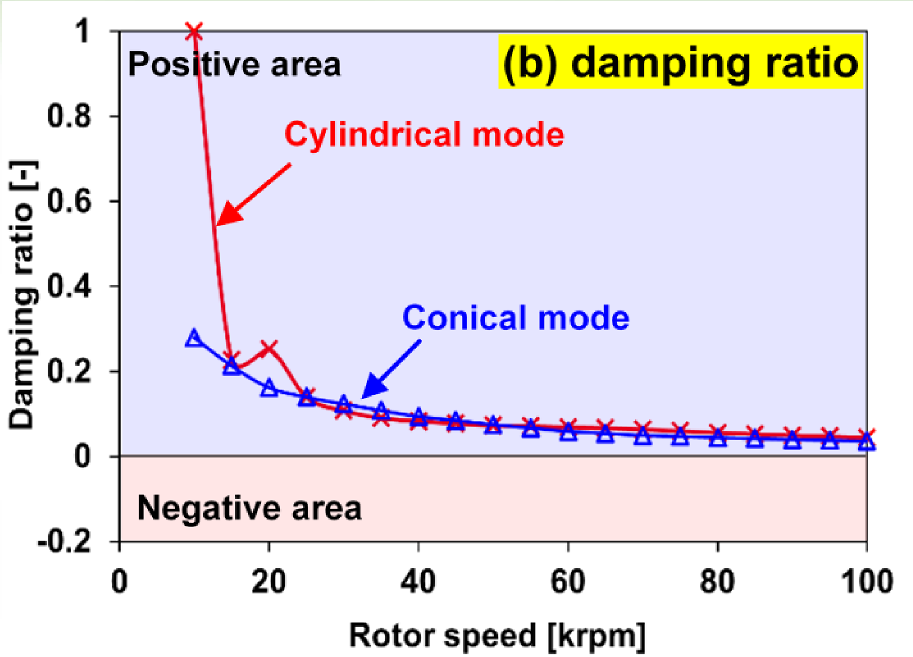


Shim foil generally increases both direct stiffness and damping coefficients.

Analysis results

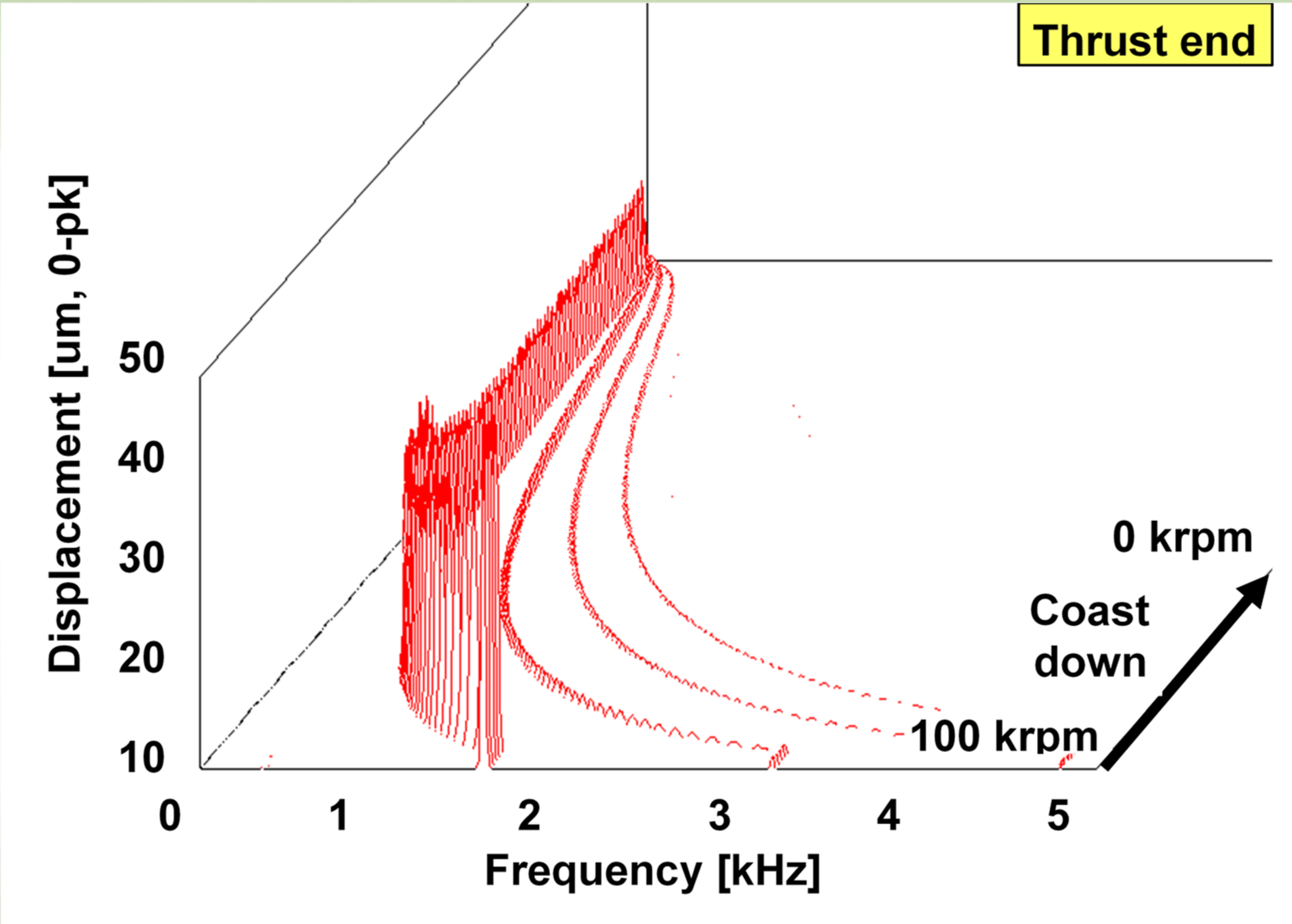
Eigen value analysis





Damping ratio for the 2nd natural mode of rotordynamic system becomes positive up to 100 krpm, implying rotordynamically stable system.

Vibration data after shim foil installation



Lessons learned

- Installation of a shim foil between top foil and bump strip layer produces hydrodynamic edge and enhances hydrodynamic pressure generation.

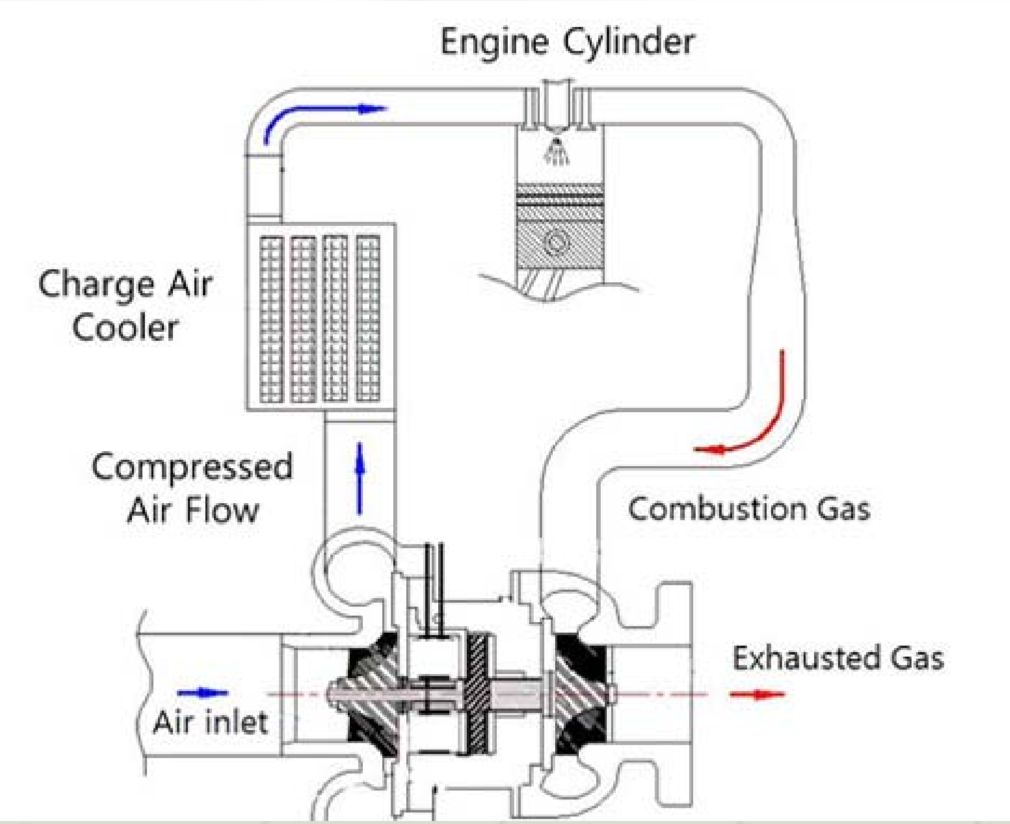
- Simple and practical method for fabrication of shim foil into GFB at low cost is very important for commercial applications.

- Enhanced hydrodynamic pressure and increases in stiffness and damping result in favorable effects on rotordynamic stability.

- Rotordynamic analysis using GFB model predictions was very helpful to find root cause of the problem and it aids to find solutions too.

Case study 3

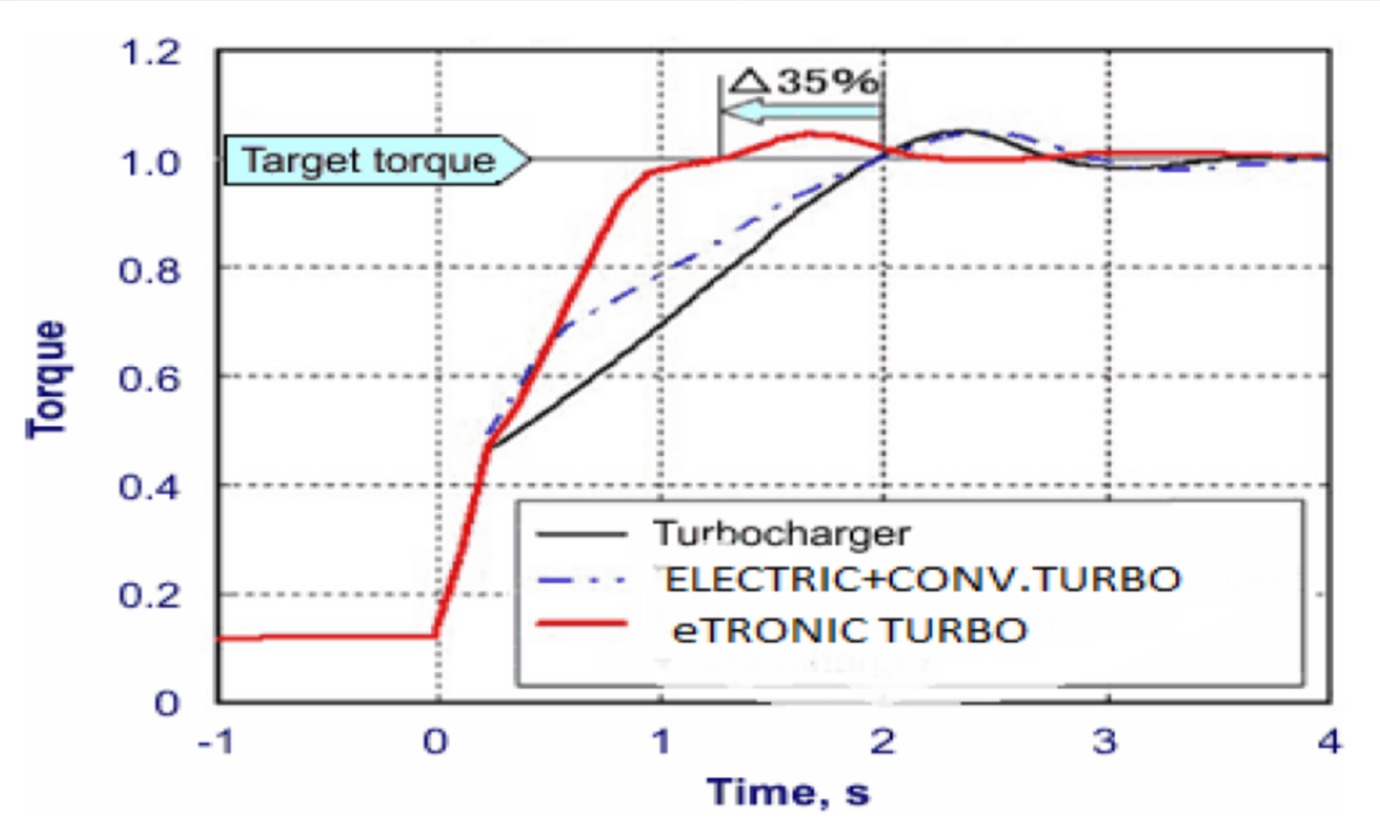
Problem statement: Electric motor for assistant electric superchargers shows large amplitude rotor vibrations



Turbocharger for internal combustion engine

https://www.americanmuscle.com/fox-body-mustang-turbocharger-guide.html

Electric turbocharger

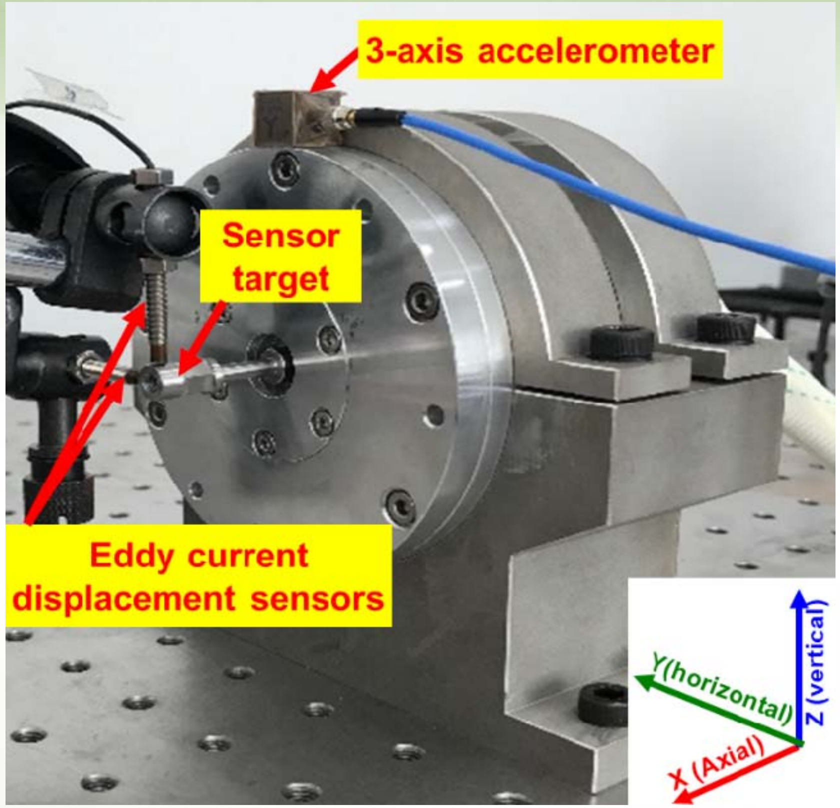


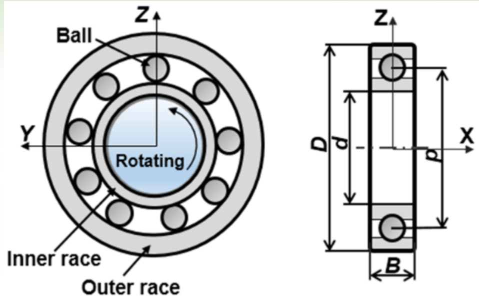
Assistant electric supercharger aids to minimize response time (turbo lag) of turbocharger and reach max. engine toque in shorter time.

Sivaraman, M, et al. (2018) Design and Performance Analysis on E-Tronic Turbocharger to eliminate Turbo Lag

High speed electric motor

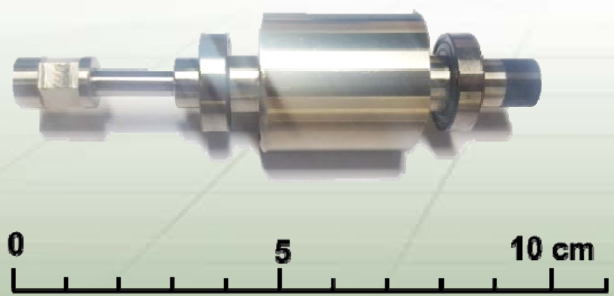
High speed electric motor for assistant electric superchargers



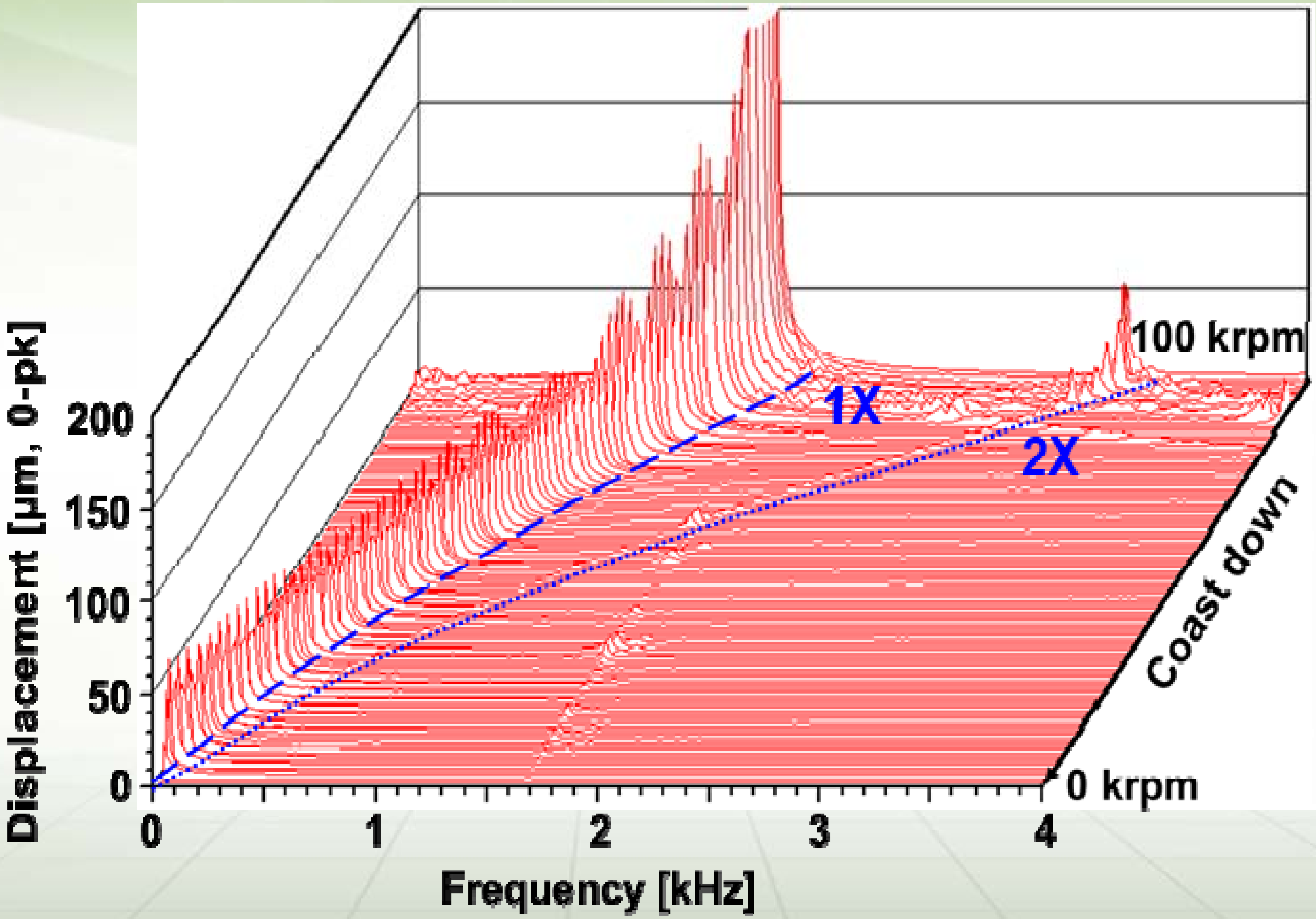


High speed deep groove ball bearing (Max. speed: 97,000 rpm for grease lubrication)

Retail price < 5 USD



Event: vibration data



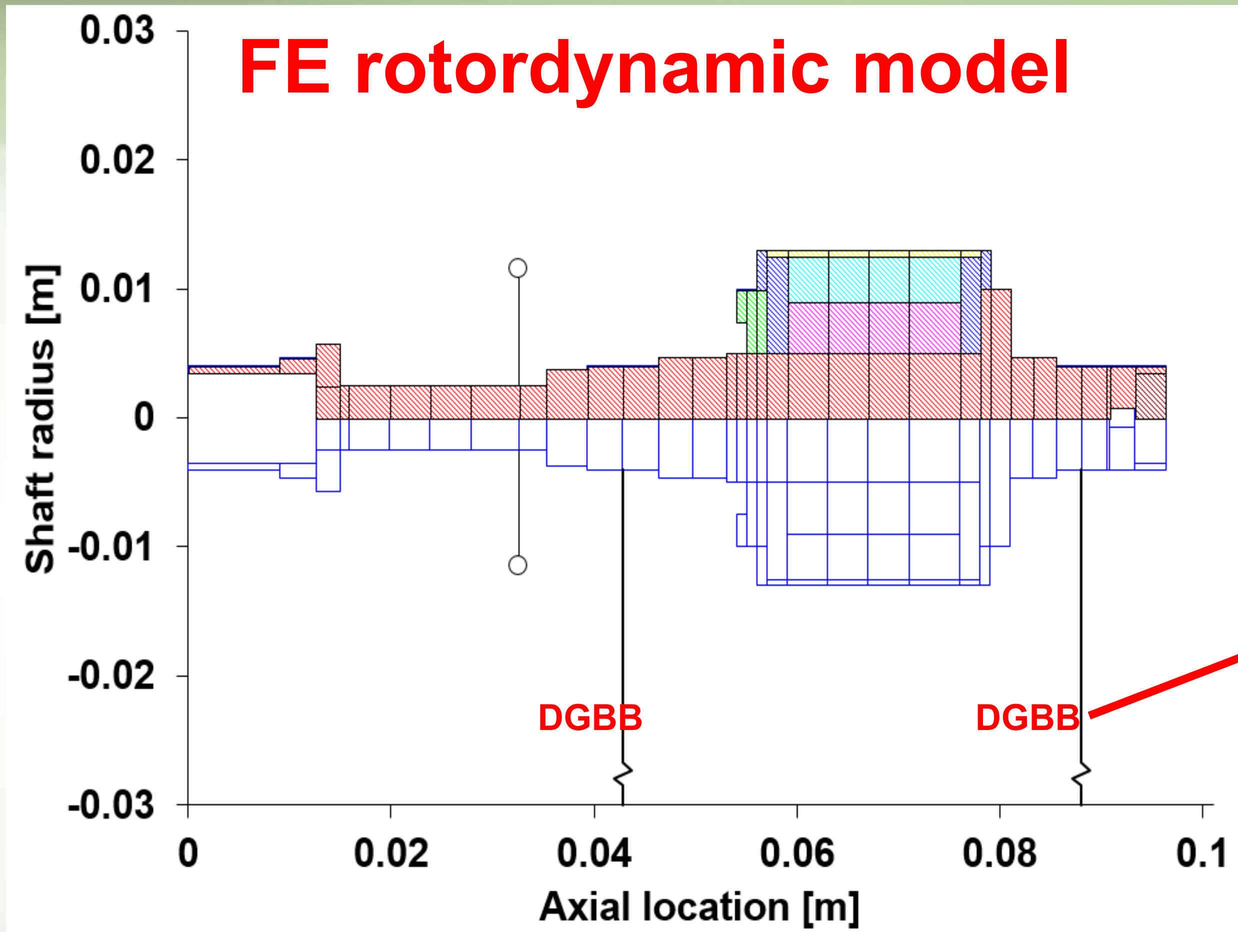
Analysis approach

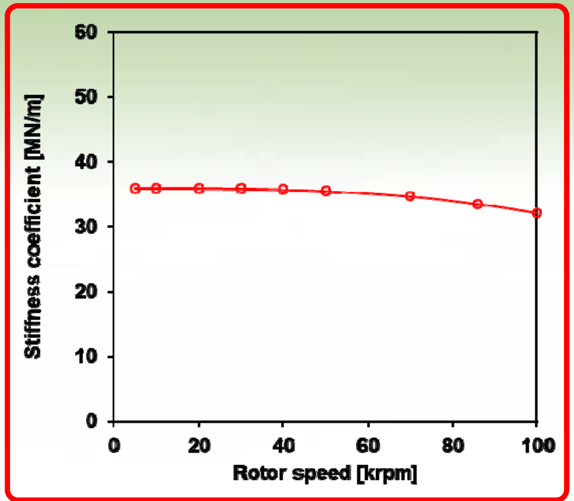
- Vibration data show large amplitude synchronous rotor motion while approaching max. speed.

- Based on the vibration data, it was decided to perform a rotordynamic analysis to find the possible causes of the large synchronous vibration.

- From the analysis results, problem solution will be discussed and validated.

Analysis

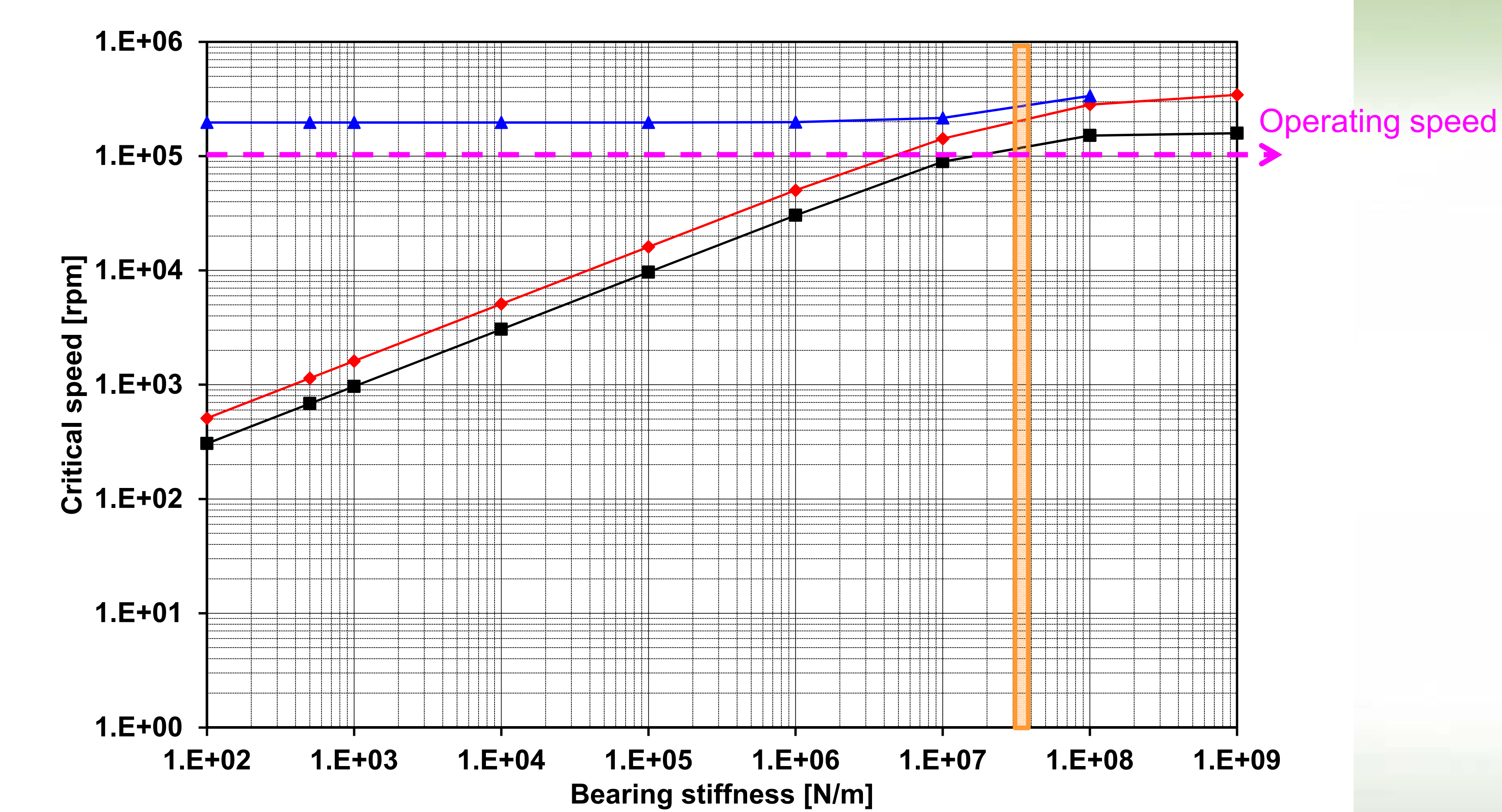




XIrotor (rotordynamic software) aids to develop rotordynamic model integrating ball bearing dynamic coefficients.

Analysis results

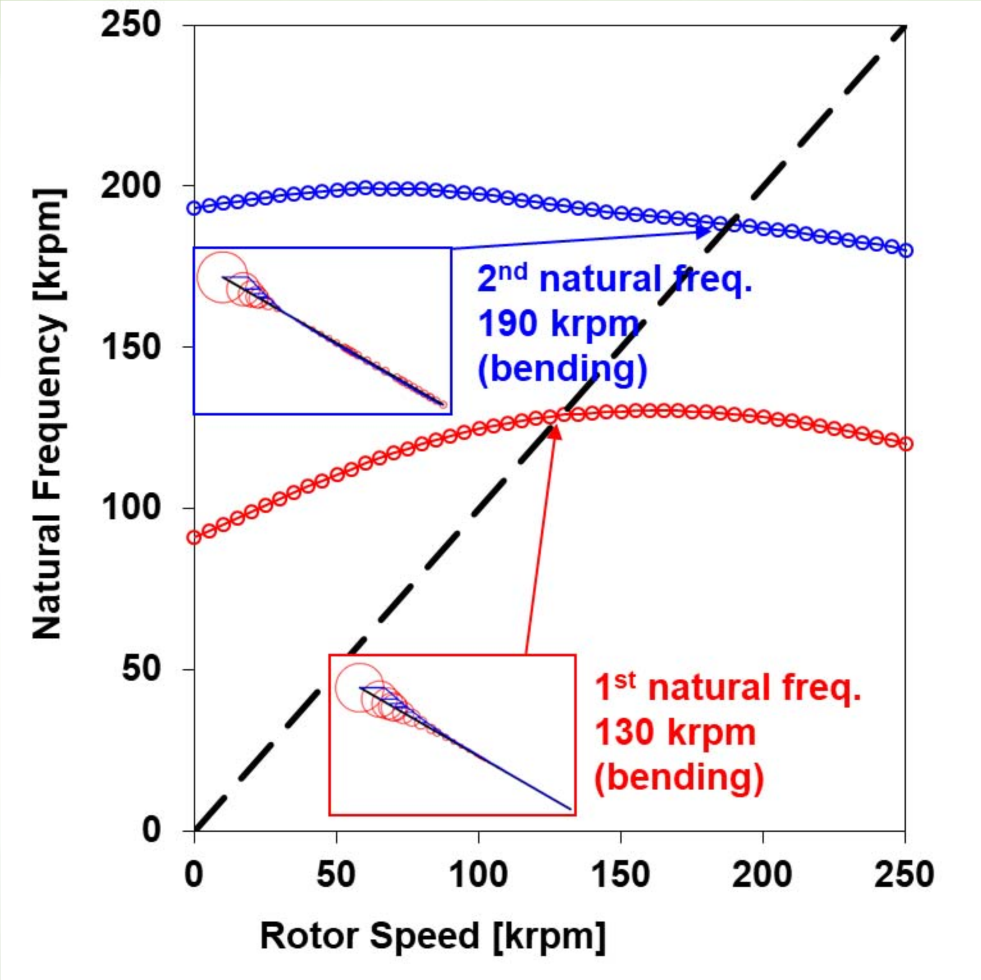
Critical speed map



For the bearing stiffness, 1st natural frequency is close to operating speed of 100,000 rpm.

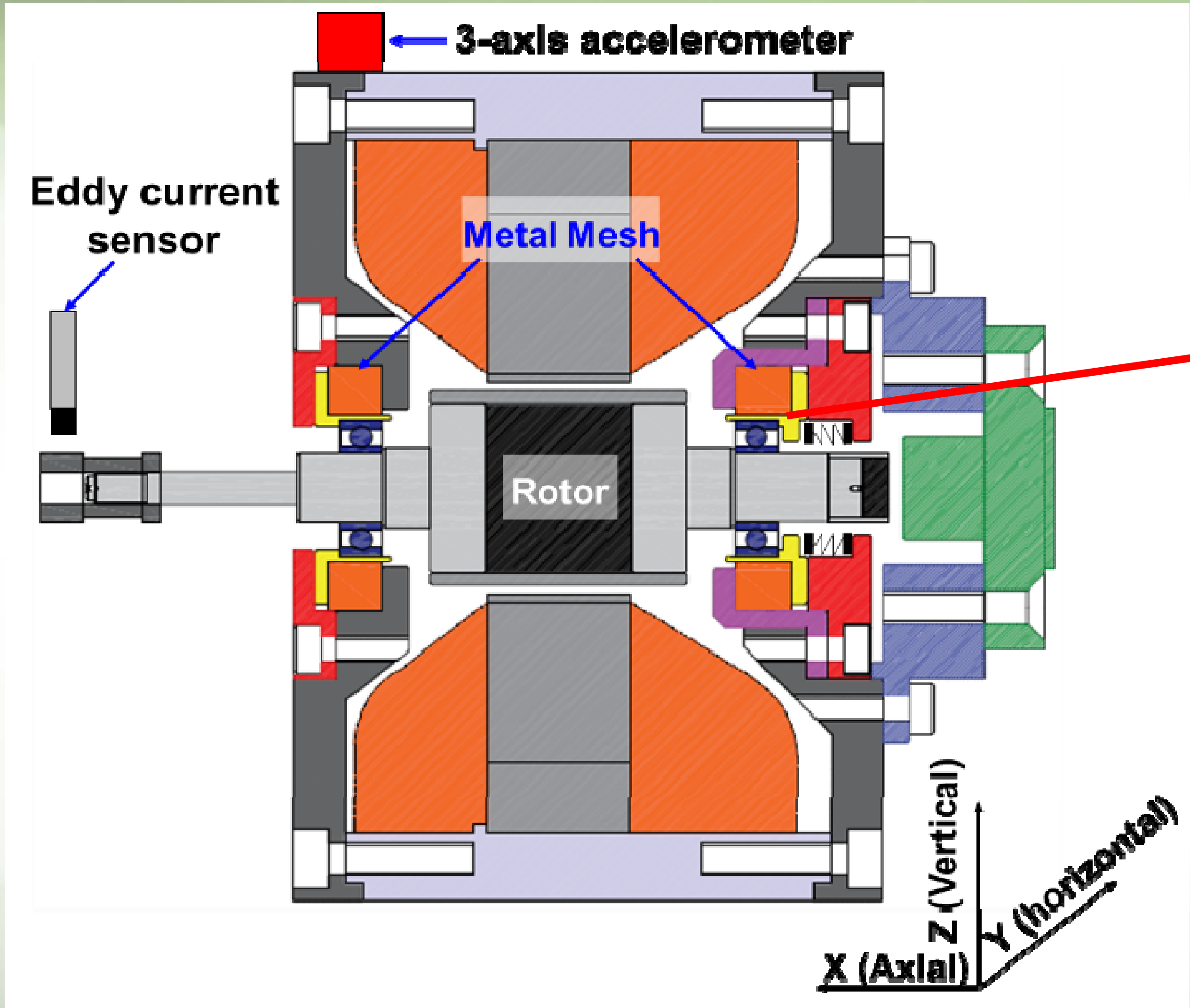
Analysis results

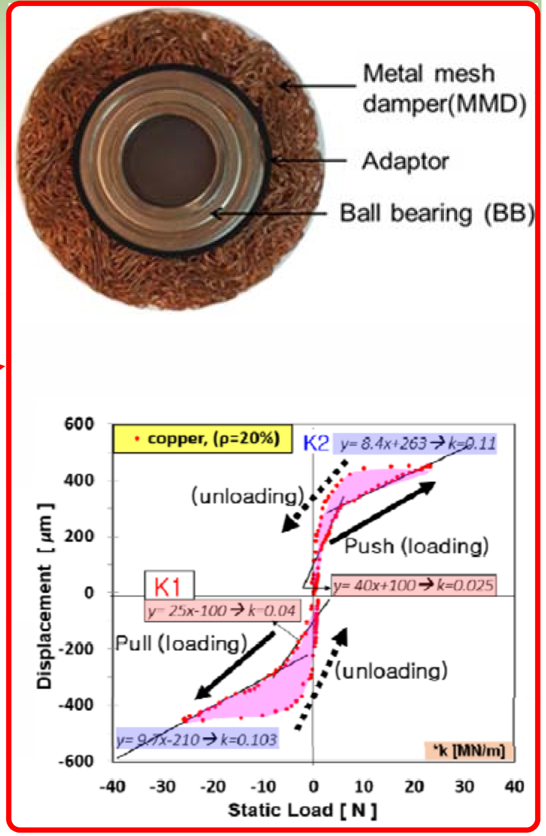
Damped natural frequency



Predicted natural frequencies and mode shapes imply large synchronous rotor motion due to bending mode at the left end of the motor.

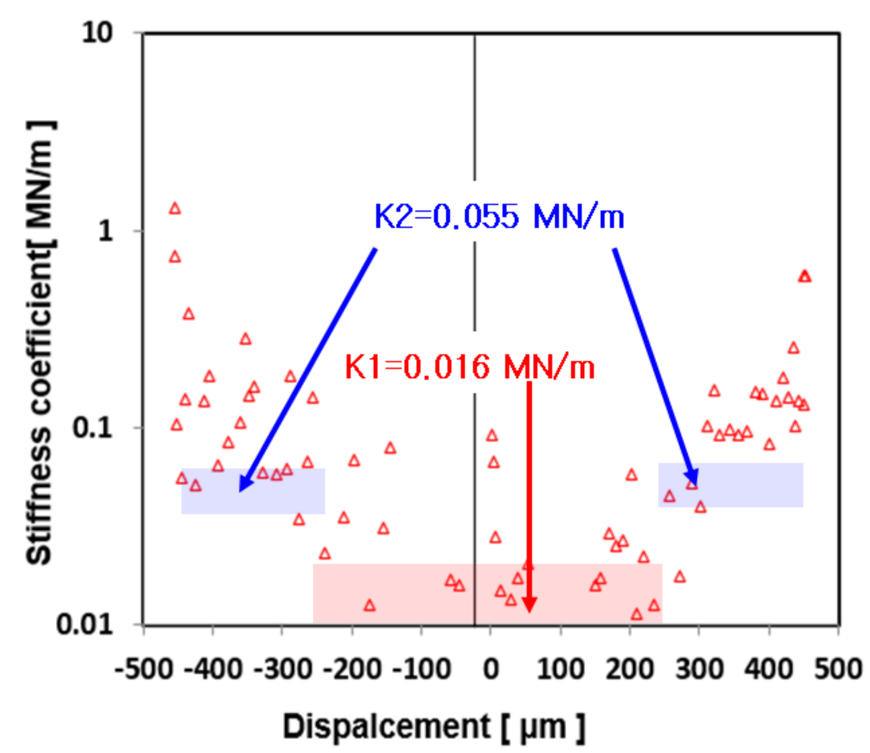
Solution approach 1

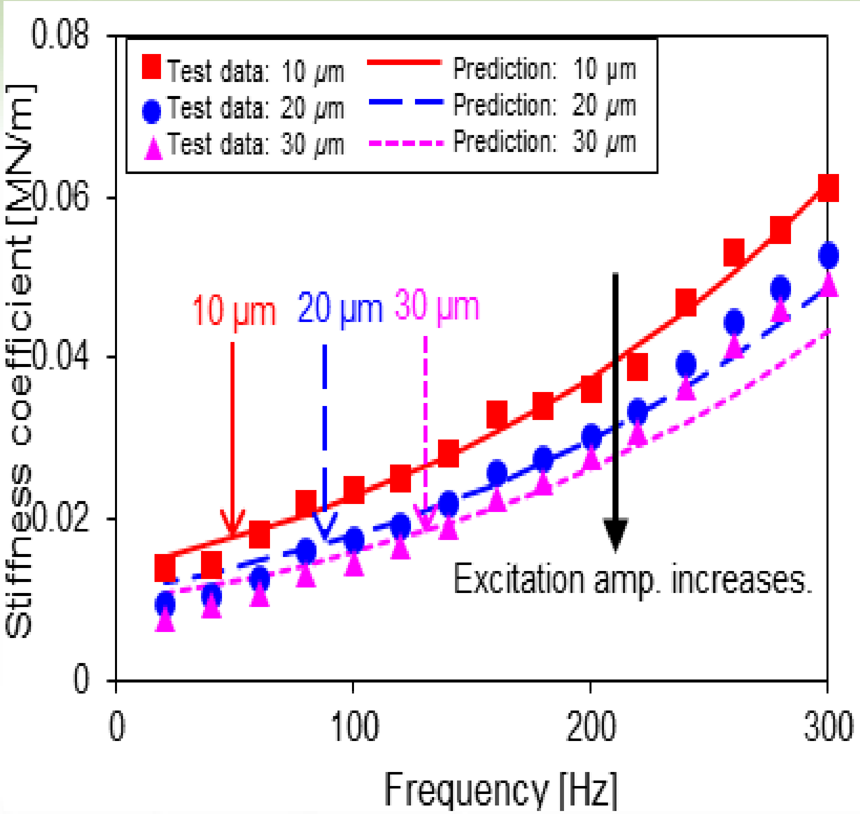




Installation of metal mesh damper (MMD).

Metal mesh damper

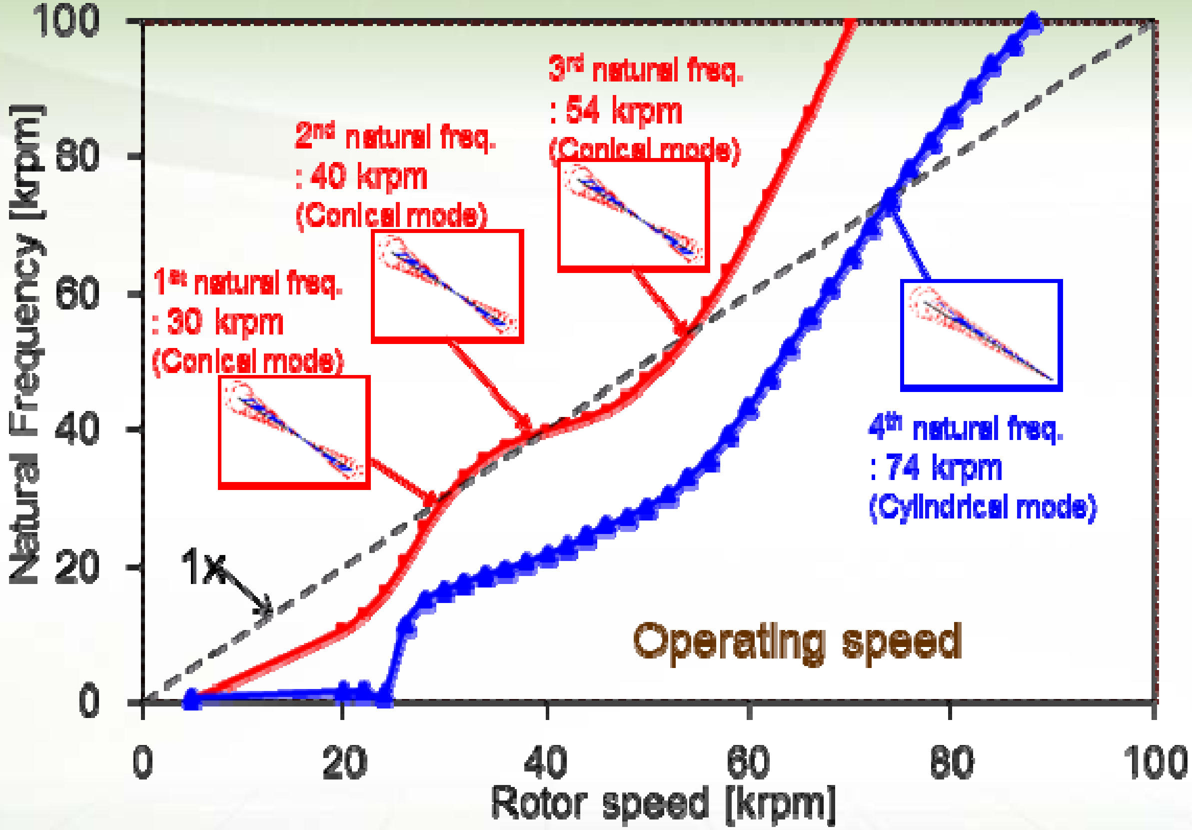




Metal mesh damper shows relatively low stiffness than ball bearing. => Curve-fit predicts stiffness coefficients.

Analysis results

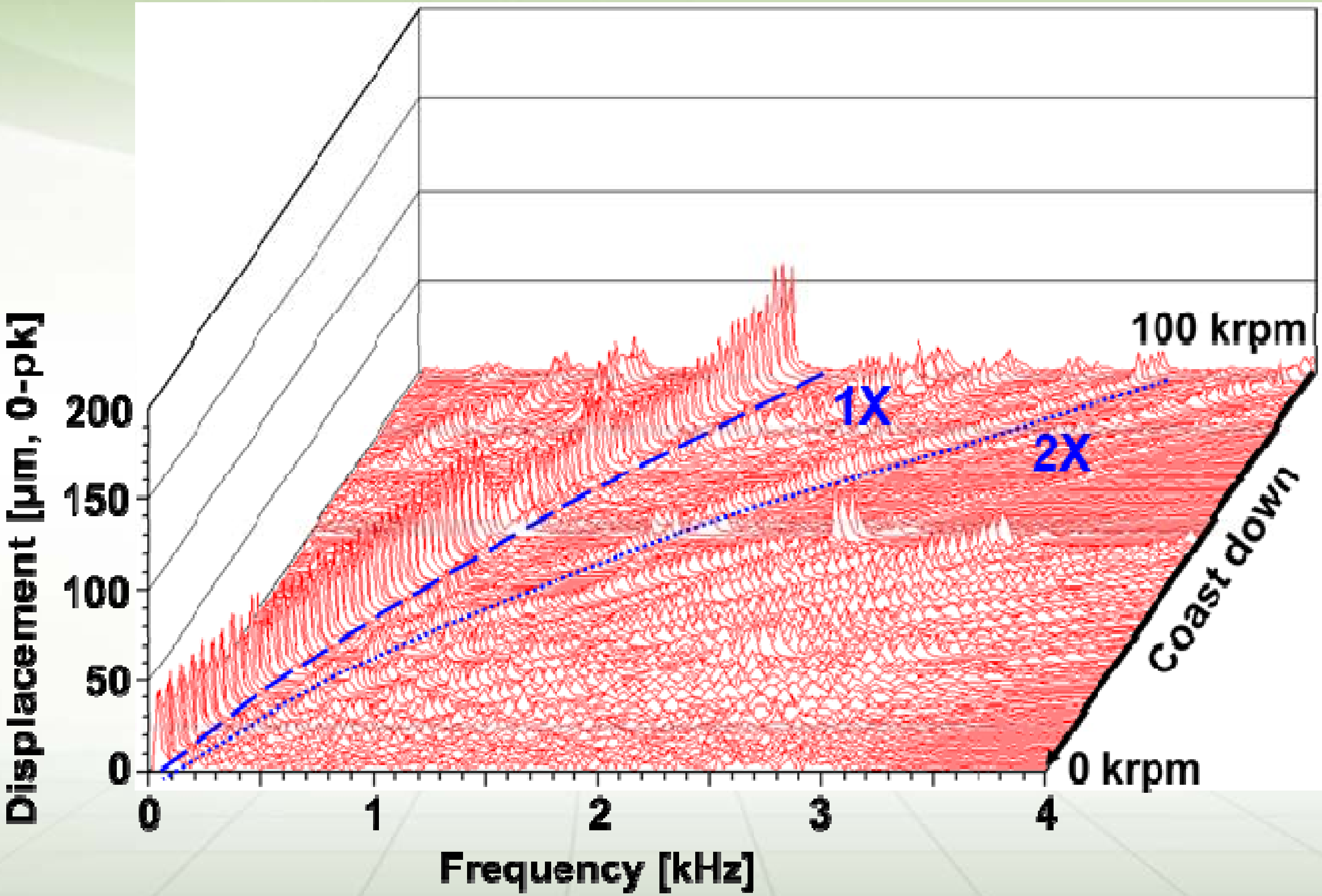
Eigen value analysis



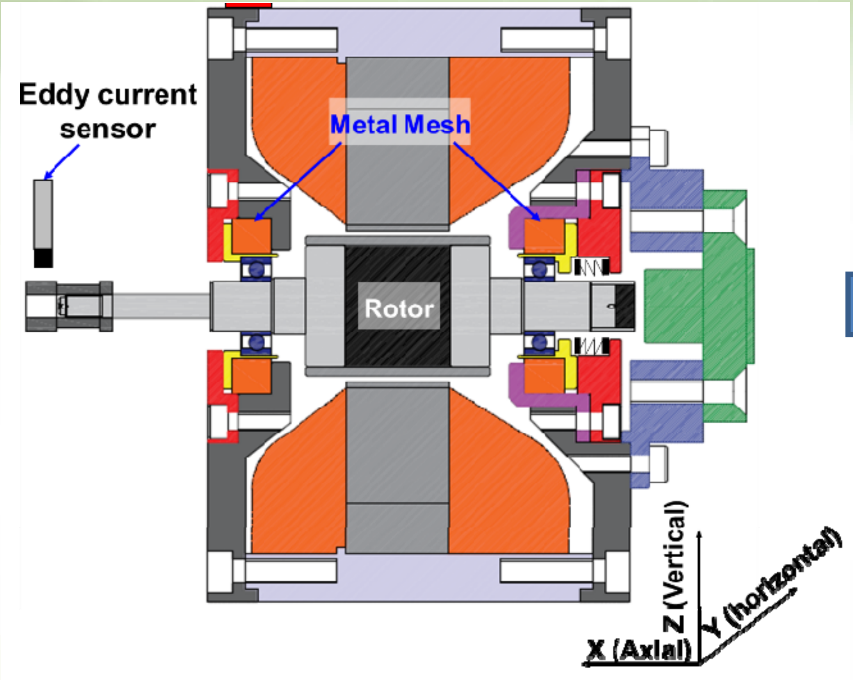
Several rigid body modes are located below operating speed of 100,000 rpm.

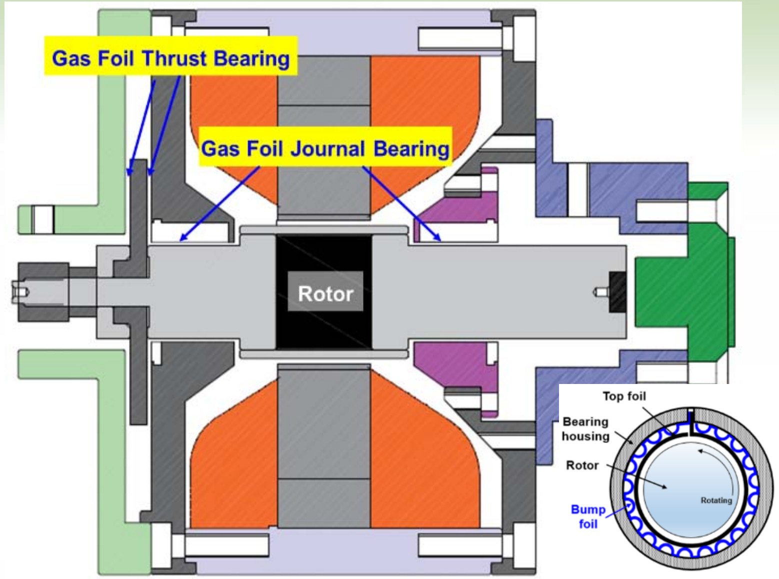
Note that 1st bending critical speed is ~ 200,000 rpm.

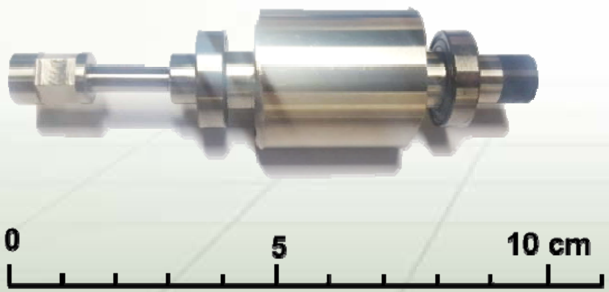
Vibration data after MMD installation

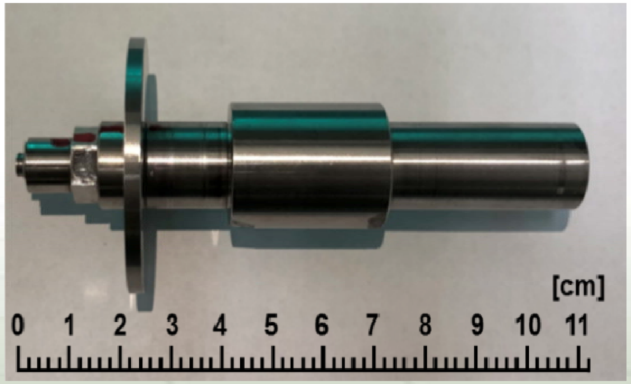


Solution approach 2



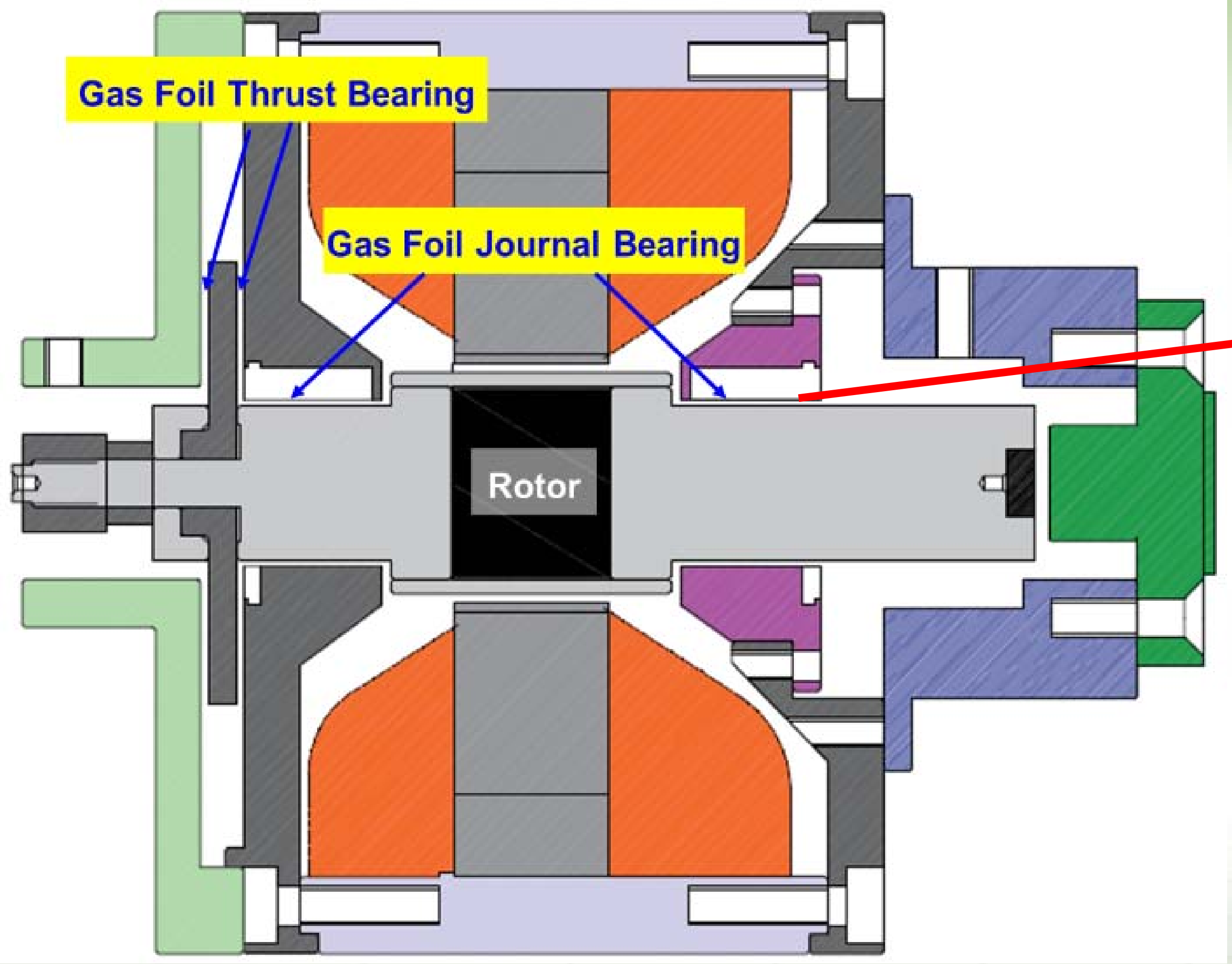


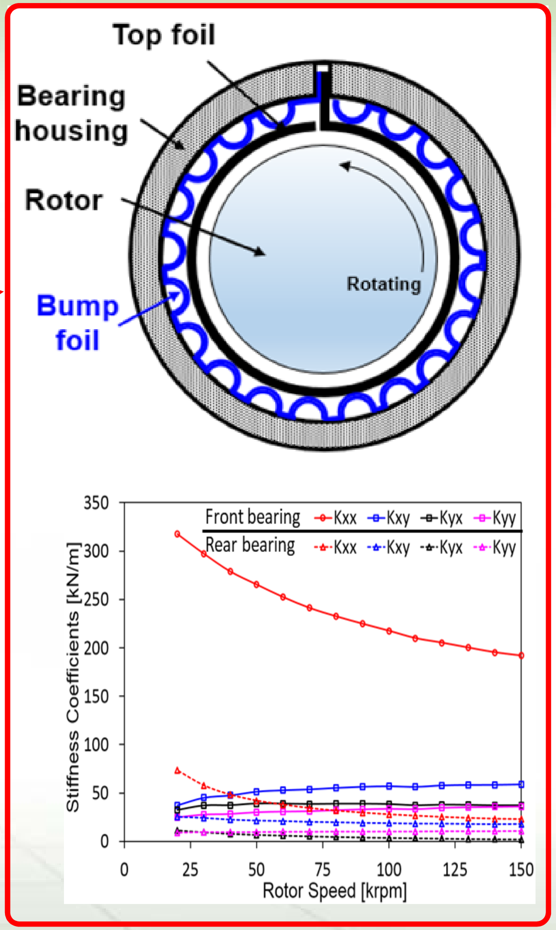




Modification of rotor-bearing systems using GFBs

Modification of rotor and bearings

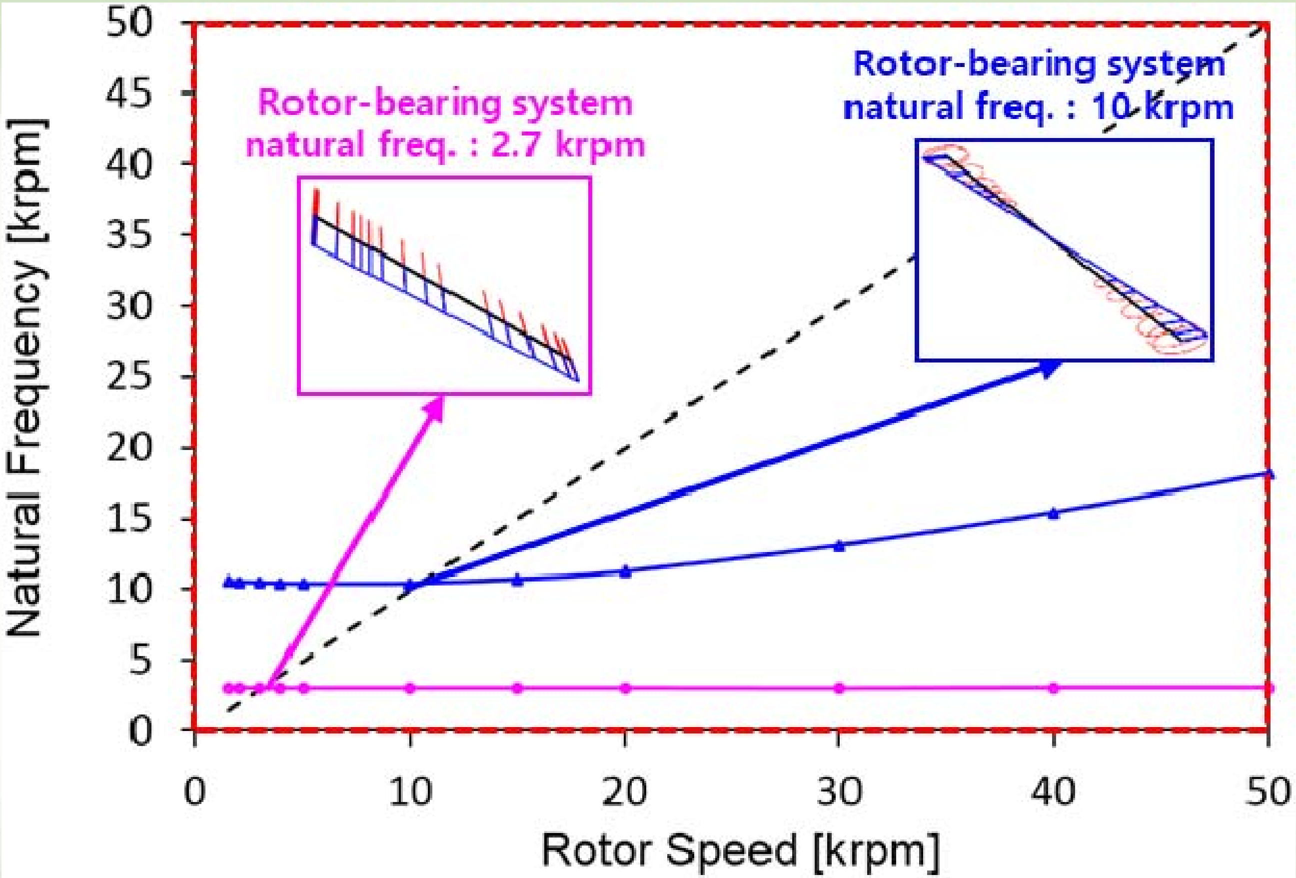




Modification of rotor and bearing parts only.

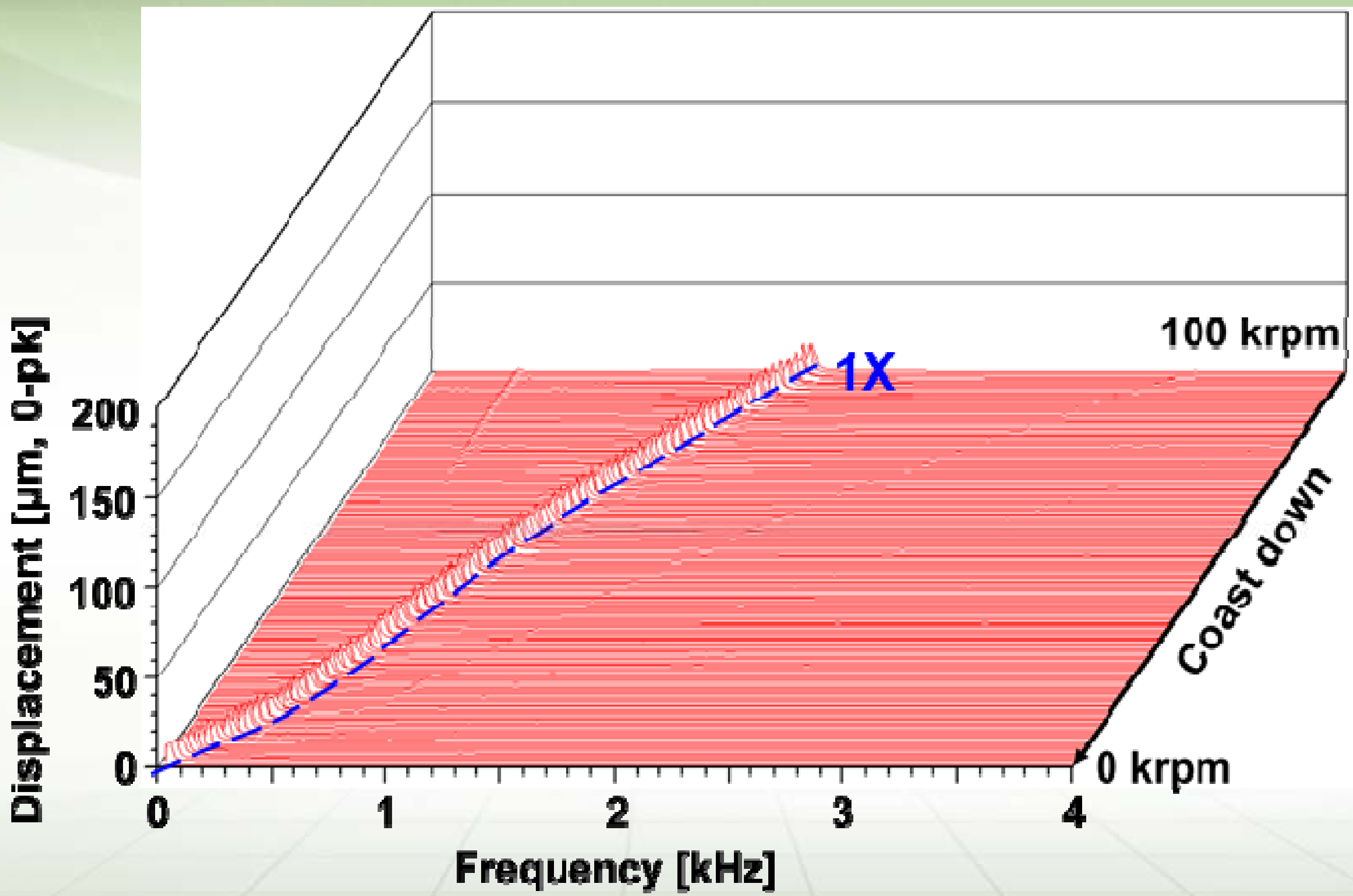
Analysis results

Eigen value analysis



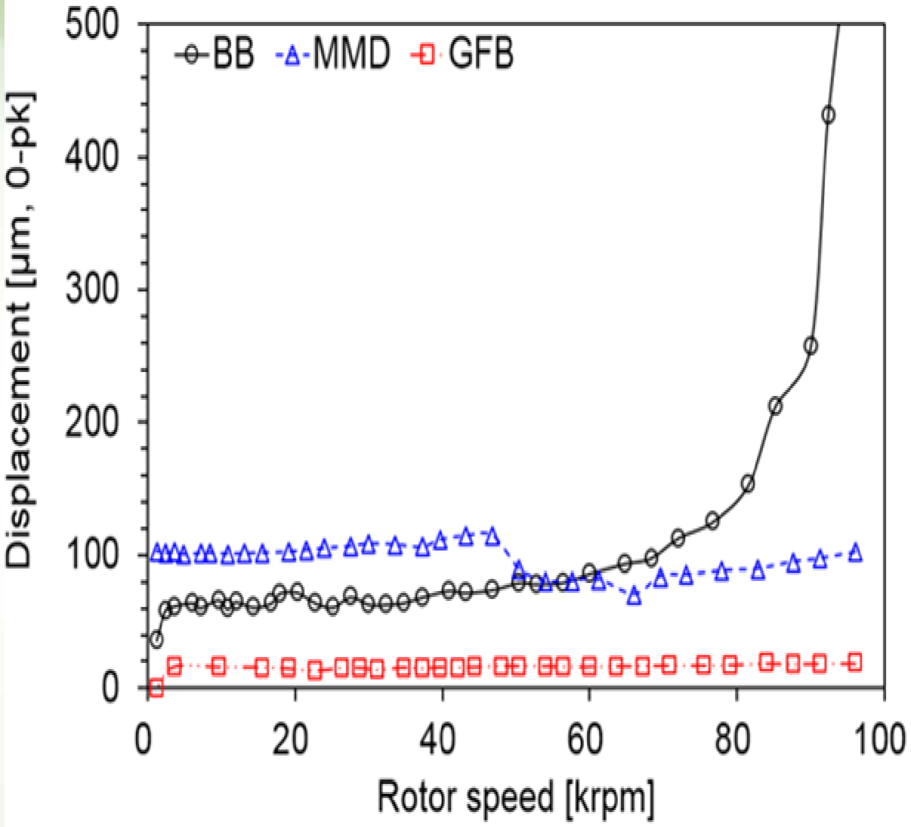
- Two rigid body modes are located below 20,000 rpm.
- Rotor 1st bending critical speed is above 400,000 rpm.

Vibration data for rotor using GFBs

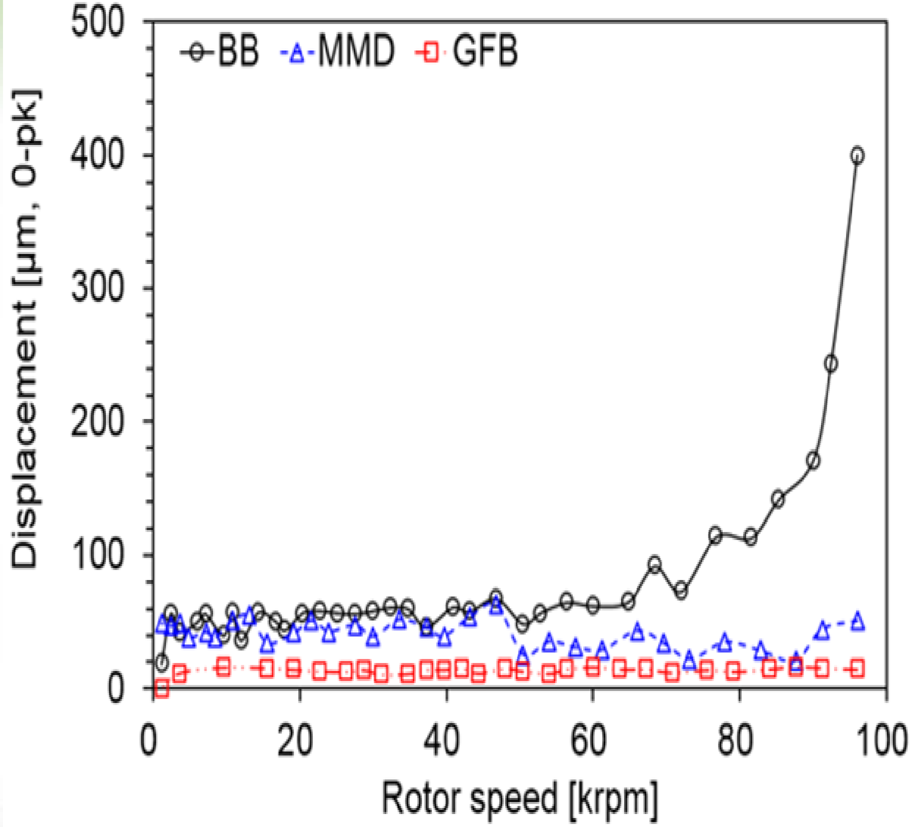


Vibration data: comparisons

Overall vibration



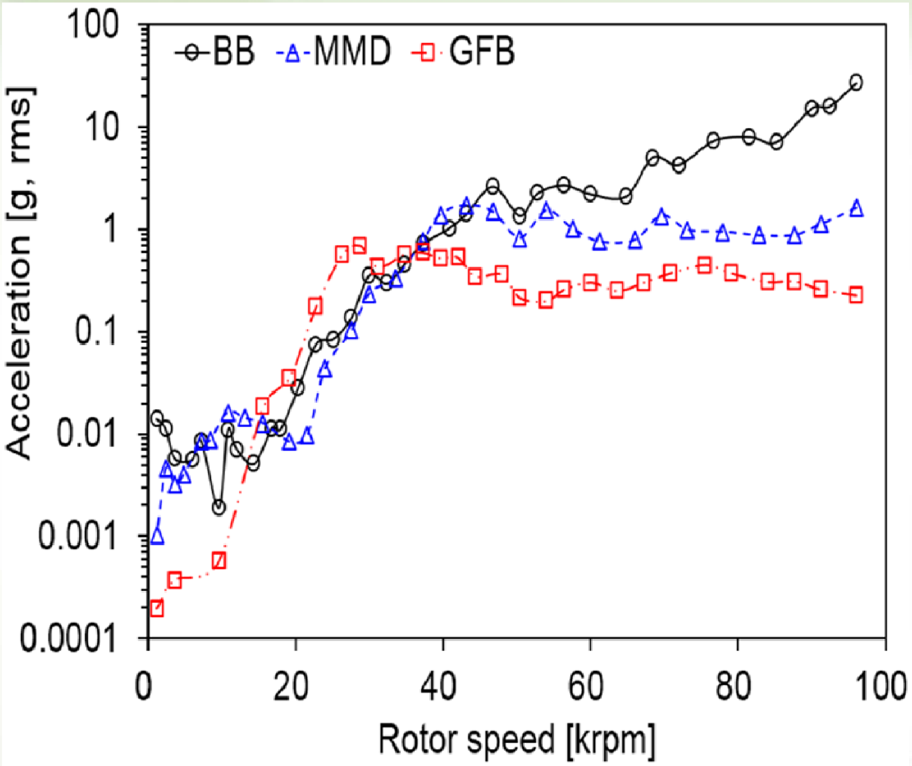
Synchronous vibration



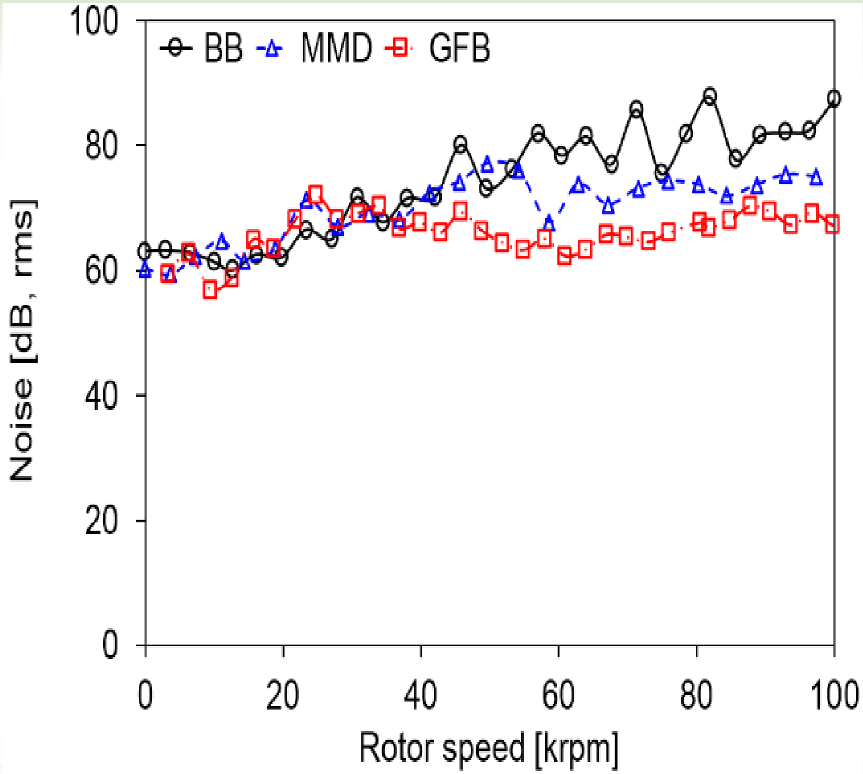
- MMD reduces mitigates vibration at operating speed of 100,000 rpm.
- GFB demonstrates the smallest vibration.

Vibration data: comparisons

Casing acceleration



Acoustic noise level



- MMD reduces casing acceleration and acoustic noise.
- GFB demonstrates smallest acceleration and noise.

Lessons learned

- Rotor operation near bending critical speed causes large synchronous rotor motions which may result in catastrophic failure.

- Metal Mesh Damper (MMD) decreases stiffness and increases damping for bearing support effectively. It helps rotor avoid resonance with bending critical speed.

- Replacement of ball bearings with gas foil bearings (GFBs) decreases rotor vibrations dramatically along with casing acceleration and acoustic noise.

- Rotordynamic analysis was very helpful to find root cause of the problem and conduct rotordynamic design modifications.

Acknowledgement

This presentation includes R&D works while working with SEAH industry company, Hyundai Motors company, Hanon Systems company, Neuros company, and Keyyang Precision company. The presenter thanks them for close collaborations and technical supports. The partial financial supports from Korean Ministry of Trade, Industry and Energy are gratefully acknowledged too.

Thank you!

Questions?