Evaluation of Gyrometric shaft monitoring technology on the ORE Catapult 15MW wind turbine test facility

GyroMetric SYSTEMS

June 2018

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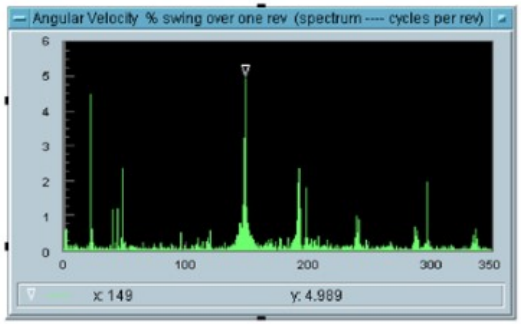
Introduction

- Gyrometric have a unique patented shaft monitoring technology
- Used worldwide on ships
- Evaluating the technology for use in wind turbine monitoring with ORE Catapult by using 7MW test nacelle



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How it works (1)

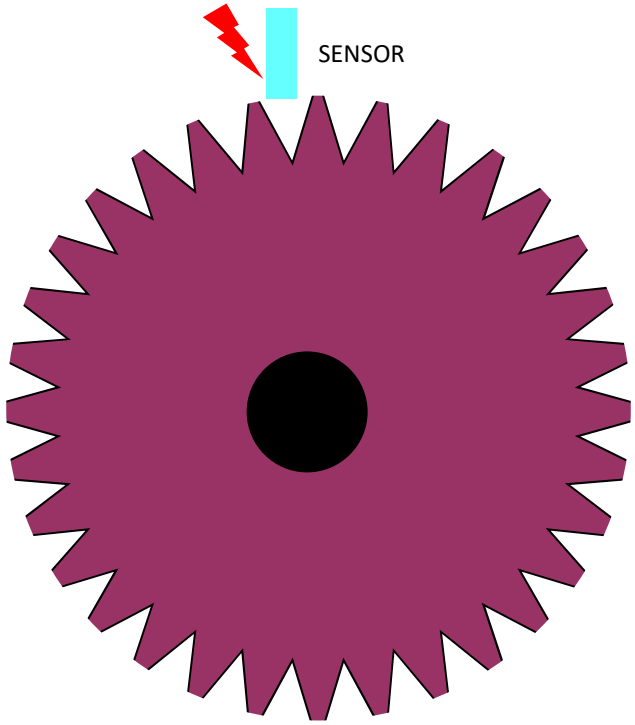
Conventional rotary encoder

Rotary Encoders are used for shaft speed measurement & control

They consist of a disc with regularly spaced features, and a sensor

As each feature passes the sensor, an output is generated

Angular displacement and rotational speed can be measured



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How it works (2)

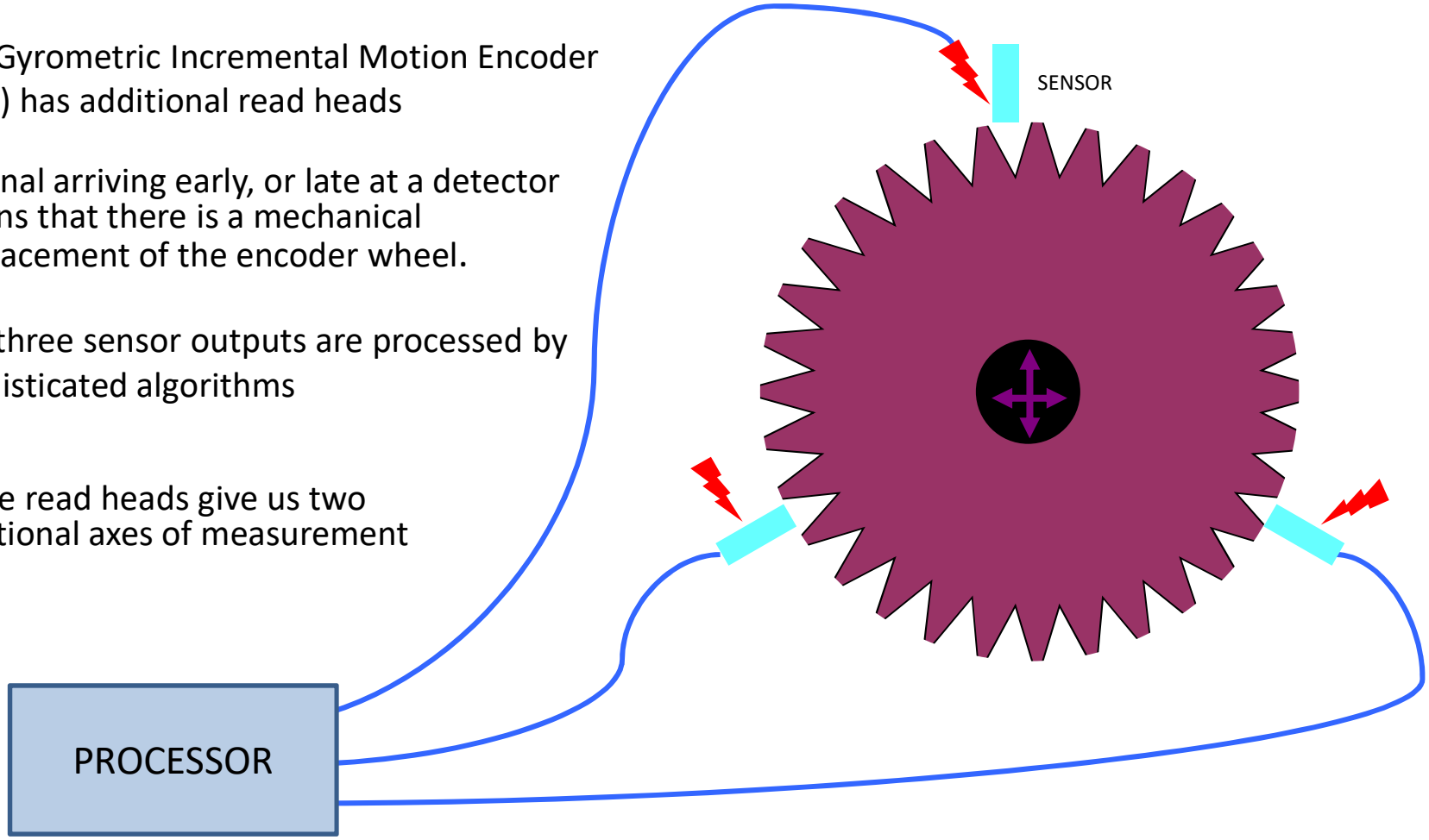
Gyrometric Incremental Motion Encoder(IME)

The Gyrometric Incremental Motion Encoder (IME) has additional read heads

A signal arriving early, or late at a detector means that there is a mechanical displacement of the encoder wheel.

The three sensor outputs are processed by sophisticated algorithms

Three read heads give us two additional axes of measurement



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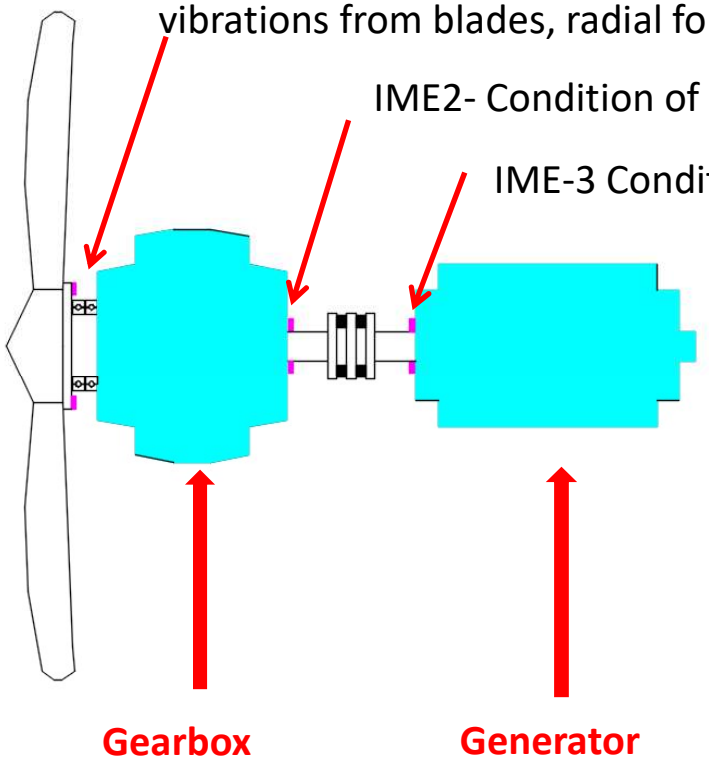
Layout of Gyrometric Sensing System



Data from IME1 + IME2 is used to monitor gearbox condition

Data from IME2 + IME3 is used to Monitor the condition of the coupling and the torque across the coupling to generator

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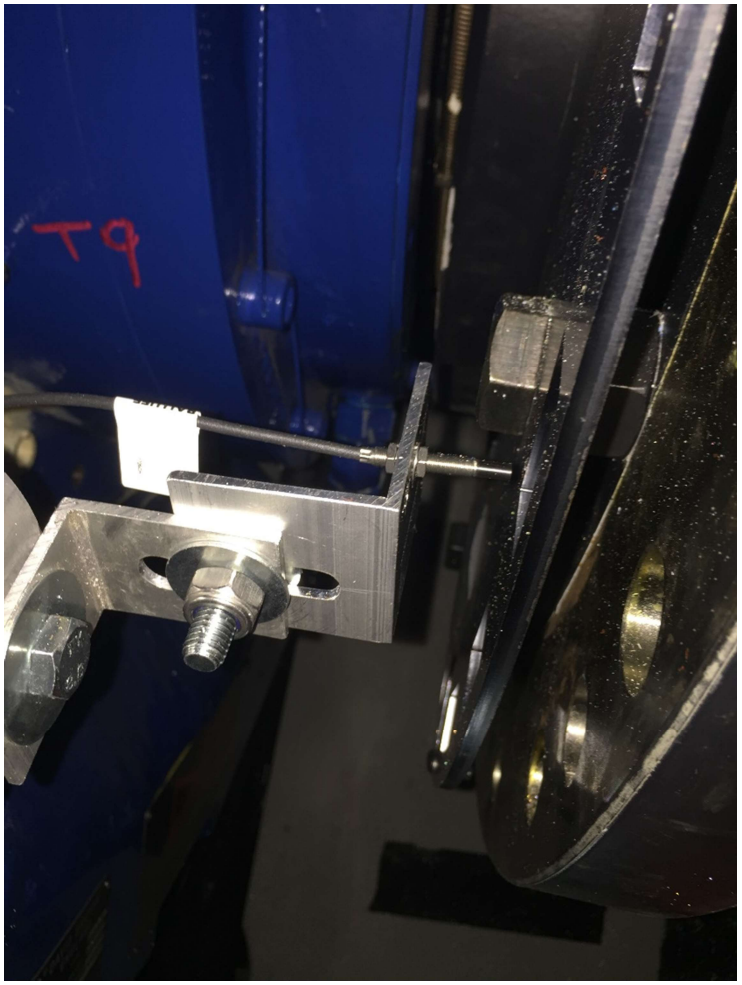
Sensors



- Off the shelf inductive sensors
- Relatively inexpensive
- Trigger as metal passes in front of them
- Image shows sensor monitoring gearbox output shaft

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Gratings

For IME1 position

- Retrofit design for convenience and speed for this evaluation test
- Further optimization will be made for commercial products

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Connection boxes

- Powers the sensors
- Collects timing information
- Timestamps
- Sends to main unit

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Gyromon Main unit

- Collects timing data from the connection boxes
- Processes and analyses the data into useful information
- Located at the test nacelle

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Measurements

- Twist
  - Between any pair in different locations
  - Very accurate 0.001 degree at 6000 RPM
  - Continuously – non contact – digital
  - This is in the time domain
  - Live analysis
    - In the frequency domain
    - Vibrations in the twist
    - Drive and driven vibrations

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Measurements (2)

- From sets of 3 timings
  - Orbit plot Movement in rotating plane (Y and Z)
    - Real time
    - Accuracy - sub micron capable at up to 6000 RPM
  - Centre plot
    - Tracks average centre of rotation over time
    - Shows movement due to temperate changes
  - Frequency domain
    - Y & Z spectrums
    - Torsional vibration spectrums

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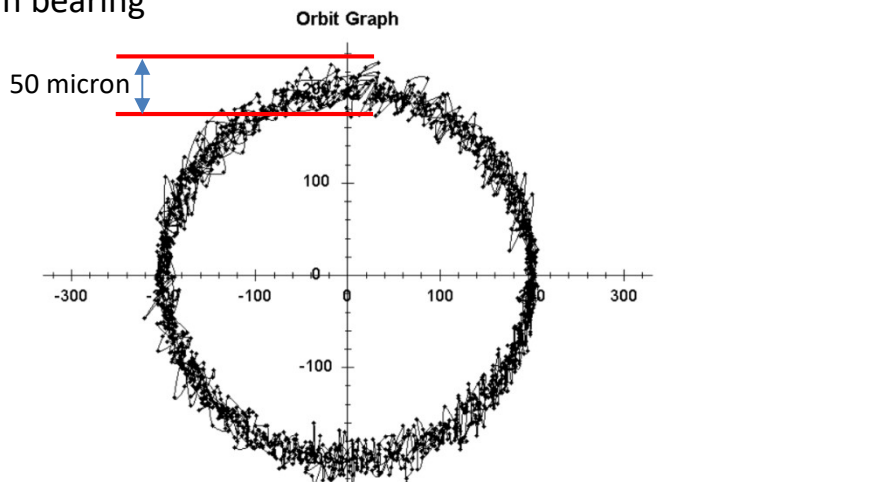
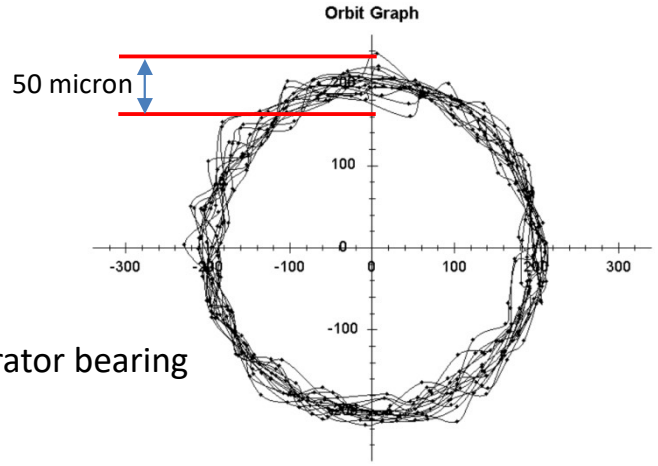
Measurement from Gyrometric system

-Bearing orbit plots

Main bearing





Generator bearing

- The variation in this orbit plot indicate the relative movement between shaft system and supporting structure
- Change of this orbit plot in long term monitoring can indicate the abnormal condition of bearings in this shaft system

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Units: micron

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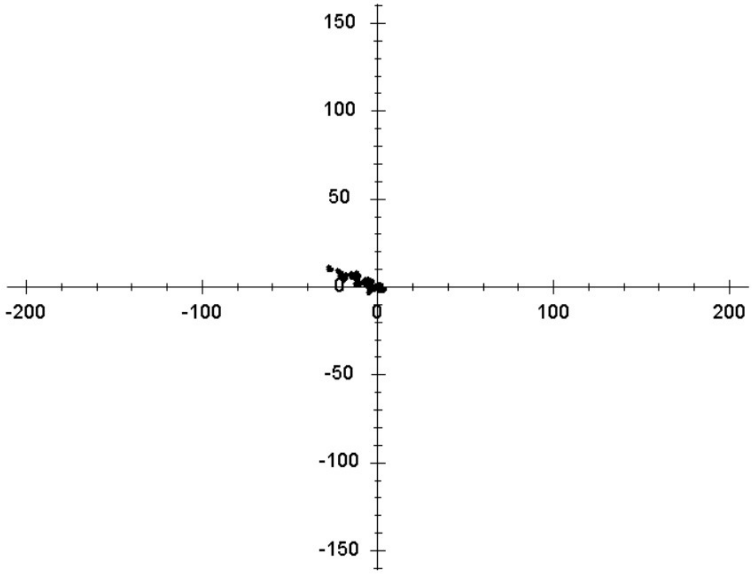
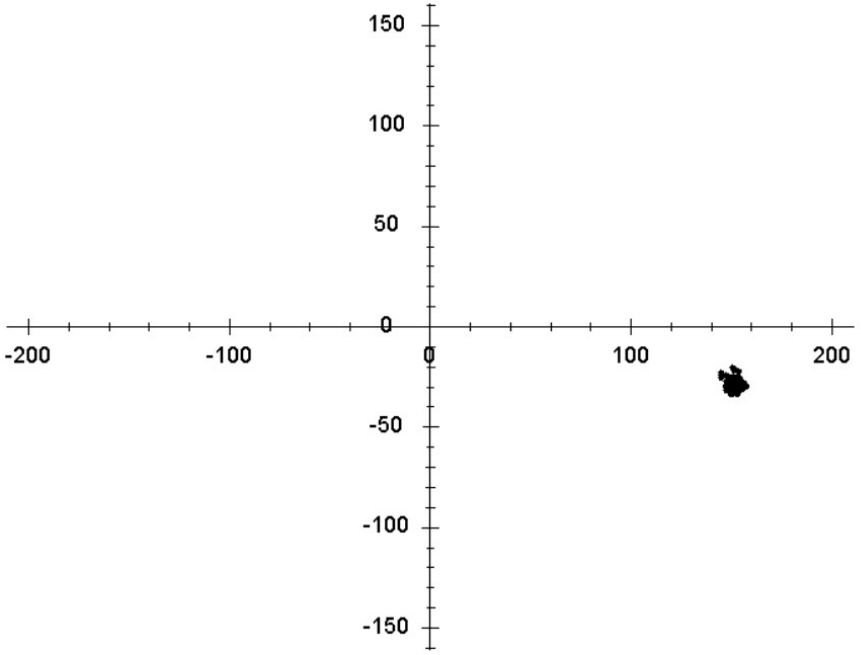
Measurement from Gyrometric system

Generator bearing centre location

- Due to the thermal expansion, the location of bearing centre is changed
- Change of this centre location in long term monitoring can indicate the abnormal condition of bearing



Low speed condition



High speed condition

Units: micron

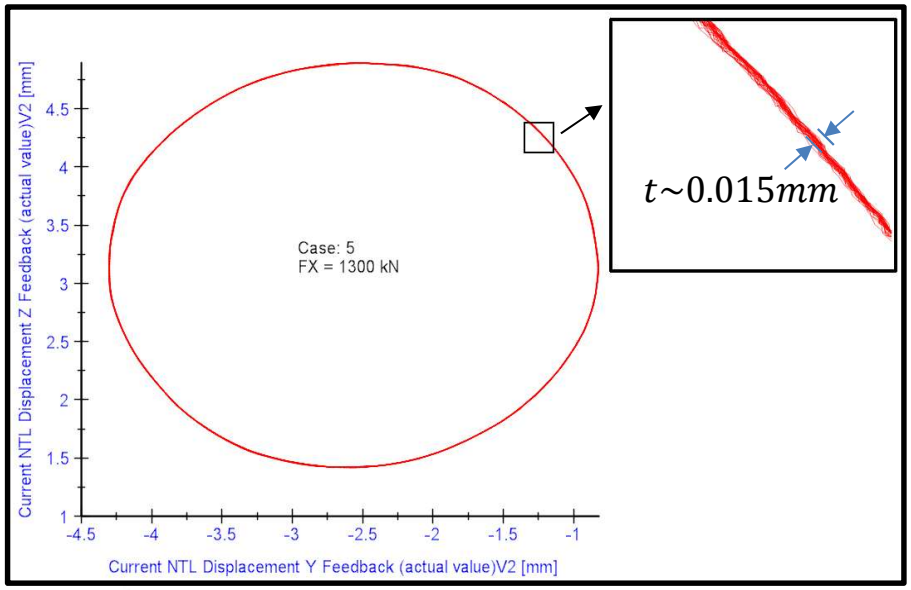
Evaluation of measurement

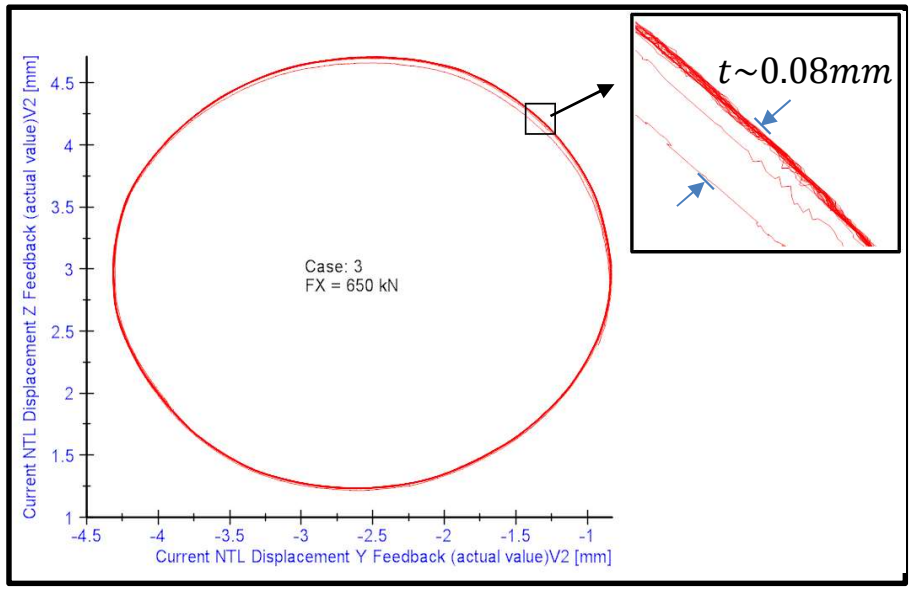
-Orbital plot of FAS Displacements (1)

Orbital plot of FAS With applied axial force

Shows a non zero centre of rotation (FAS= Force Application System i.e. output of test rig into the Nacelle)

$F_X \sim 1300\ kN$





$F_X \sim 600\ kN$

- This plot indicates the movement of shaft at the force application system which is used to apply loads on the test piece
- **The trend of variation in this orbital plot is well matched with the variation in Gyrometric's orbital plot**

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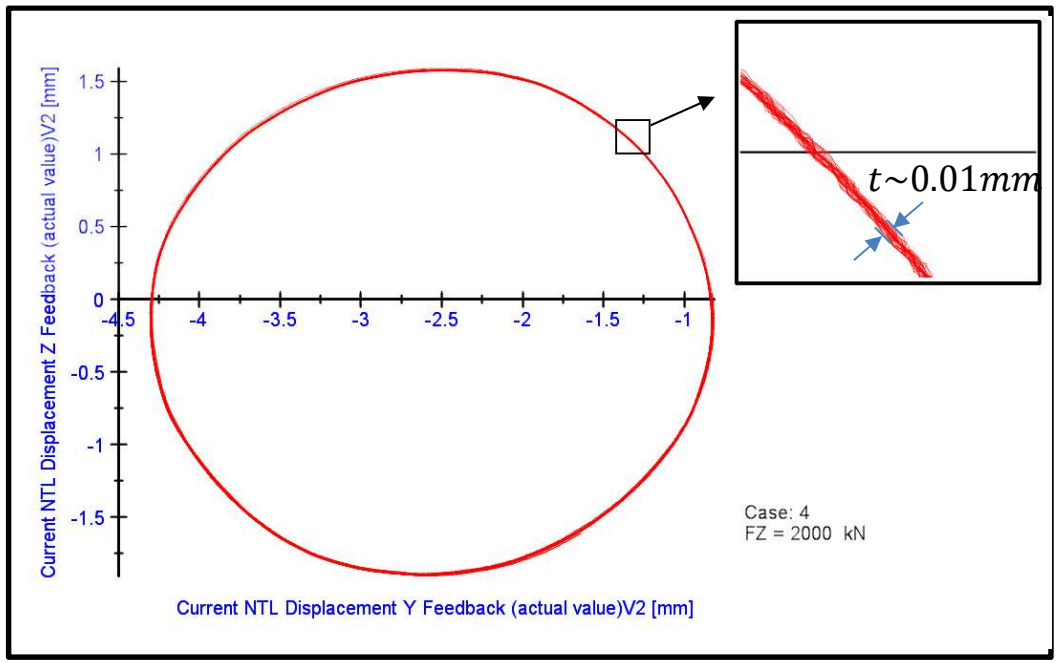
Evaluation of measurement

-Orbital plot of FAS Displacements (2)

Orbital plot of FAS with applied vertical force of 2000kN

Centre of rotation is shifted toward zero in z direction

Rotation is fairly centric



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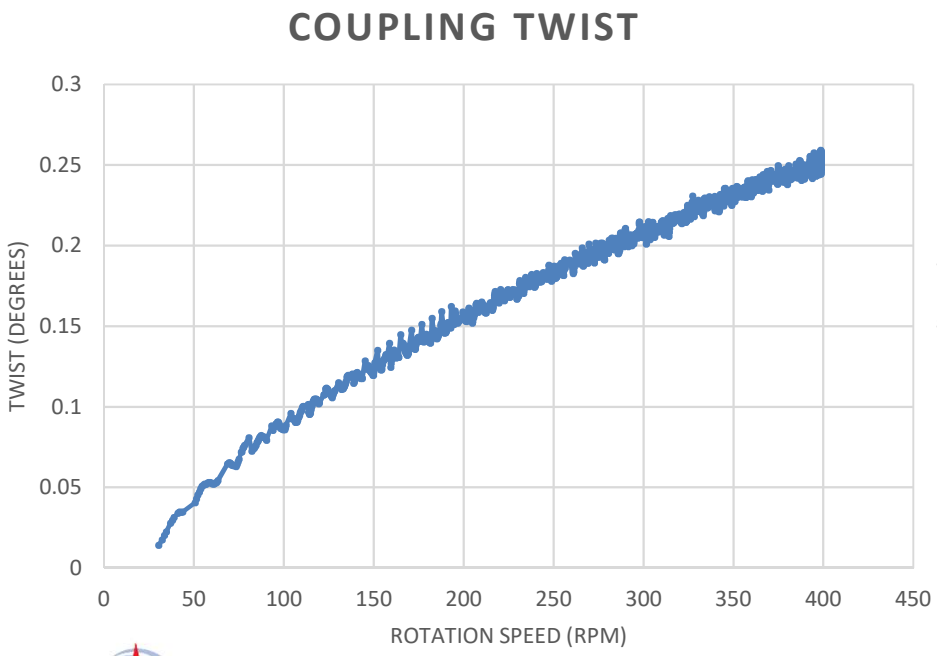
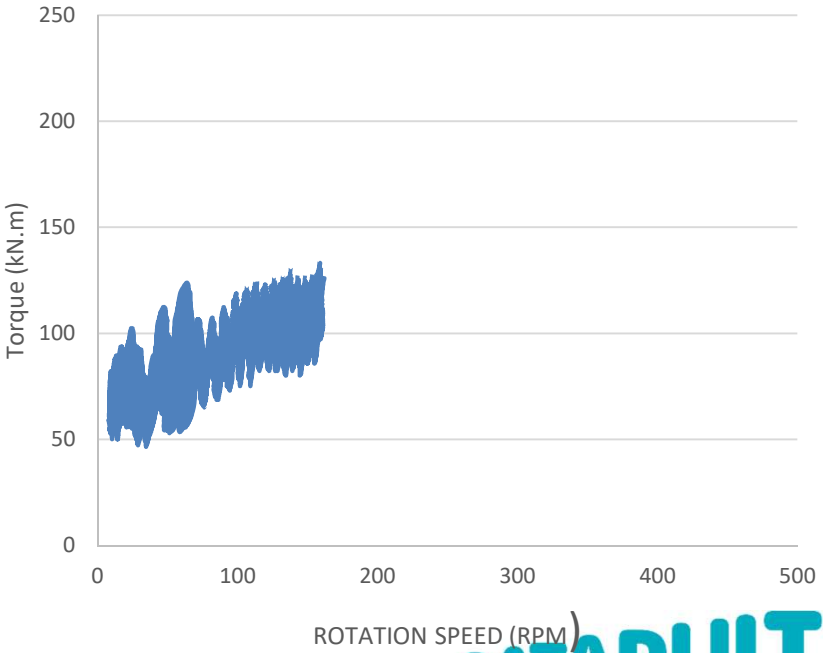
Measurement from Gyrometric system -Coupling twist vs Rotating speed

- At the beginning of rotation, strong relationship between rotating speed and amount of twist is observed
- **This relationship can be used to measure high dynamic torque which can not be measured with a conventional measurement system**





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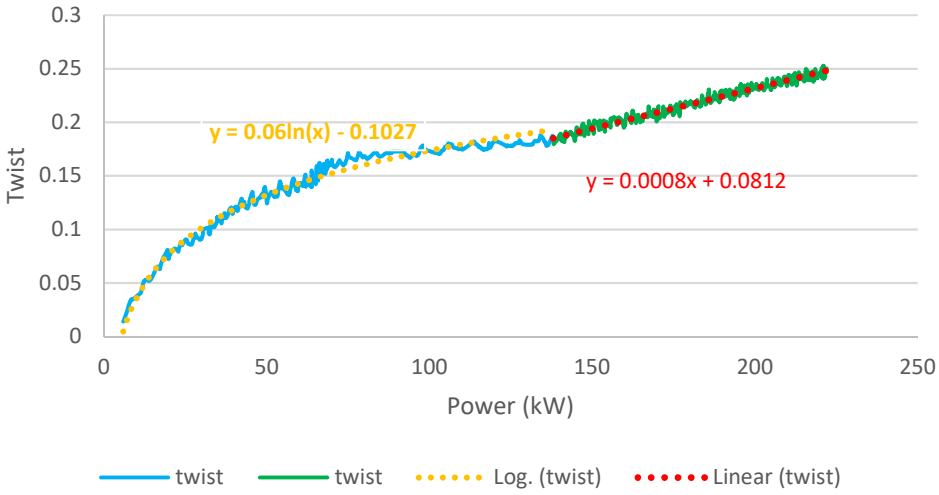
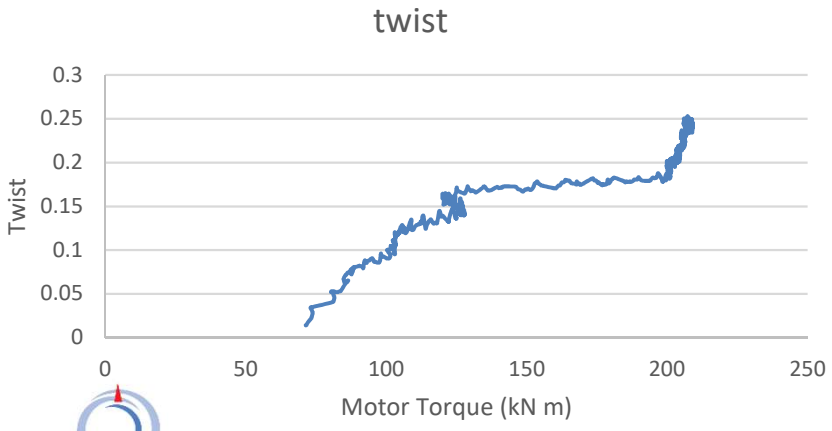
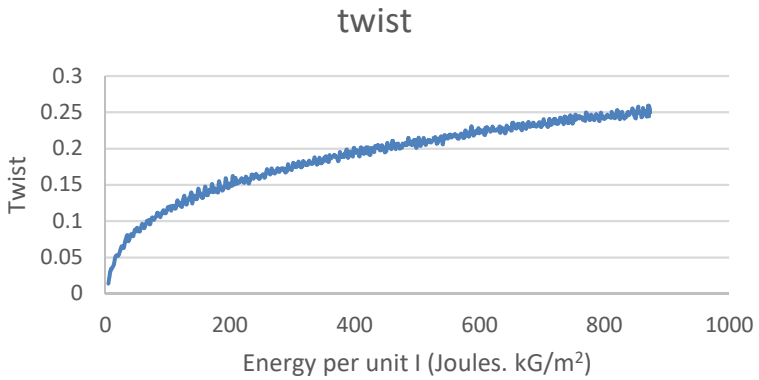
Evaluation of measurement
- Twist

- Generator control strategy appears to have affected the experiment.
- Distinct regions can be distinguished in the Torque-Twist curve
- **There is a strong relationship between Power and Twist**
- More data and information will be needed to finalize the equation of power-twist curve
- **This shows great potential to measure the dynamic torque, not previously measurable**







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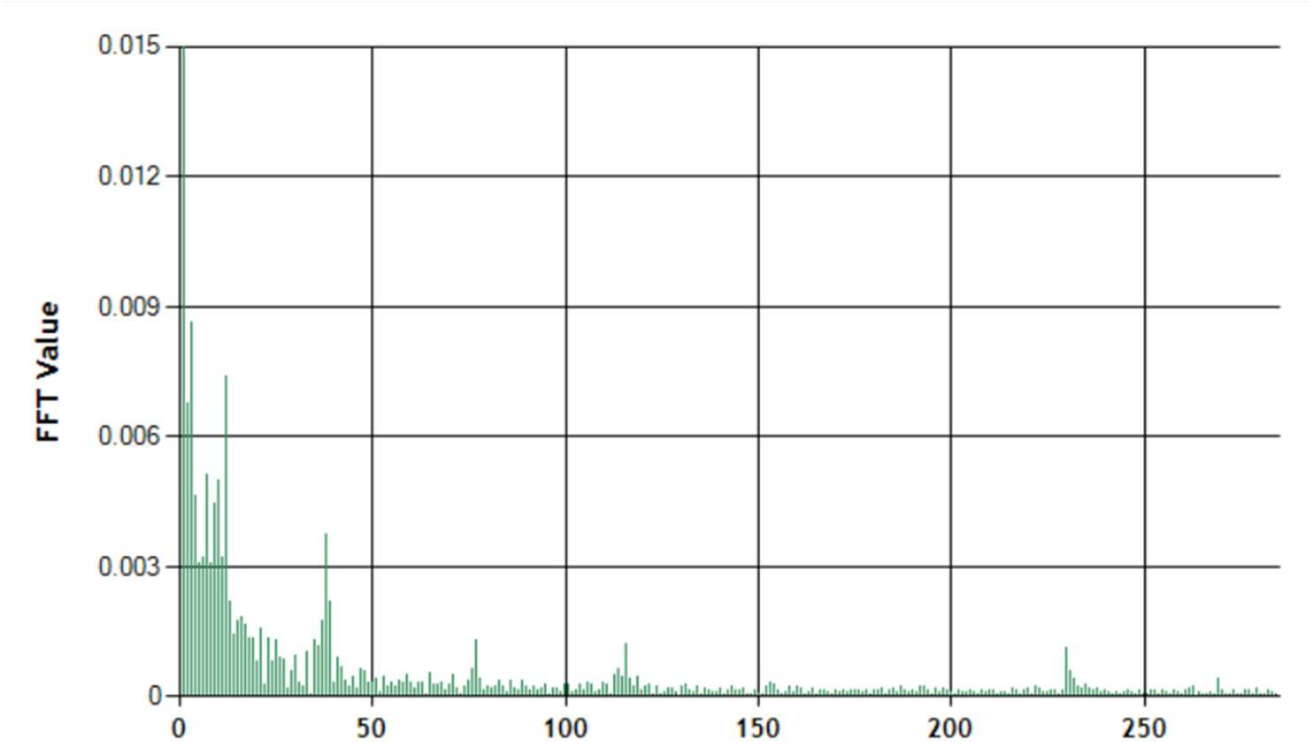
Gearbox twist – frequency analysis



Horizontal scale – Cycles per revolution – referenced to gearbox input
Rotation speed 6.0 RPM

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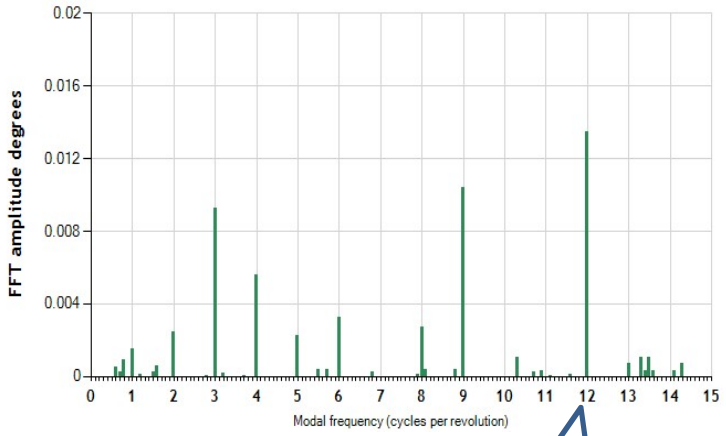
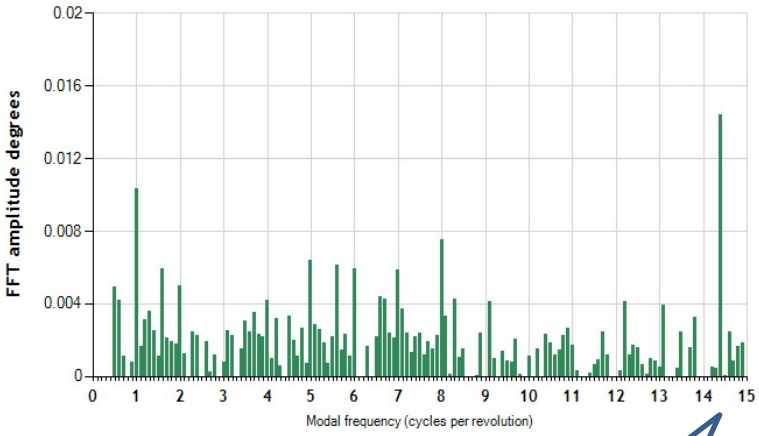
Measurement from Gyrometric system

Coupling twist – vibration analysis



Resonance of 12 cycles per revolution between 63 and 100 RPM



Resonance of 14.5 cycles per revolution at 354 RPM

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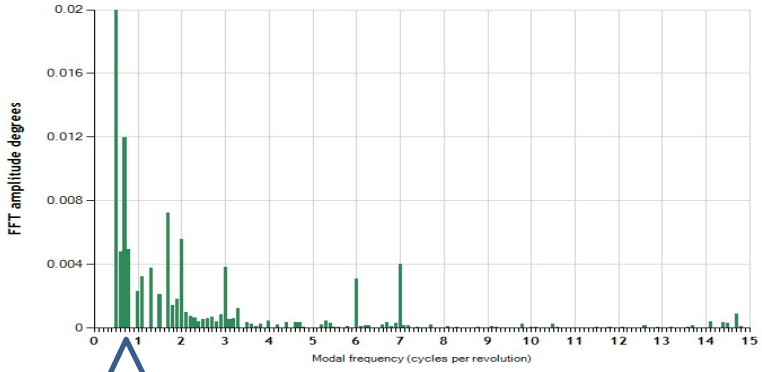
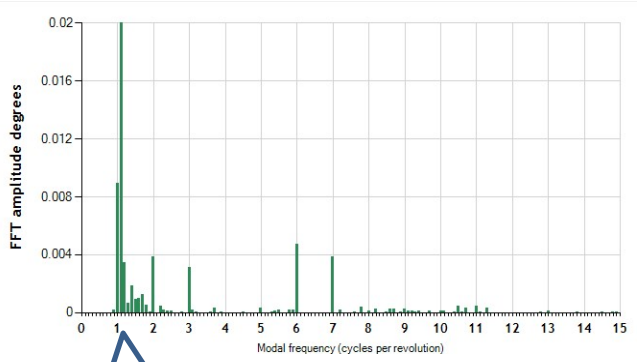
Measurement from Gyrometric system

Generator input - vibration analysis



Resonance of 0.6 cycles per revolution between 165 to 190 RPM and 204 to 206 RPM



Resonance of 1.0 cycles per revolution between 220 to 230 RPM and 237 to 322 RPM

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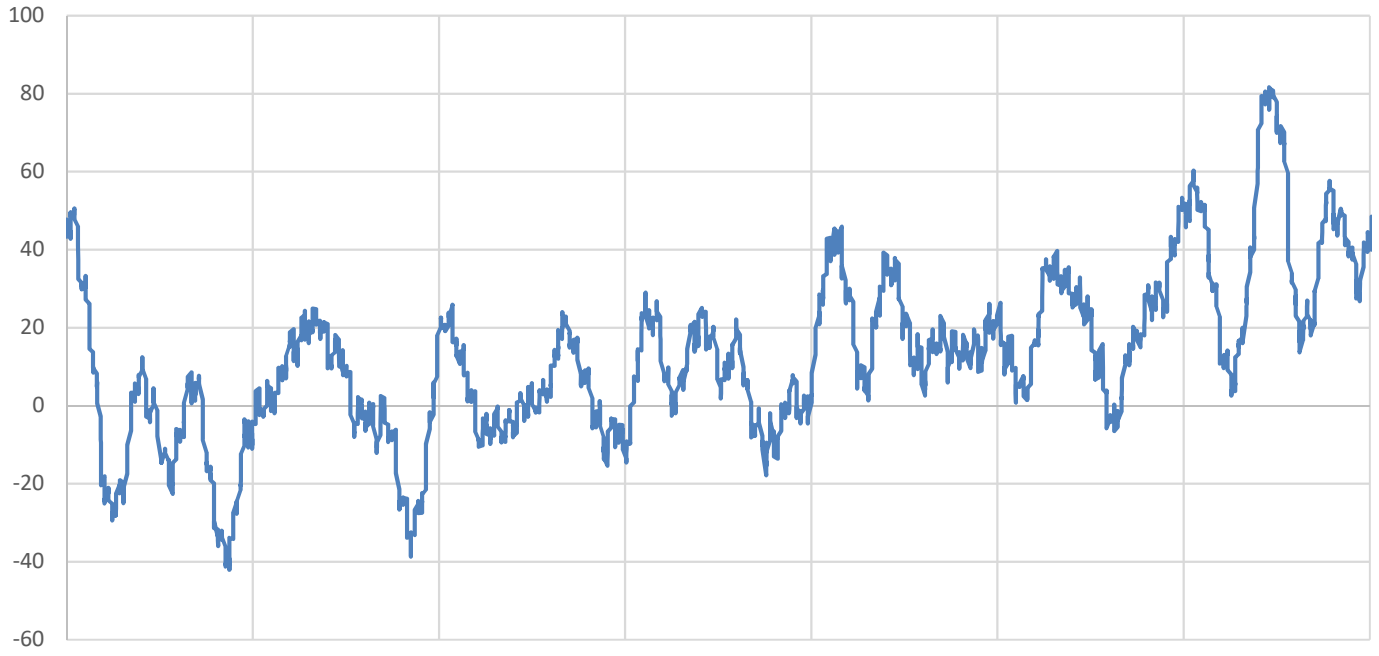
Measurement from Gyrometric system

Primary bearing movement with applied load

Displacement in microns



Primary Bearing displacement with simulated wind load over 10 minutes

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Measurement from Gyrometric system

Primary bearing movement with applied load

X load constant – constant speed	Displacement
Start of test	0
End of test	7.8

Y load constant – constant speed	Displacement
Start of test	43.0
End of test	28.3

Z load constant – constant speed	Displacement
Start of test	53.0
End of test	43.8

All displacement in microns

Test over 10 minutes

Differences over time are presumed to be due to heating effects

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Evaluation of measurement

Primary bearing movement with applied load

X load constant – constant speed	Displacement (microns)	Stiffness (calculated) -N/m	Stiffness (NTL calculated)- N/m
Start of test	0	∞	0
End of test	7.8	83e9	81e6

Y load constant – constant speed	Displacement (microns)	Stiffness (calculated)- N/m	Stiffness (NTL calculated)- N/m
Start of test	43.0		
End of test	28.3		

Data not available

Z load constant – constant speed	Displacement (microns)	Stiffness (calculated) -N/m	Stiffness (NTL calculated)- N/m
Start of test	53.0	37.7e9	
End of test	43.8	45.6e9	3e8

- Calculated stiffness (Main Bearing)
  - From FAS force and FAS displacement
  - Constant 6 rpm rotation in all cases

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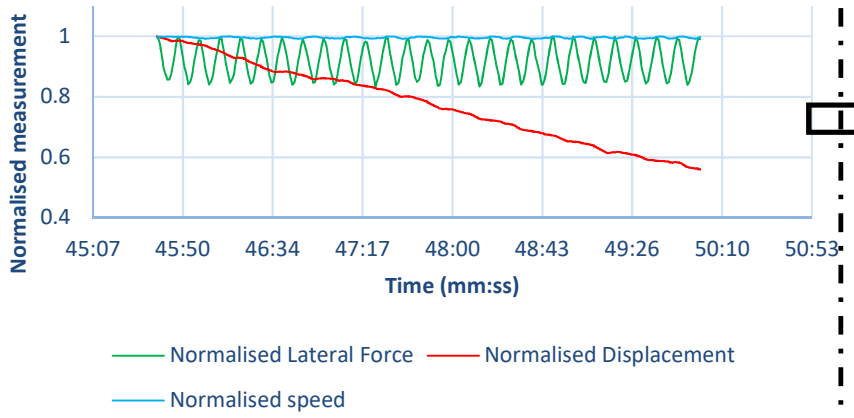
HL1

Evaluation of measurement

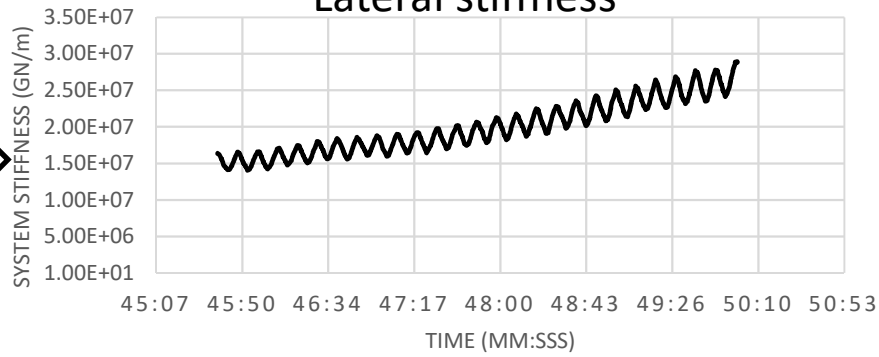
Stiffness

The Gyrometric system allows shaft stiffness to be measured

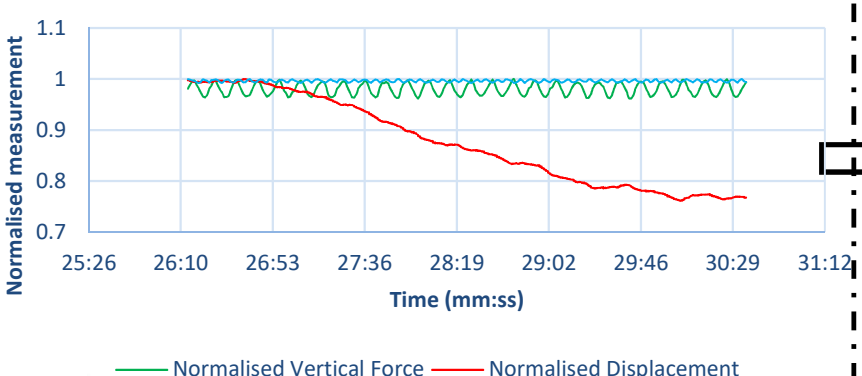
Lateral Load (Fy) applied



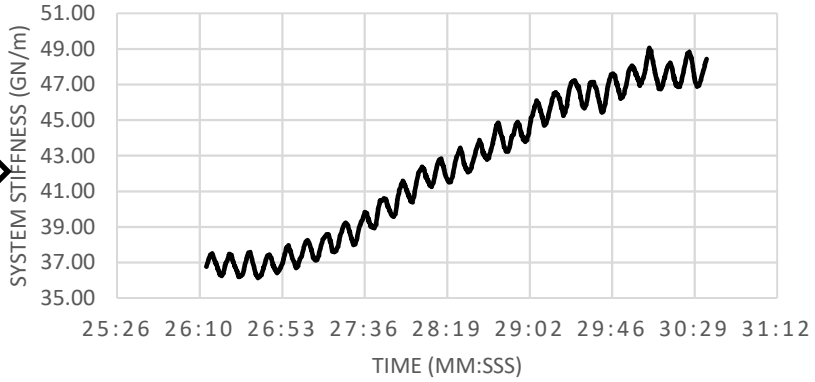
Lateral stiffness



Vertical Load (Fz) applied



Vertical stiffness



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HL1 Gyrometric system measured the stiffness of shaft system

Hyunjoo Lee, 19/07/2018

HL2

Evaluation of measurement

Primary Bearing Displacements

- Comparison with an advanced static model of test setup model shows reasonable agreement
- Stiffness values are of **similar order of magnitude**.
- Static models remains to be validated and optimised hence values are approximate
- The comparison is between static and dynamic cases therefore must be taken in the right context
- **The Gyrometric system can measure 'actual' stiffness**
- **This helps validate the ORE Catapult model which uses 'state of art' simulation technology**

Case number	Force Type	Value (kN)	Absolute displacement (primary bearing) (μm)	Relative displacement of raceway centres (μm)	Average-Gyrometrics _displacement (μm)	Stiffness in direction of force (N/mm)
1	None	0 kN	2.04e-3	4.8e-4		
5	FX	1300	421.9	5.0	**8.7**	4.9 e7
3	FY	650	456.8	6.5	**33.7**	7.7e7
4	FZ	2000	1276.4	26.0	**47.7**	6.5e7

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Slide 25

HL2 Gyrometric can measure ' actual' stiffness which can not be calculated accurately by using 'state of art' simulation technology...
Hyunjoo Lee, 19/07/2018

Evaluation result

Benefits – Orbit plots

- Measurements
  - Bearing build quality
  - Bearing wear
- Applications
  - Maintenance
  - Lifetime extension

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Evaluation result

Benefits – Centre plots

- Measurements
  - Bearing quality
  - Bearing wear
  - Relative movements of shafts
  - Indirect measurement of direct drive airgap
- Applications
  - Maintenance
  - Lifetime extension
  - Direct drive efficiency

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Evaluation result

Benefits - Frequency analysis

- Measurements
  - Vibrations over time
    - Long term wear
    - Maintenance
    - Lifetime extension
  - Vibrations v speed
    - Monitor for resonance
    - Changes over time
- Applications
  - Maintenance
  - Lifetime extension
  - Resonance tuning
  - Efficiency

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Benefits – Twist measurement

- Measure
  - Dynamic twist (torque)
  - Coupling set (deflection over time)
  - Resonance
  - Gearbox phase shift (“twist”)
  - Cogging torque
- Applications
  - Maintenance
  - Lifetime extension
  - Efficiency

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Summary

- Gyrometric technology has proven to operate and be effective in the wind turbine environment
- The measurements it provides can be very useful for
  - Dynamic torque measurement not otherwise possible
  - Condition monitoring to allow extended life
  - Measuring shaft alignment particularly in relation to thermal rising (shaft alignment changing with temperature)
  - Measurement of resonant frequencies to tune the control system
  - Centre position movement to estimate bearing wear and condition.
  - Measuring shaft stiffness
  - Validating nacelle model simulations ultimately improving design

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