ENERGIFORSK Vibration Group
Seminar: Vibrations in Nuclear Applications
Stockholm, October 4th 2016

TECHNISCHE UNIVERSITÄT DARMSTADT

Turbine and Generator Vibrations

Analysis and Mitigation

Prof. Dr.-Ing. Rainer Nordmann

MiM

Turbine and Generator Vibrations

Introduction – Description of the Project

Vibration Problem Areas – Grouping and Analysis

Lateral Vibrations in Shaft Trains due to

- Unbalance
- Heating – Cyclic or Spiral Vibration
- Changes of Sea Water Temperature
- Other Excitation sources (Friction, Instability,…)

Turbine and Generator Vibrations

Torsional Vibrations in Shaft Trains due to

- different Excitation sources

Stator Vibrations due to

- Electromagnetic Excitation

Identification of Vibration Problem

Conclusions

Introduction – Description of the Project

Objective of the project

To assemble knowledge and experience in the area of turbine and generator vibrations in NPP's.

To study in some depth how they were investigated and mitigated. To deliver a report, which can be used for:

- Knowledge transfer to new personnel
- planned changes in turbine trains
- fast solutions when problems occur in turbine trains

Introduction – Description of the Project

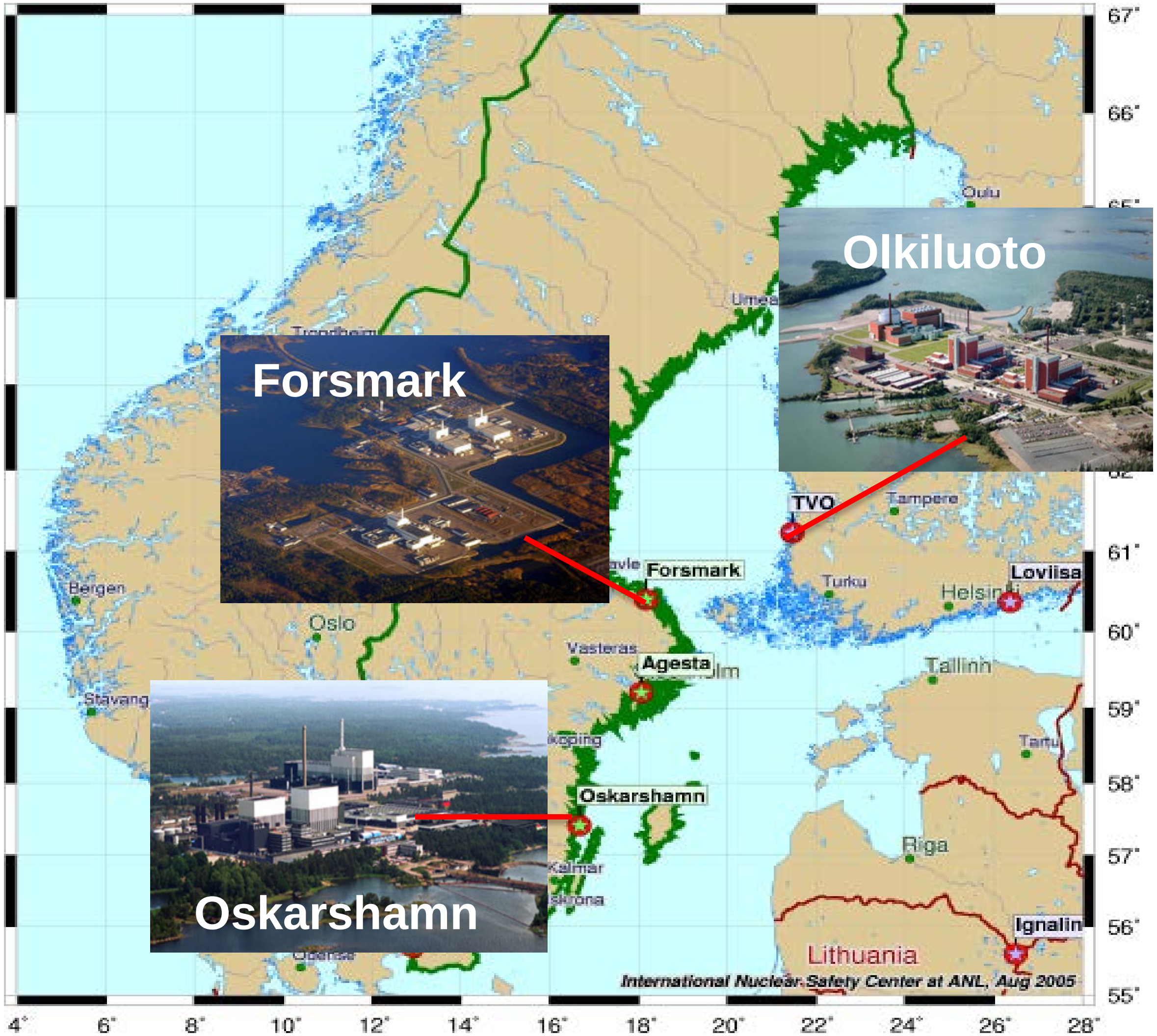
Scope of the task

- Assemble information and documentation from the participating Power Plants

- Grouping of the documentation into different vibration problem areas

- Technical Report with a Physical Description of the encountered problems, the applied Analysis techniques and the Mitigation activities.

Introduction – Description of the Project



The three participating **Nuclear Power Plants** in Sweden and Finland

Introduction – Description of the Project

The base for the Turbine & Generator Vibration studies have been about 200 selected reports (2005 – 2015) with extensive attachments, delivered from the three power plants. Furthermore meetings in each of the three plants with discussions about Turbine and Generator Vibrations were held between 12/2015 and 01/2016. With the information from the documentation and the important interviews with the Monitoring and Vibration Experts a Grouping into Vibration Problem Areas was possible.

Turbine and Generator Vibrations

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Vibration Problem Areas – Grouping and Analysis

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Vibration Problem Areas - Grouping

Lateral Vibrations

- due to Unbalance
- due to Heating (Cyclic Vibration)
- due to Friction (Generator)
- due to Seawater temperature
- due to Instability
- due to Unequal Moments of Inertia

Torsional Vibrations

- due to Electrical Faults
- **S**ub **S**ynchronous **R**esonance
- with coupled Blade Vibration

Stator Vibrations

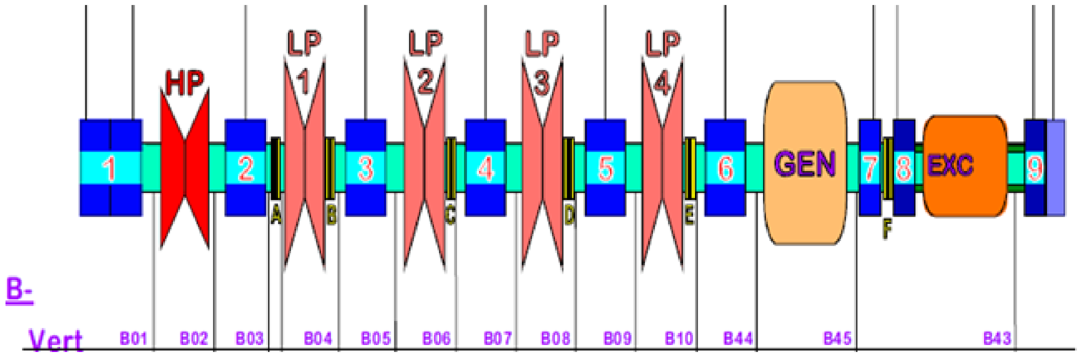
2X-End Winding Vibrations → due to Electro-magn. forces

2X-Stator Core Axial Vibrations → due to Electro-magn. forces

2X-Stator Cooling Pipe Vibrations → due to Electro-magn. forces

Vibration Problem Areas - Analysis

Measurement of absolute bearing vibrations in mm/sec



Measurement of relative shaft vibrations in um

The base for the Analysis of **Lateral** Vibrations is to measure absolute velocity vibrations in mm/sec on the bearings and relative shaft vibrations in µm close to the bearings or on shaft ends. Measurements are taken in two directions (horizontal/ vertical or under 45 °)

Vibration Problem Areas - Analysis

Transducer signals are available in the time domain. By signal processing different functions in the time or in the frequency domain can than be determined, e.g.:

- time history of the vibration signal
- vibration orbits e.g. for one location of the shaft train
- vibration amplitudes and phase over short or long time

- Frequency spectra to analyze the frequency content , e.g. 1X, 2X, 1/2X, higher Harmonics and broadband.

Vibration Problem Areas - Analysis

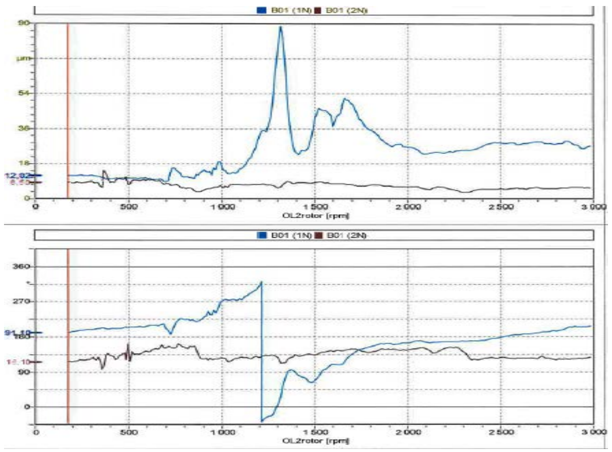
Typical presentations for power plants are:

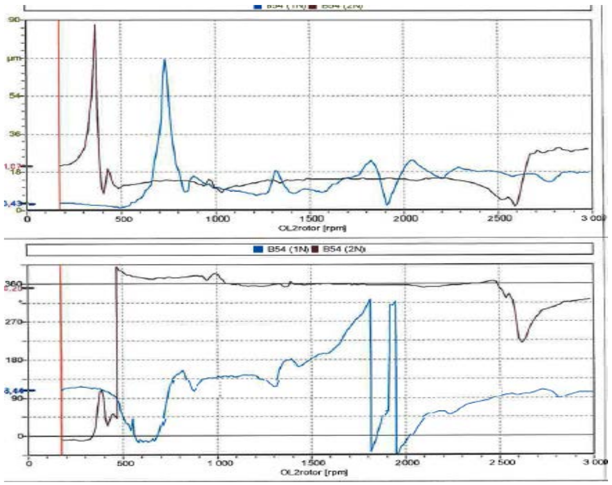
- Run up and Run down curves (Power = 0) with 1X amplitudes and phase versus rotational speed. 2X and higher components can be added.

- Run up and Run down Polar plots with amplitude and phase, rotational speed is the parameter in the plot.

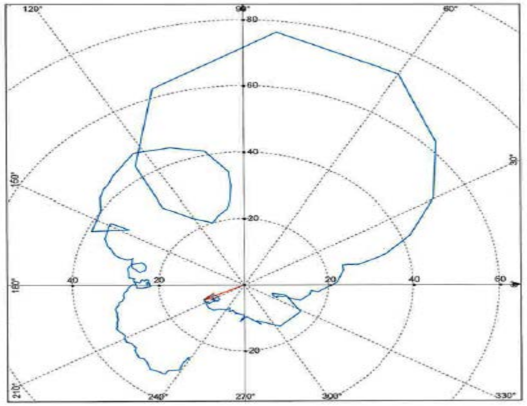
- Polar plot at low speed (e.g. 500 rpm), to check whether the amplitudes are stable and within a control circle before run up.

Vibration Problem Areas - Analysis



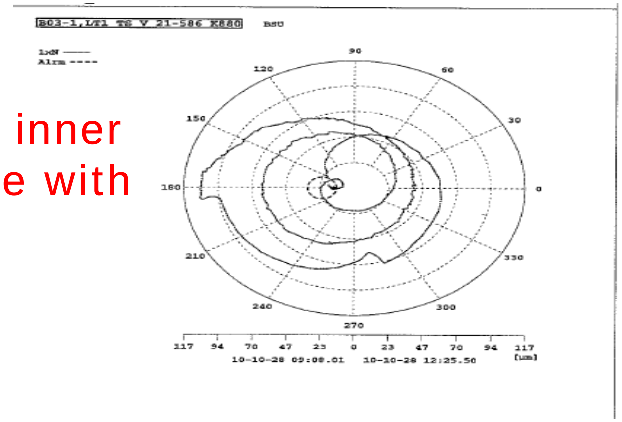


Amplitude and phase vs. Speed, 1X,2X



Polar Plot Run up

Polar plot: inner alarm circle with 10 um



Polar plot at 500 rpm

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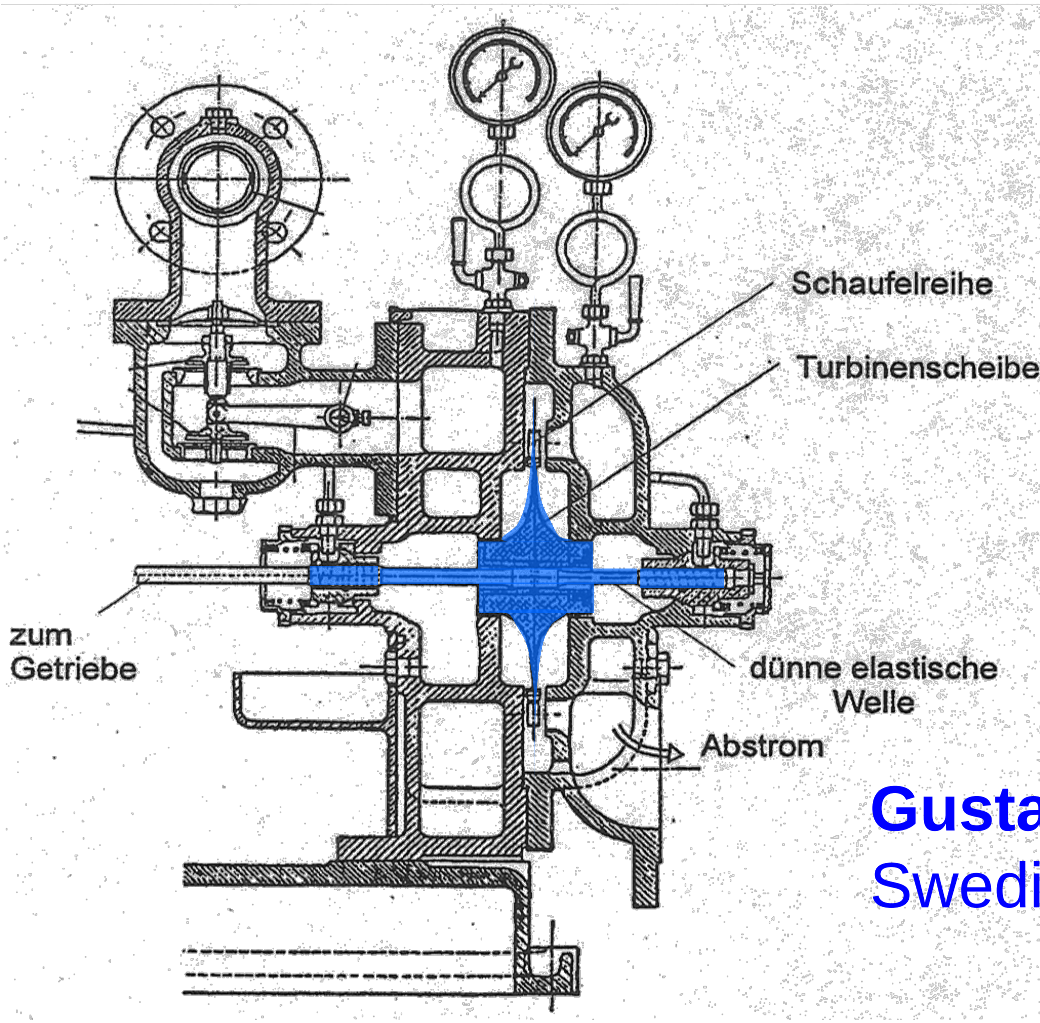
Lateral Vibrations in Shaft Trains

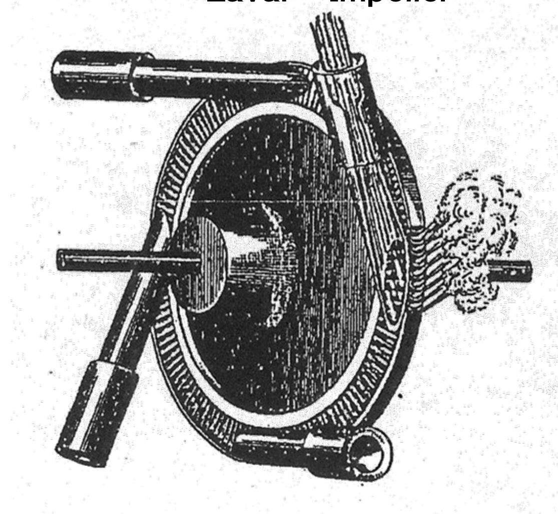
For each Lateral Vibration type the presentation is subdivided into:

- Physical Description
- Investigation Technique - Vibration Analysis
- Observed Vibrations in Shaft Trains and
- Vibration Problem Mitigation

Lateral Vibrations due to **Unbalance**

Physical Description

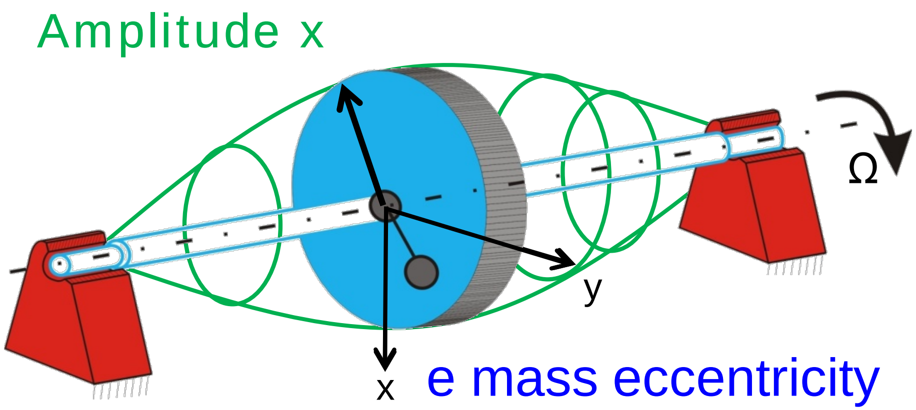




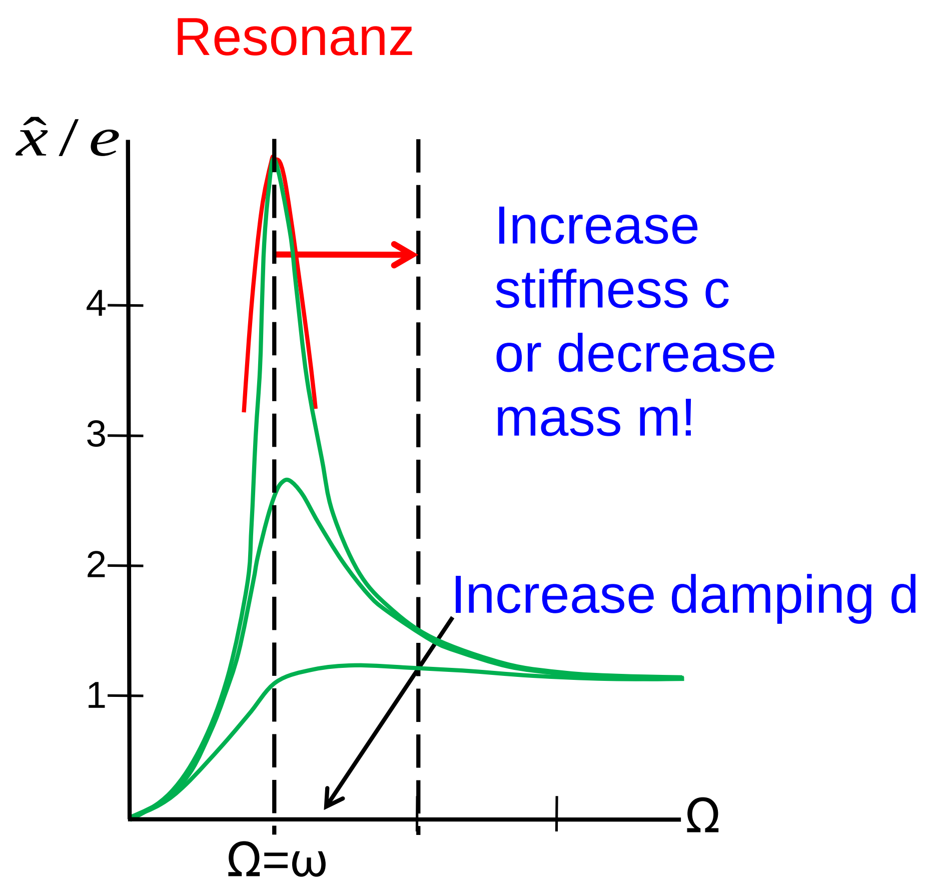
Gustav de Laval (1845 – 1913)
Swedish Engineer

Lateral Vibrations due to Unbalance

Physical Description

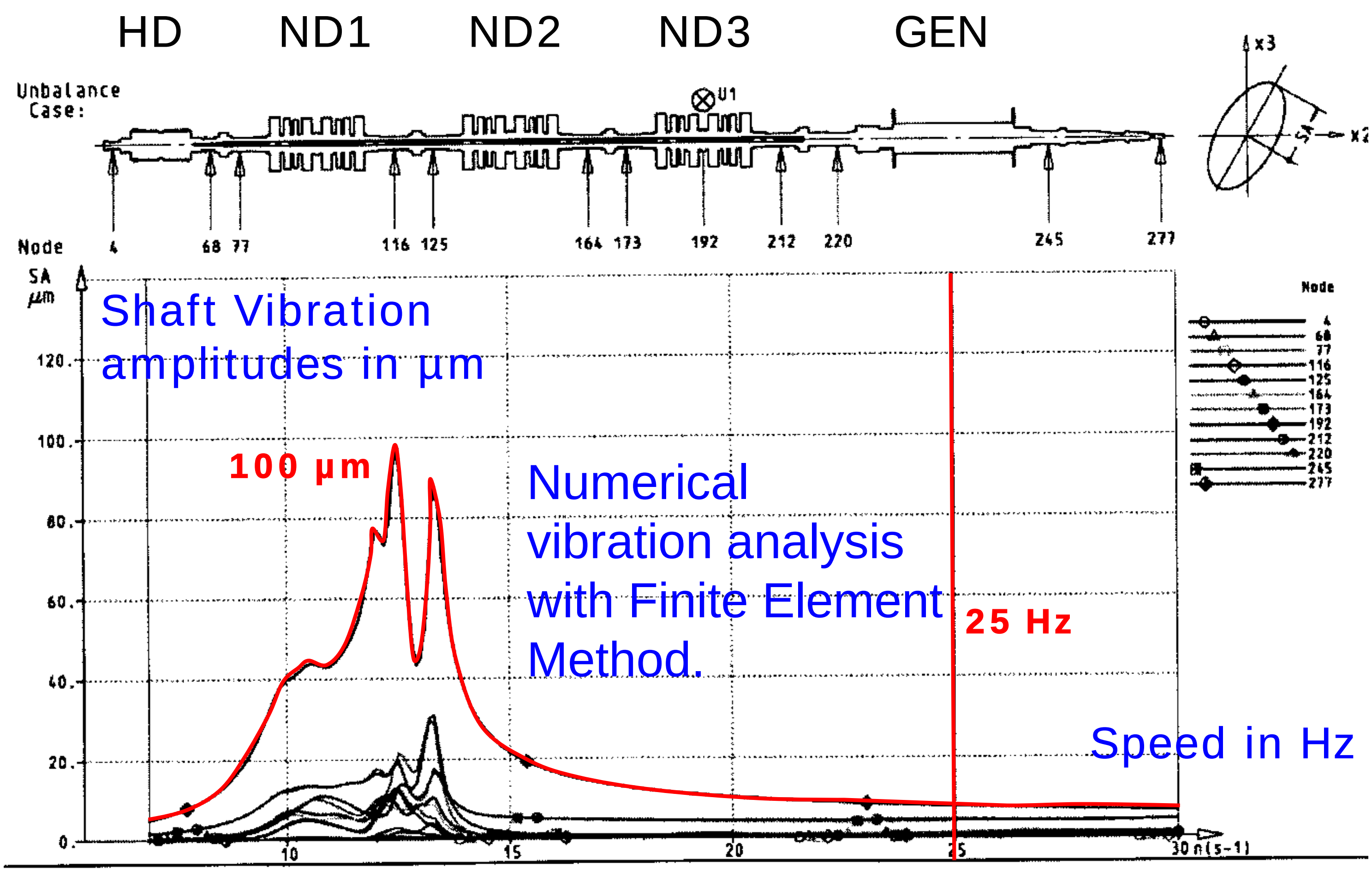


$$\left(\frac{\hat{x}}{e}\right) = \frac{m\Omega^2}{\sqrt{\left(c - m\Omega^2\right)^2 + \left(d\Omega\right)^2}}$$



Lateral Vibrations due to Unbalance

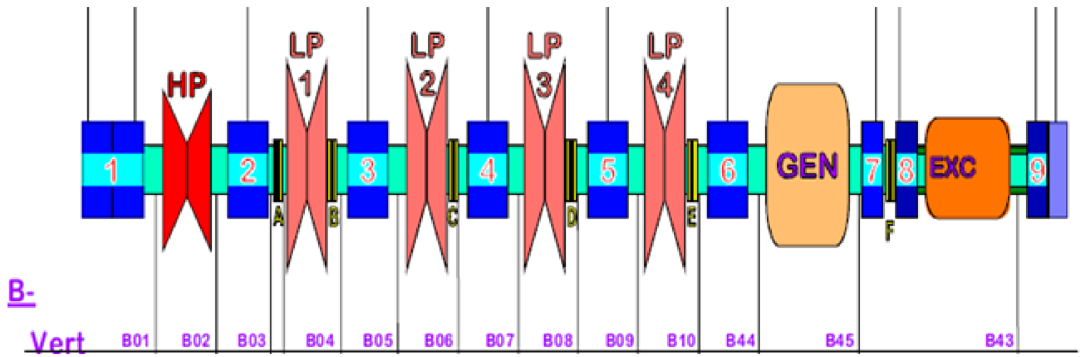
Investigation Techniques–Vibration Analysis (Design)



Lateral Vibrations due to Unbalance

Investigation Technique – Vibration Analysis on site

Measurement of absolute bearing vibrations in mm/sec

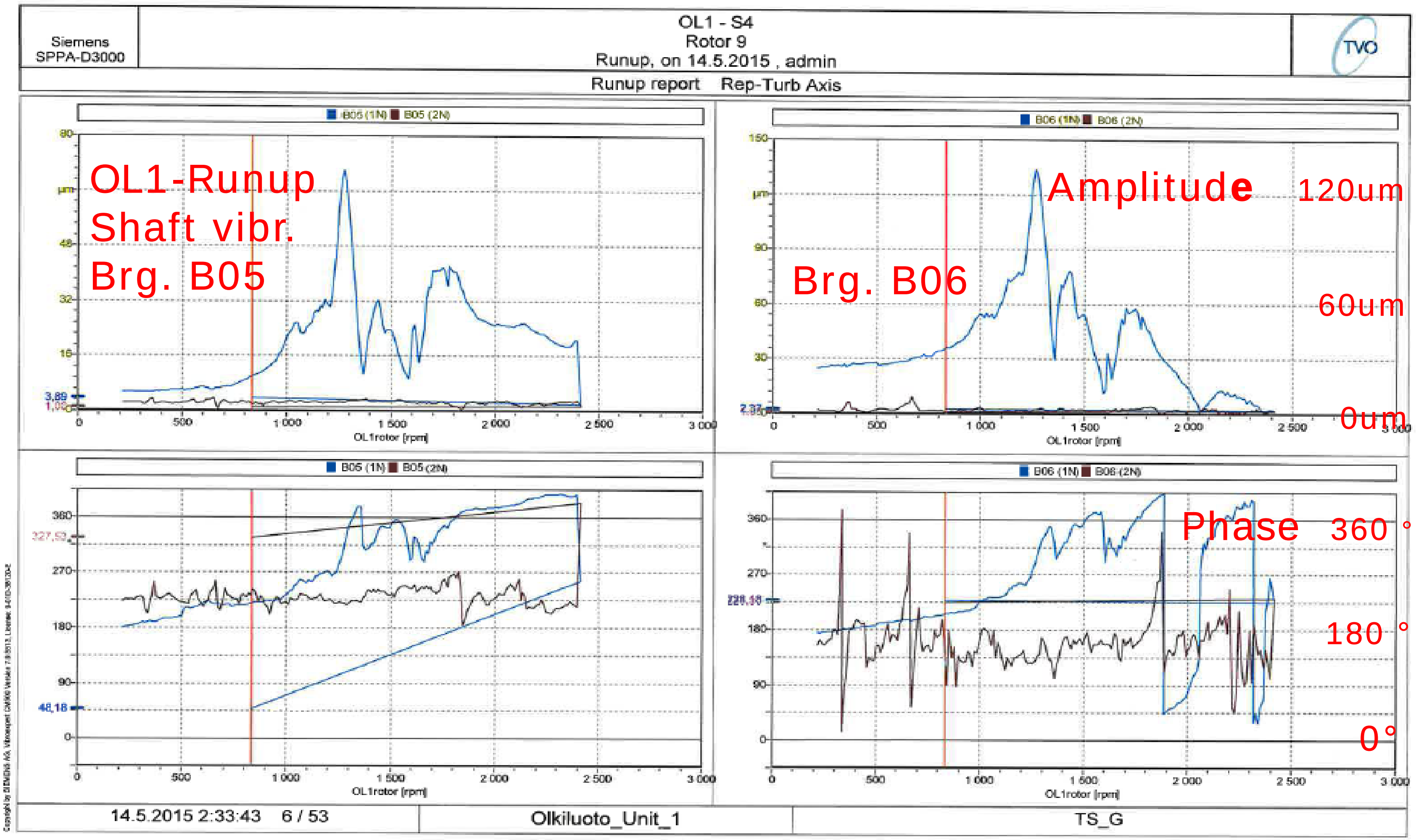


Measurement of relative shaft vibrations in um

Measurement of relative shaft vibrations in µm and absolute bearing vibrations in mm/sec with well suited transducers.

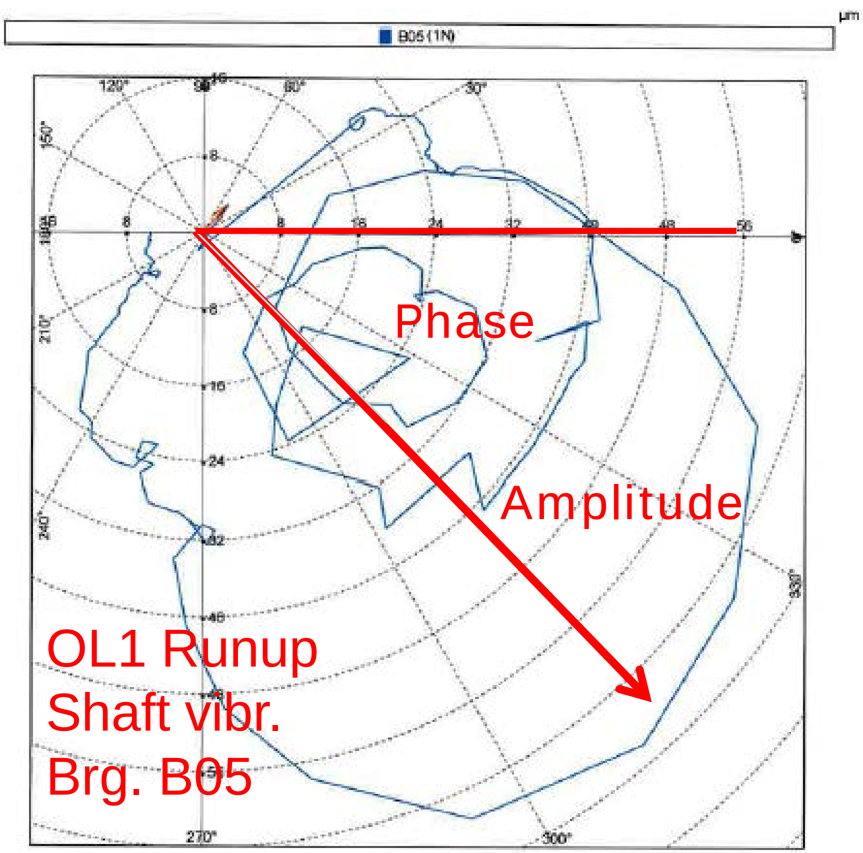
Lateral Vibrations due to Unbalance

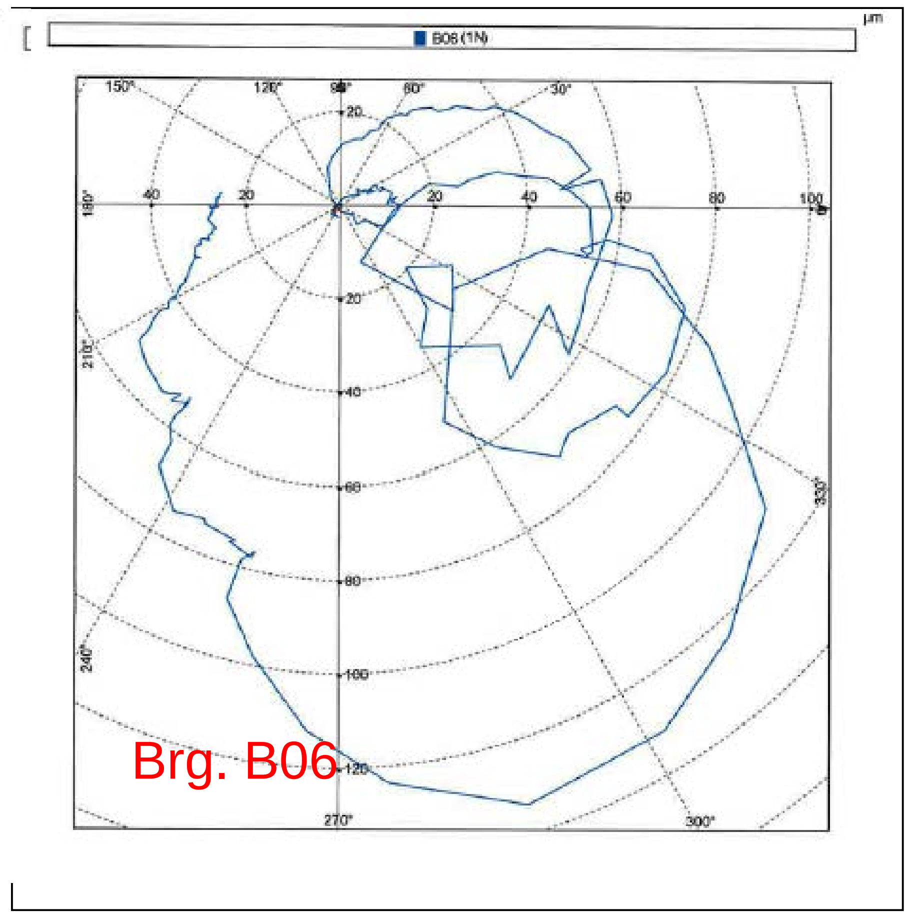
Observed Vibrations in Shaft Trains



Lateral Vibrations due to **Unbalance**

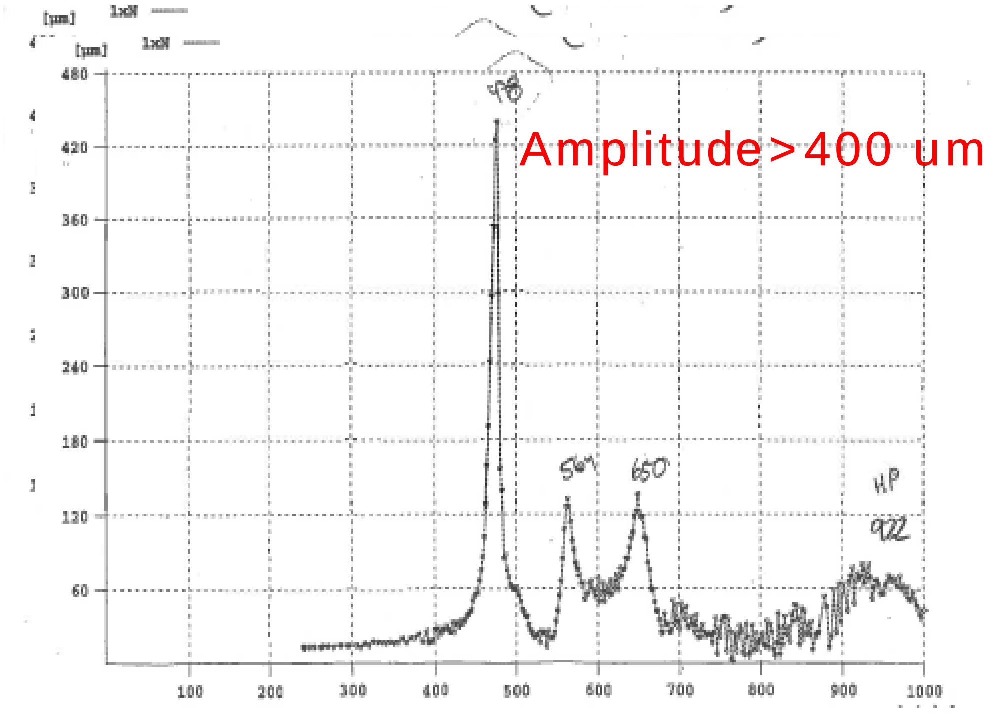
Observed Vibrations in Shaft Trains

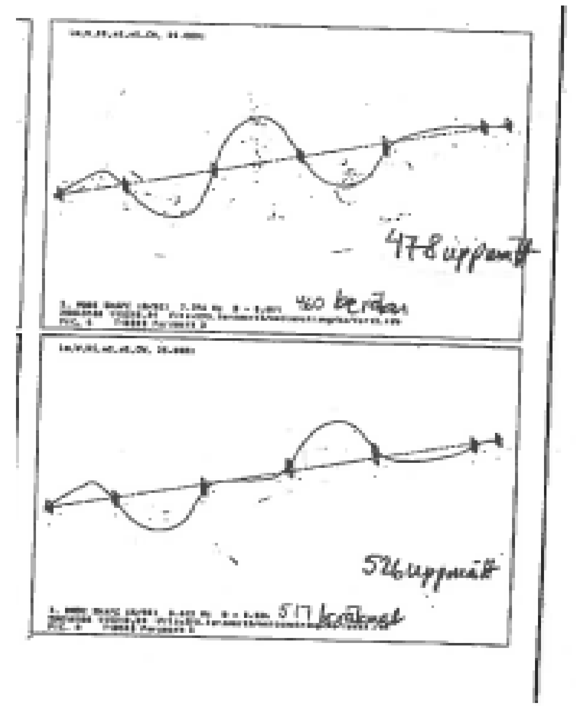




Lateral Vibrations due to Unbalance

Observed Vibrations in Shaft Trains





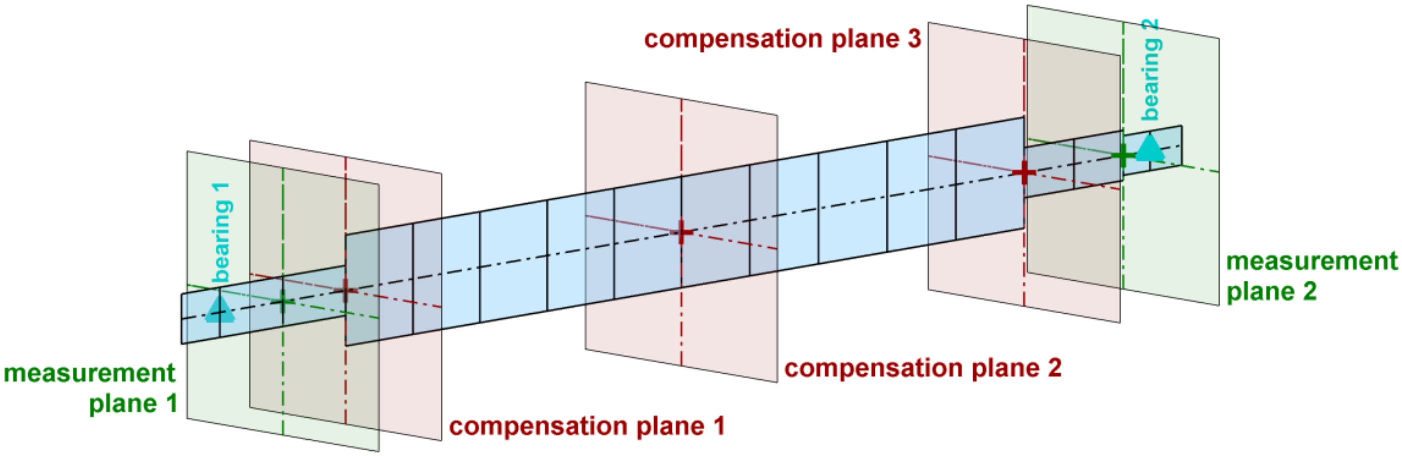
Run up curve with low damping in resonance at 478 rpm.

Mode shape with small bearing displacements .

Lateral Vibrations due to Unbalance

Vibration Problem Mitigation

$$\left(\boldsymbol{K} - \Omega^2 \boldsymbol{M}\right) \boldsymbol{x}(\Omega) = \boldsymbol{F}(\Omega)$$



Balancing with Influence Coefficients

$$\alpha_{ik}(\Omega) = \frac{x_i(\Omega)}{U_k}$$

$$\boldsymbol{F}(\Omega) = \boldsymbol{U} \cdot \Omega^2$$

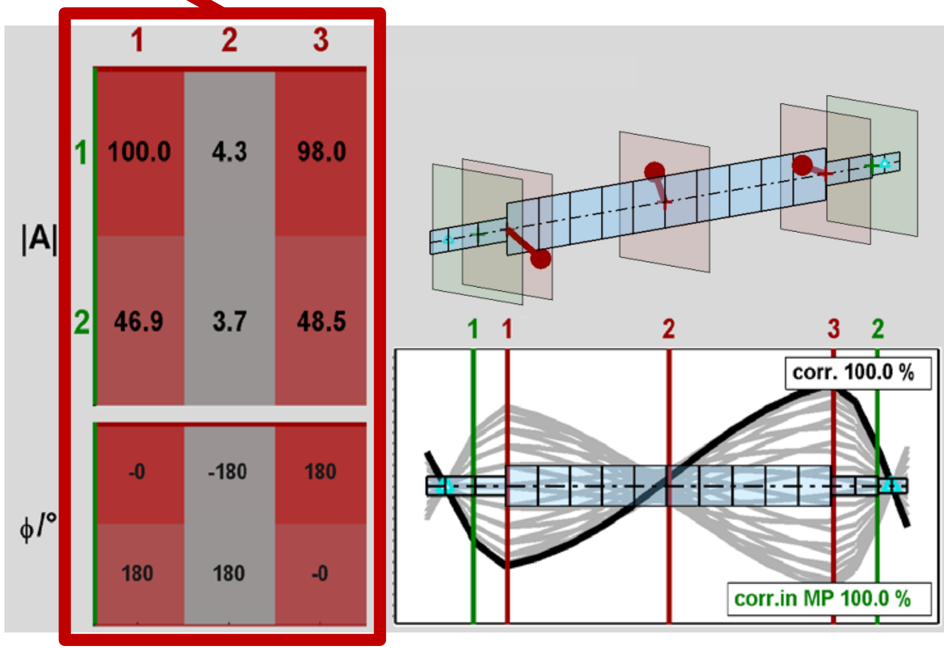
$$U_k = m_k \cdot e_k$$

Lateral Vibrations due to Unbalance

Vibration Problem Mitigation

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix}$$

- **Measured displacements x_i** and
- Unbalances U_k are connected via
- **Matrix of Influence Coefficients α_{ik}**

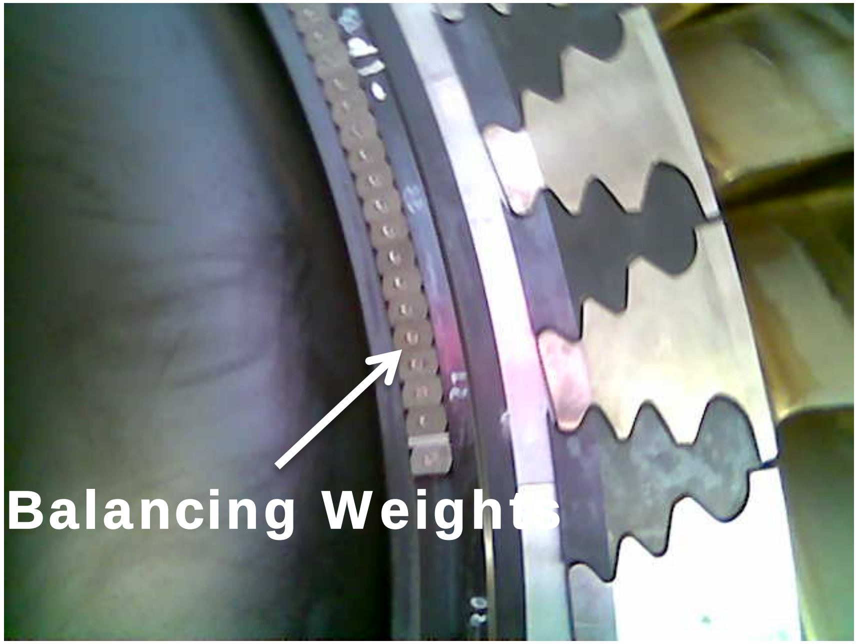


Example

2 measurement planes
3 compensation planes

Lateral Vibrations due to Unbalance

Vibration Problem Mitigation



Lateral Vibrations due to Heating**-Cyclic Vibrations**

Physical Description

Cyclic Vibrations occur due to weak rubbing between rotor and stator parts (e.g. Brushes in slip ring units, bearings, labyrinth and oil seals). Local Heating leads to a thermal unbalance which is superimposed to the mechanical unbalance. The resulting unbalance vector rotates.

Cyclic Vibrations can be stable or unstable.

The occurrence of this Vibration Phenomenon depends on the dynamics of the rotor - Natural Frequency and Damping - and on the ratio of Heat input to Heat output.

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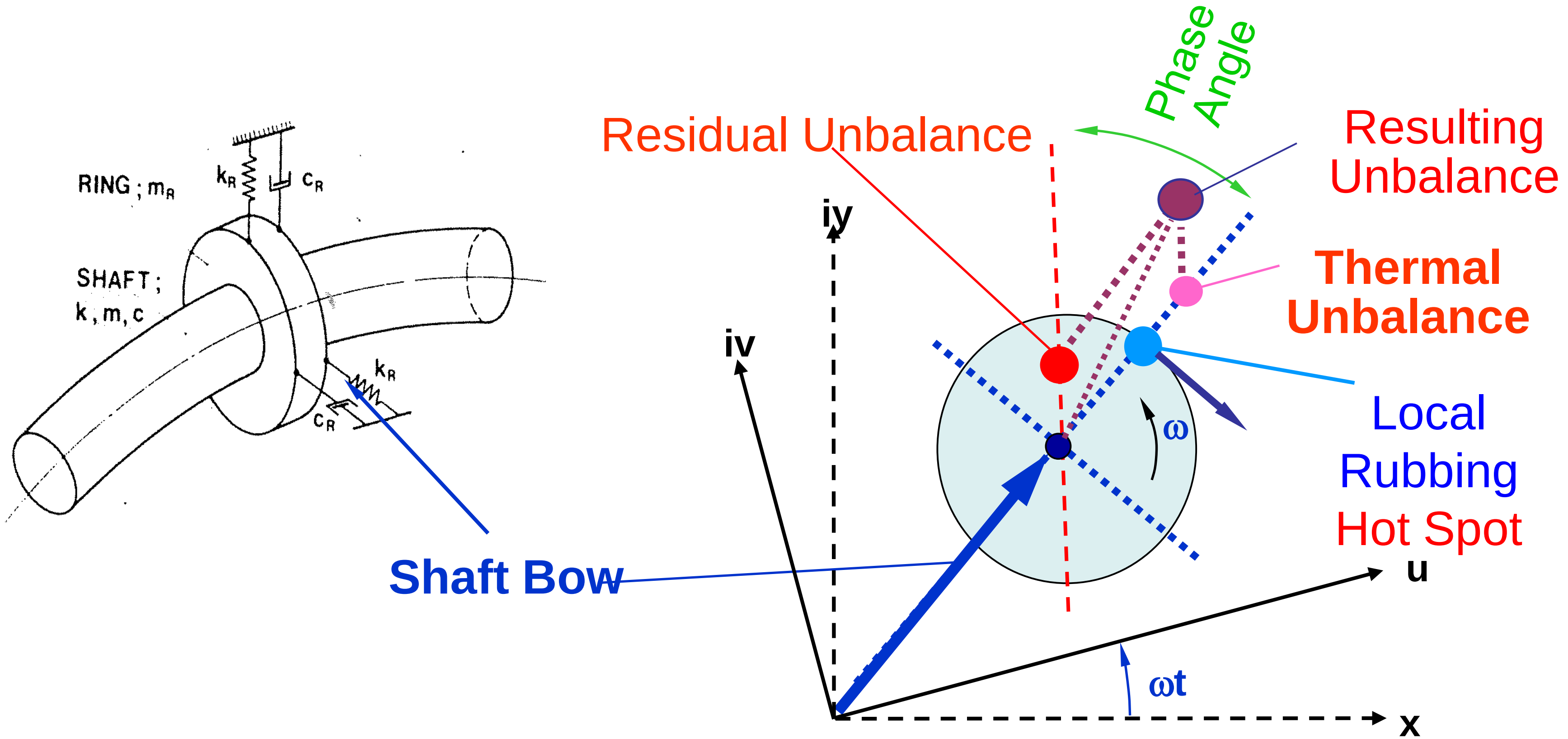
Lateral Vibrations due to Heating-**Cyclic Vibrations**

Physical Description: Local rubbing on shaft = Hot Spot
Local heat input, thermal deflection, thermal unbalance, superposition of unbalance leads to Vector rotation

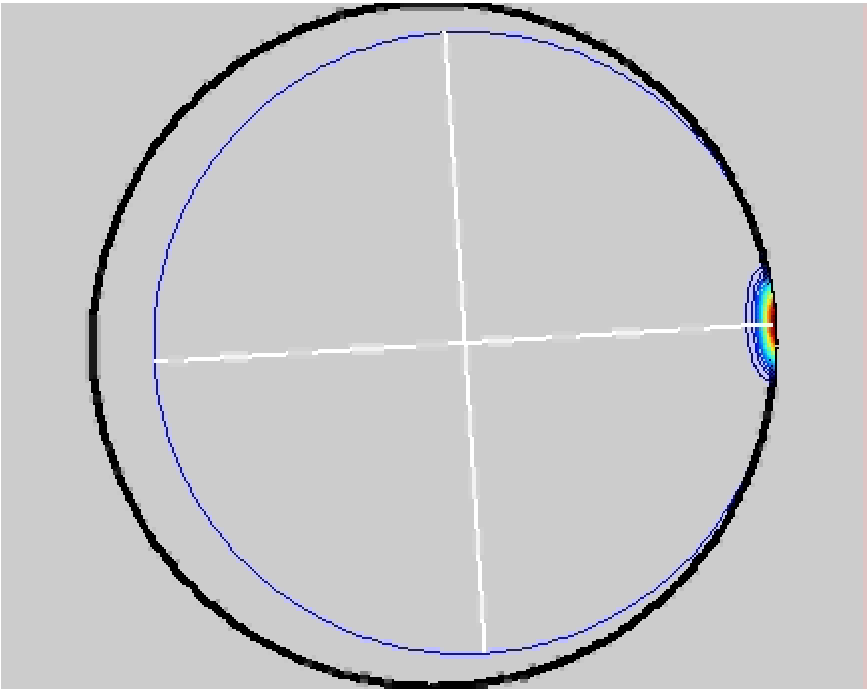


Lateral Vibrations due to Heating-**Cyclic Vibrations**

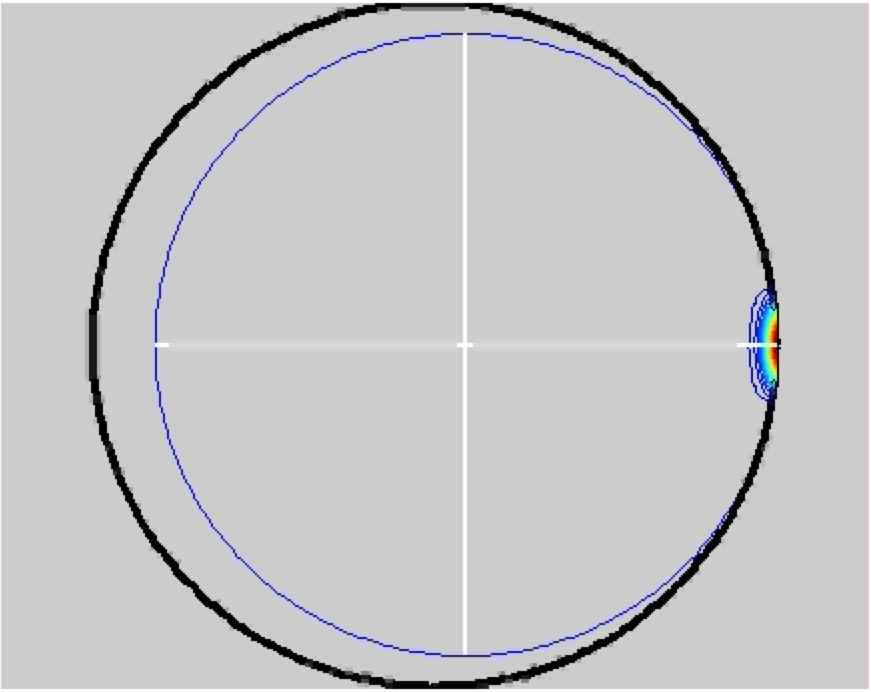
Physical Description: Demonstration of the Hot Spot.

Example: Rubbing between rotor and stator (seals, brushes)

Fixed Coordinate System



Rotating Coordinate System

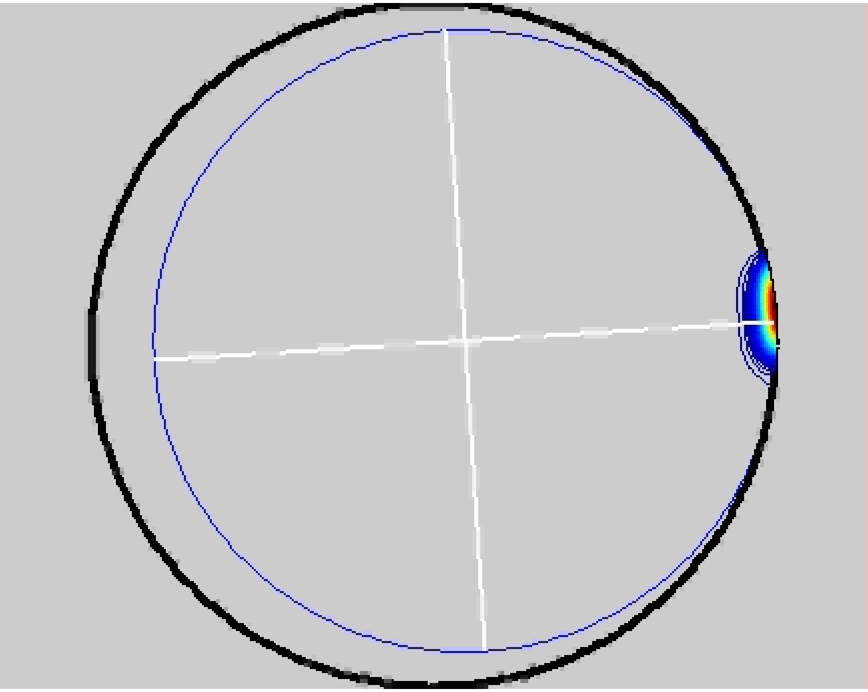


Freq. ratio 1: Hot Spot-Local Heat input causes a **Thermal Bow**

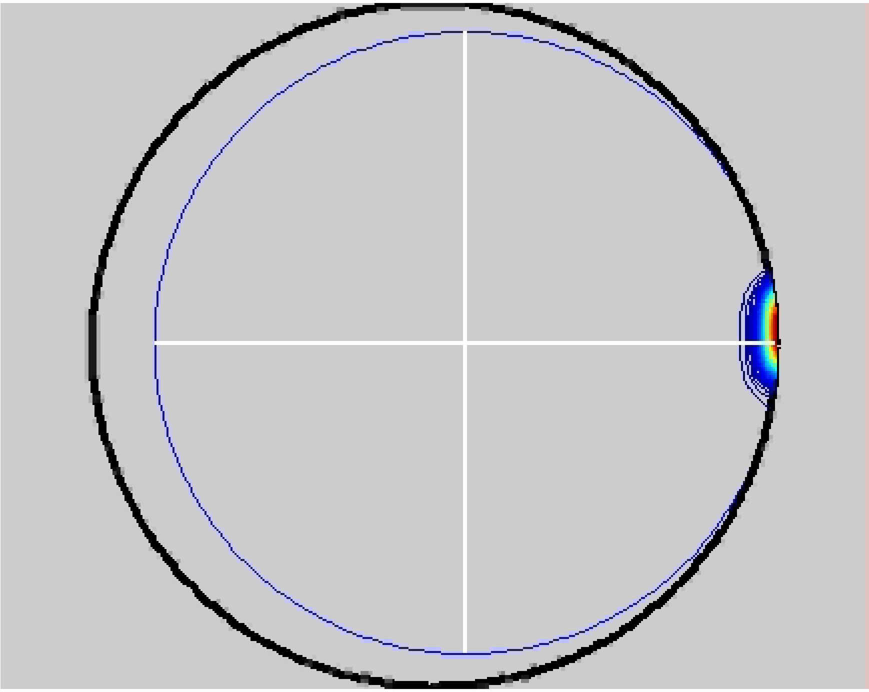
Lateral Vibrations due to Heating-Cyclic Vibrations

Physical Description: Demonstration of the **Hot Spot**

Fixed Coordinate System



Rotating Coordinate System

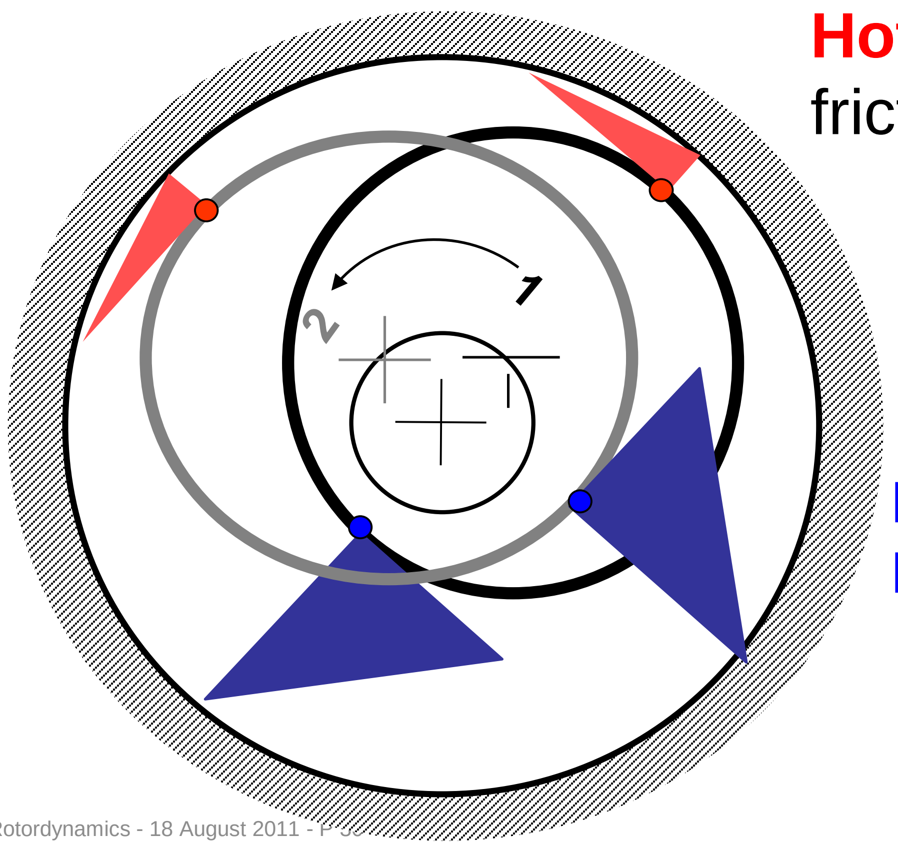


Freq.ratio 2 : Location of Heat input changing –No **thermal bow**

Lateral Vibrations due to Heating-Cyclic Vibrations

Physical Description: Demonstration of the **Hot Spot**

Friction in Fluid bearings or other fluid filled clearances

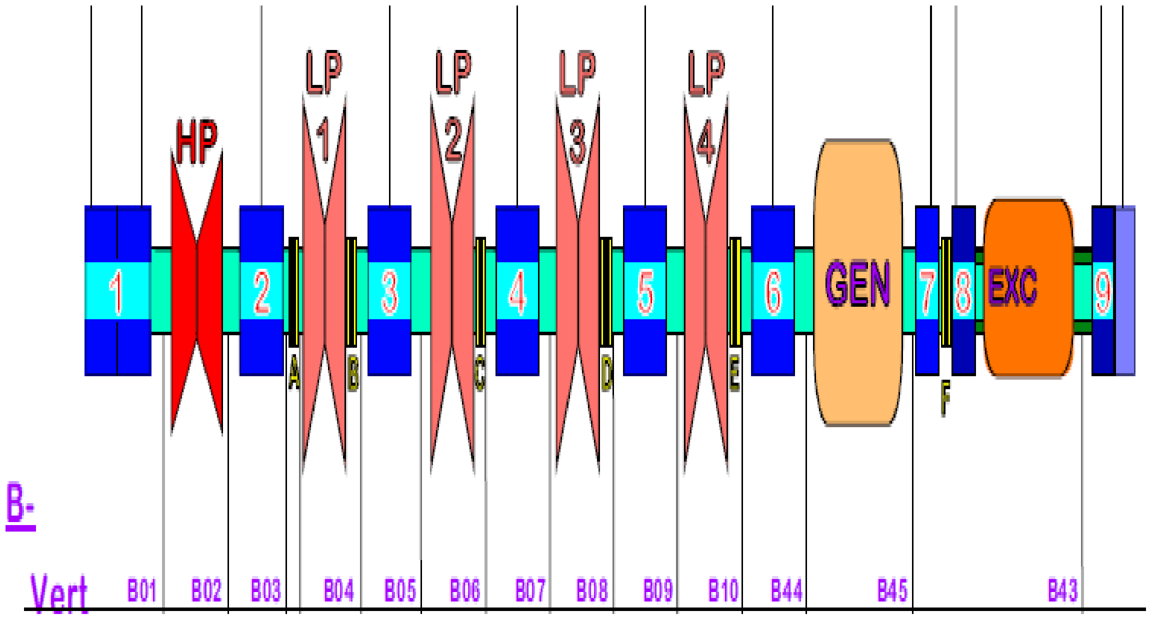


Hot Spot at narrow gap, friction between rotor & fluid

Kellenberger – Morton Effect

Lateral Vibrations due to Heating-**Cyclic Vibrations**

Investigation Techniques-Vibration Analysis

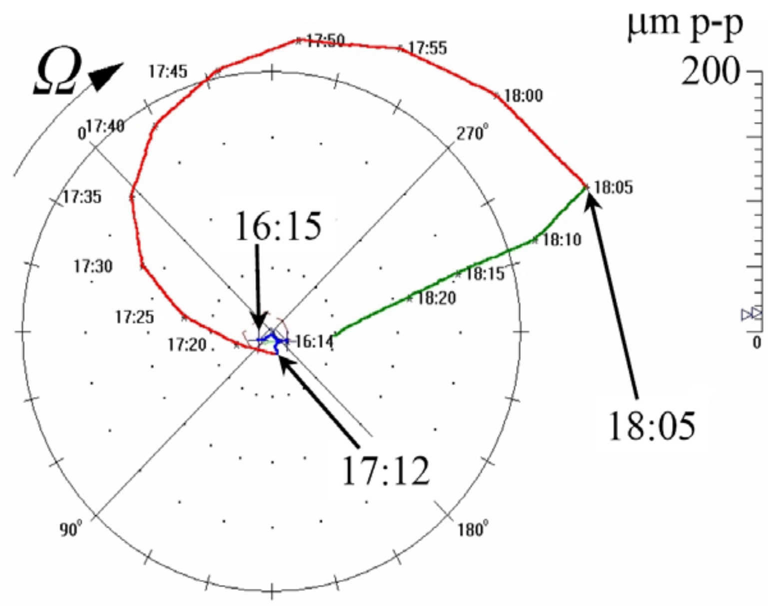


Measurement of 1X- shaft vibrations. Transfer to Frequency Domain. Observe the vector plot with changing amplitude and phase. Stable or unstable?

Num. Analysis with extended Rotordynamic tools possible

Lateral Vibrations due to Heating-**Cyclic Vibrations**

Investigation Techniques-Vibration Analysis

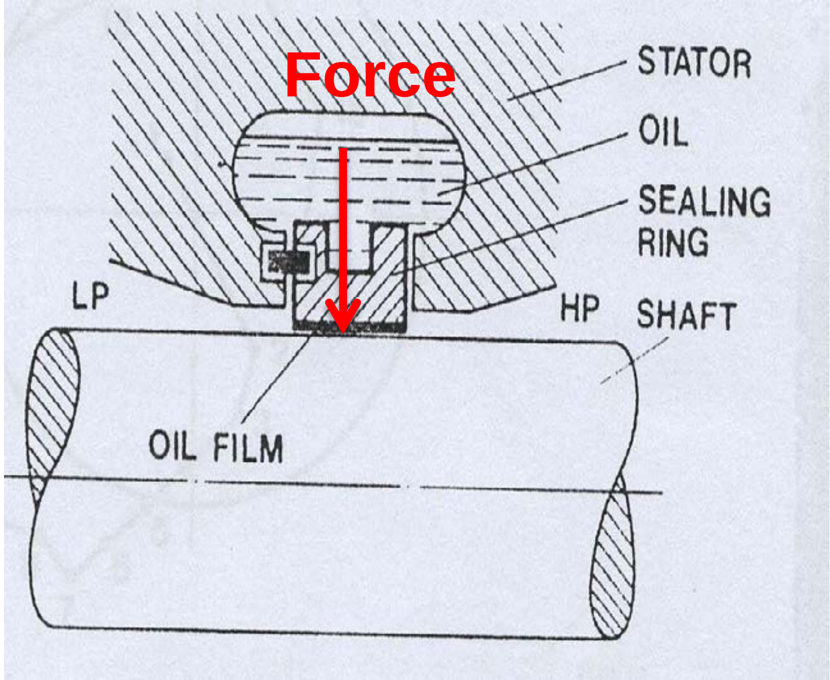


16:15 – 17:12:
Run at rated speed of 3600 rpm without brush
→ Stable vibration amplitude.
17:12: Brushes installed
→ Spiral vibration started (red line)
18:05: Brushes removed
→ Spiral vibration stopped (green line)

Figure 3: Measured relative shaft vibration at NDE-bearing. Rotor speed n = 3600 rpm

Test with installed and removed Exciter Brushes

Lateral Vibrations due to Heating-**Cyclic Vibrations**



In gas cooled turbogerators shaft sealing rings are fitted to prevent the pressurized gas from leaking. The rings encircle the shaft and are mounted in the stator. They slide on the shaft, the eccentricity of which causes them to translate in their stator mountings.

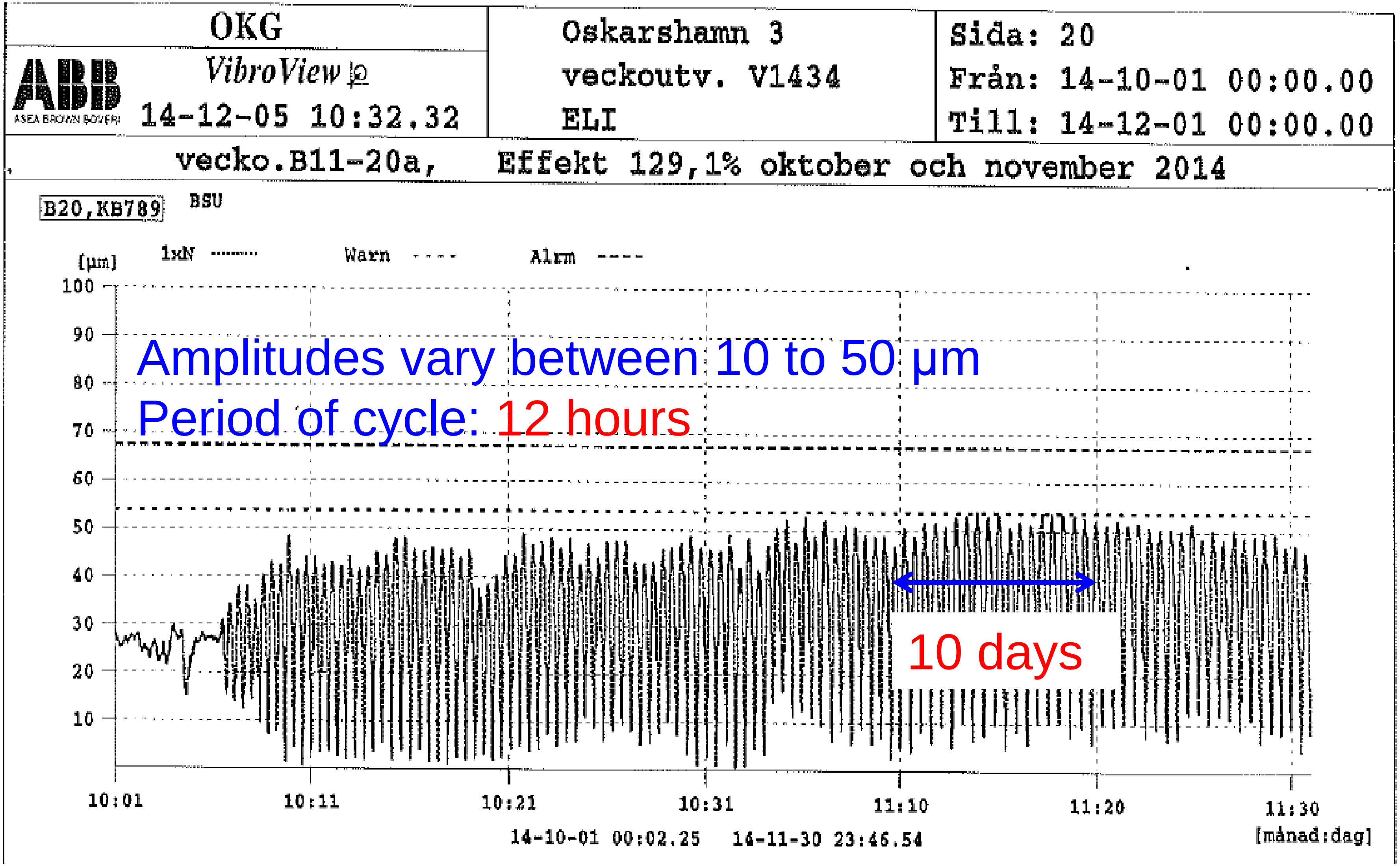
The mountings are oil lubricated and the motion in the oil produces a Force on the ring, which is transferred to the shaft. The heat arising from the resulting friction loss is partly absorbed into the shaft. The heat supply is not uniform round the shaft circumference and causes the shaft to bow.

Lateral Vibrations due to Heating**-Cyclic Vibrations**

Observed Cyclic vibrations in Oskarshamn/O3

The source of this vibration is assumed to be in the oil sealing rings in the gas cooled turbogenerator. The following diagram shows the change of 1X vibrations versus time at a transducer location at the Generator bearing.
In the investigations it has also been assumed, that pressure variations in the oil system might be the source of the problem.

Lateral Vibrations due to Heating-**Cyclic Vibrations**



Lateral Vibrations due to Heating**-Cyclic Vibrations**

Vibration Problem Mitigation

Avoid rubbing by adjusting the oil seal ring position.
Pressure control in the oil system helped to reduce the cyclic vibrations.

Study of the design and mechanism of the oil seal system.
Estimation of heat input and heat output.

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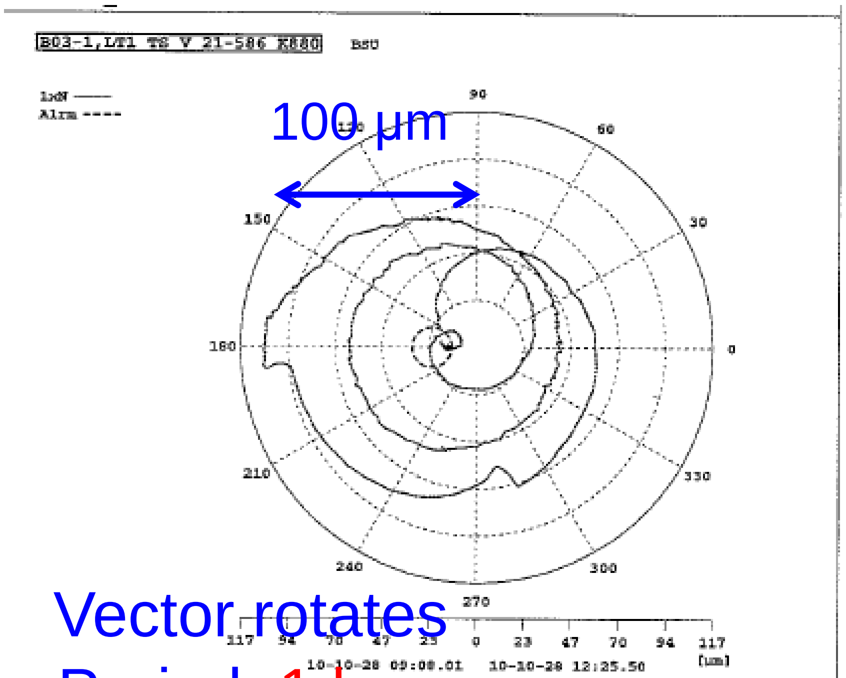
Lateral Vibrations due to Heating-**Cyclic Vibrations**

Observed Cyclic vibrations in Forsmark F21

Cyclic vibrations were also observed in Unit F21 during Runout tests at rotational speed 500 rpm. High 1X vibrations mainly occured at a transducer (LT1/TS) in vertical direction. It was assumed, that the hot spot was at the steam seals in LT1.

Lateral Vibrations due to Heating-Cyclic Vibrations

Observed Cyclic vibrations in Forsmark21



Vibration Problem Mitigation

Avoid rubbing in steam seals by adjusting the seal positions
Improve damping in the rotor.
Various test runs with different speeds 400 – 600 rpm resulted finally in a stable condition..

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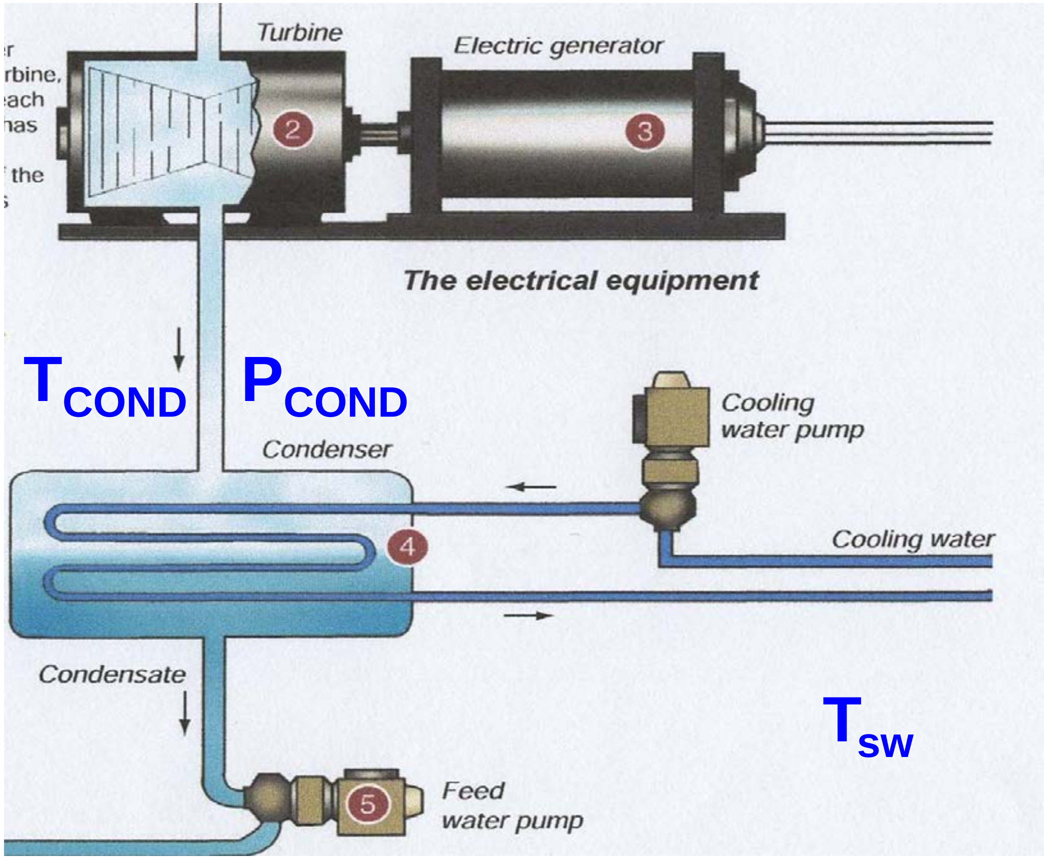
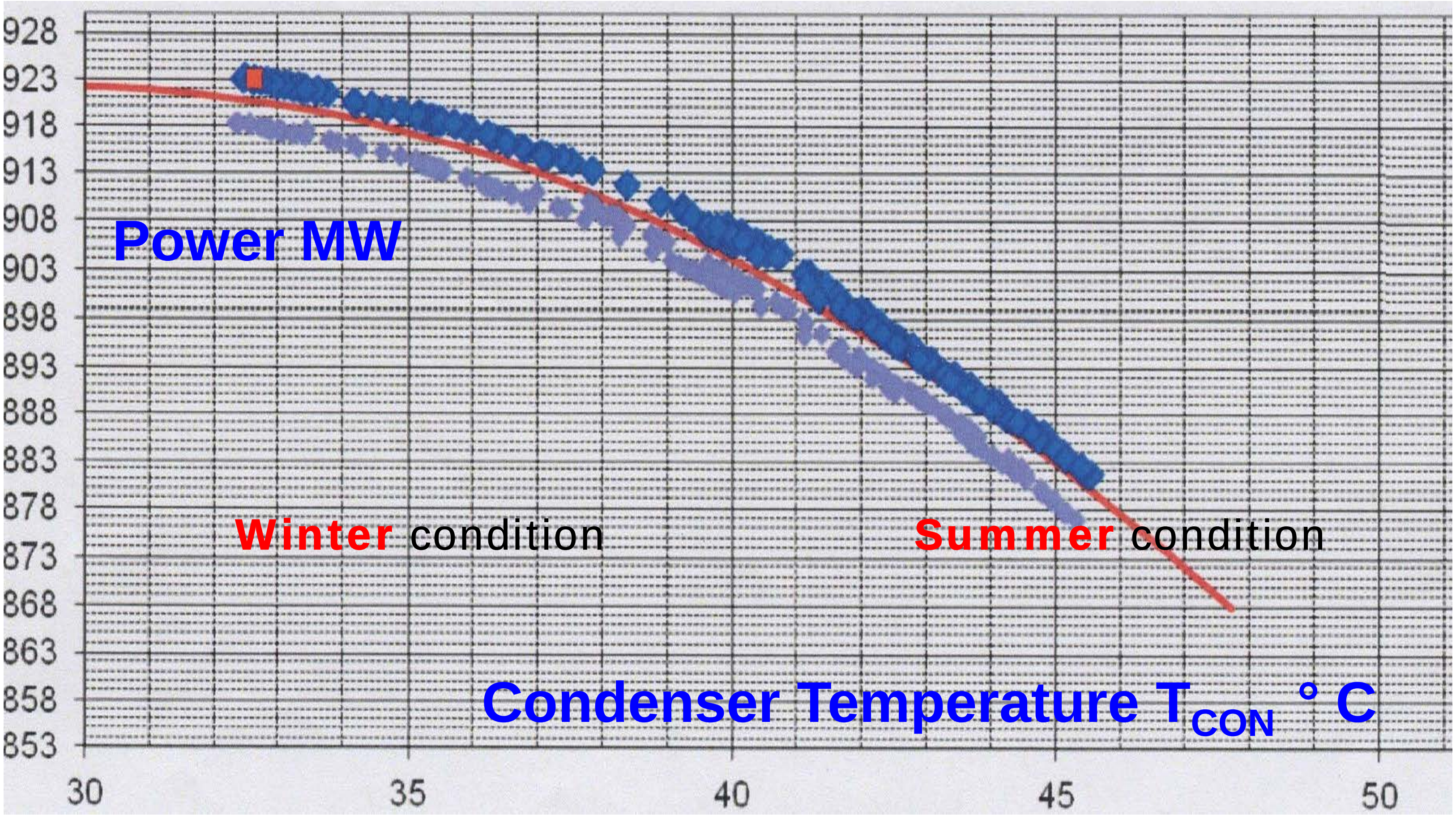
Lat. Vibrations due Change of Seawater temperature

Physical Description



In the condenser steam from LP turbines is cooled down and turned back to water. For this sea water is used as cooling water. In Winter the temperature of the sea water is decreasing and with that the condenser temperature and pressure and the LP turbine pressure as well. This leads to a higher Power output (due to a higher Δp). The changing sea water temperature influences the lateral vibrations of the rotor train in different ways.

Lat. Vibrations due Change of Seawater temperature



Lat. Vibrations due **Change of Seawater temperature**

Observed Lateral Vibrations in Oskarshamn O3

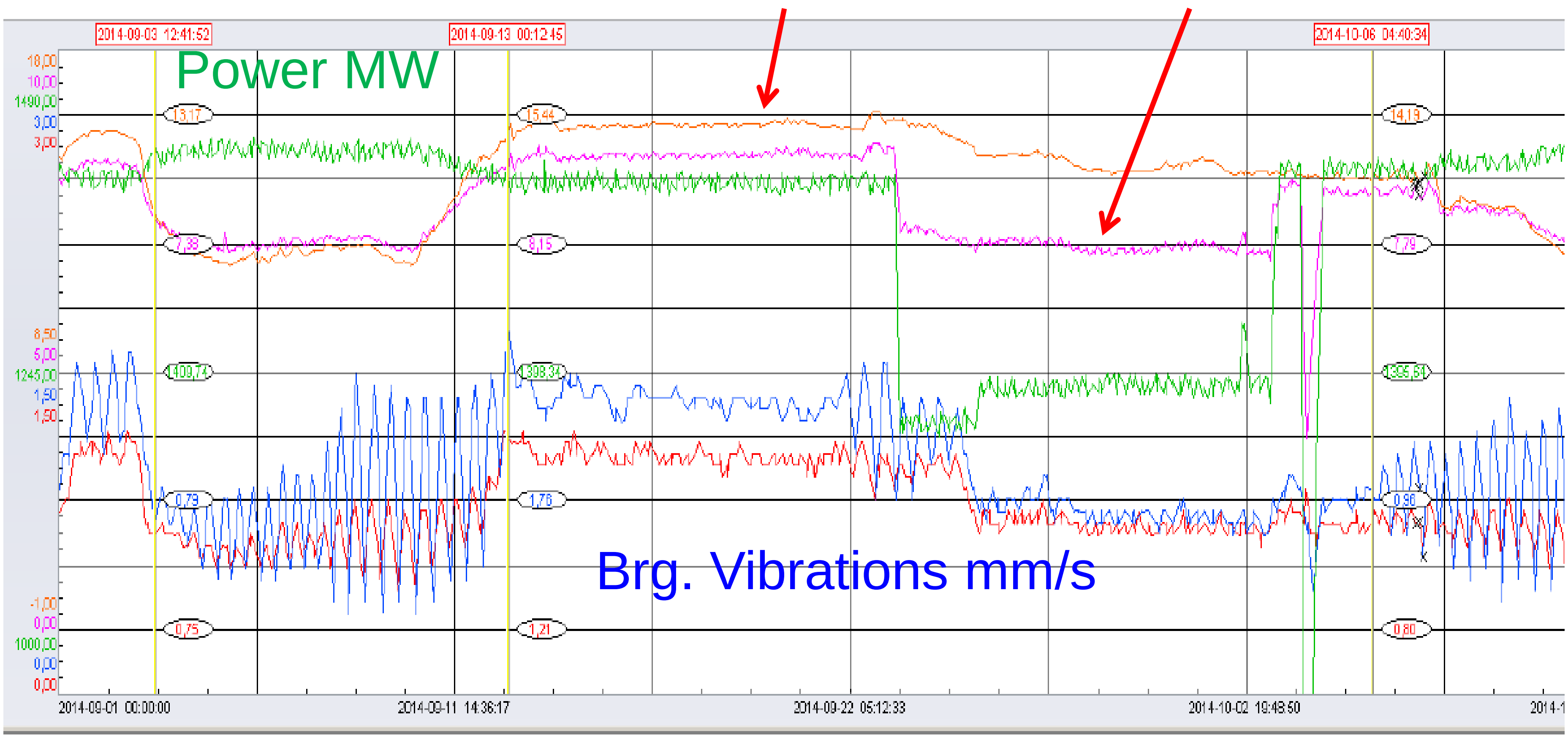
When the cooling water temperature becomes higher than 10 – 14 ° C, the percentage of water in the LP turbine increases. Usually sheet-metals are used to avoid, that the water falls down to the shaft. It seems that water came down to the shaft in the O3 unit, leading to a thermal shaft bow with increasing 1X unbalance vibration. There is a hypothesis from EDF, based on a numerical CFD study, which is not well understood needs to be analyzed in more detail.

Lat. Vibrations due **Change of Seawater temperature**

The next figure shows vibration velocities in mm/s for two bearings. The average vibration values follow the condenser temperature and pressure curves, e.g. decreasing vibrations with decreasing temperature and pressure and vice versa. This confirms the hypothesis of a thermal bow due to water streaming on the rotor. The superimposed cyclic vibration was assumed to have its origin in the oil seal system of the generator The period of one cycle is again about 12 hours. It seems, that also the cyclic part is influenced by condenser pressure and temperature.

Lat. Vibrations due Change of Seawater temperature

Condenser Temperature and Pressure



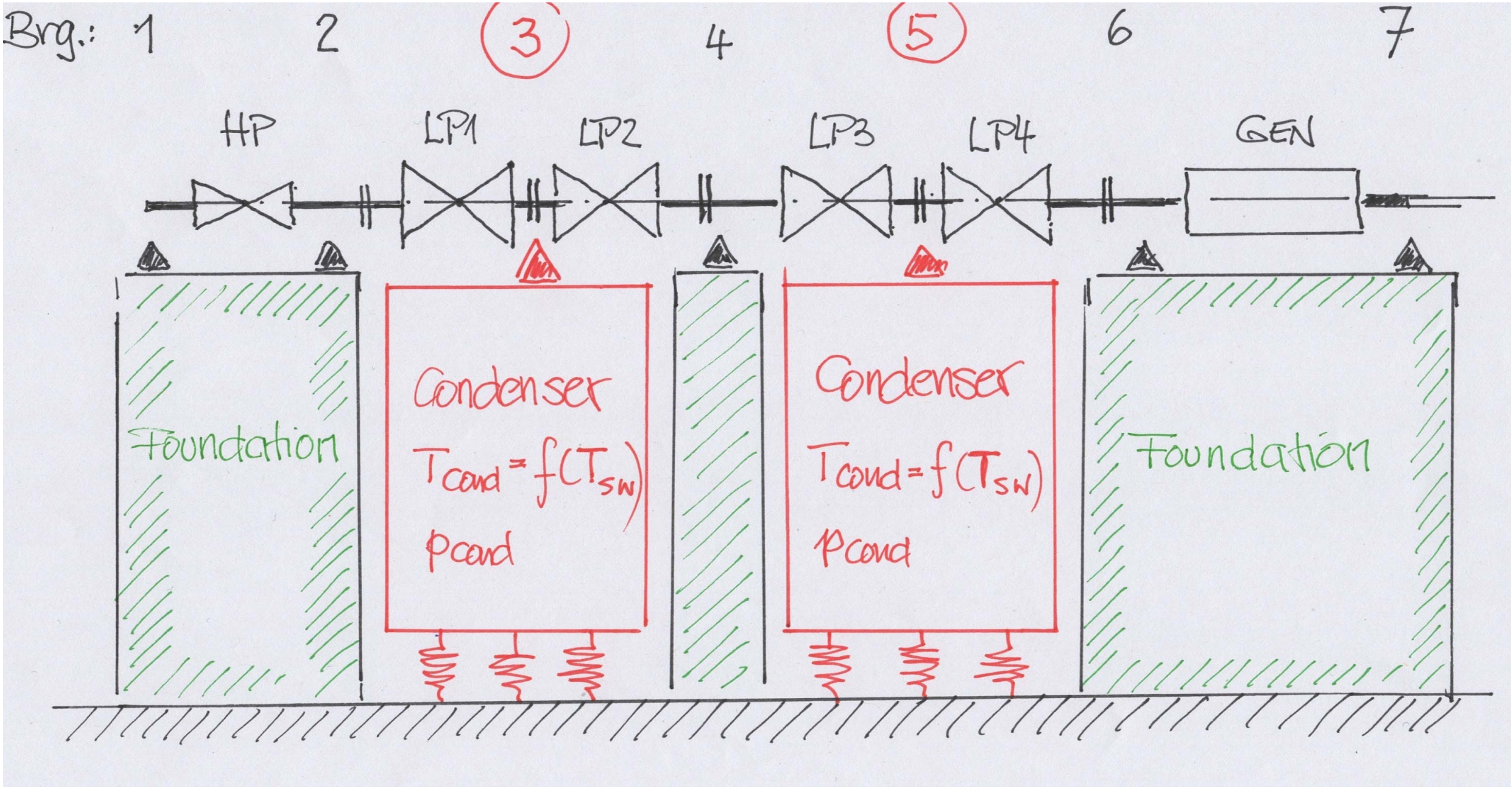
Lat. Vibrations due Change of Seawater temperature

Observed Lateral Vibrations in Olkiluoto

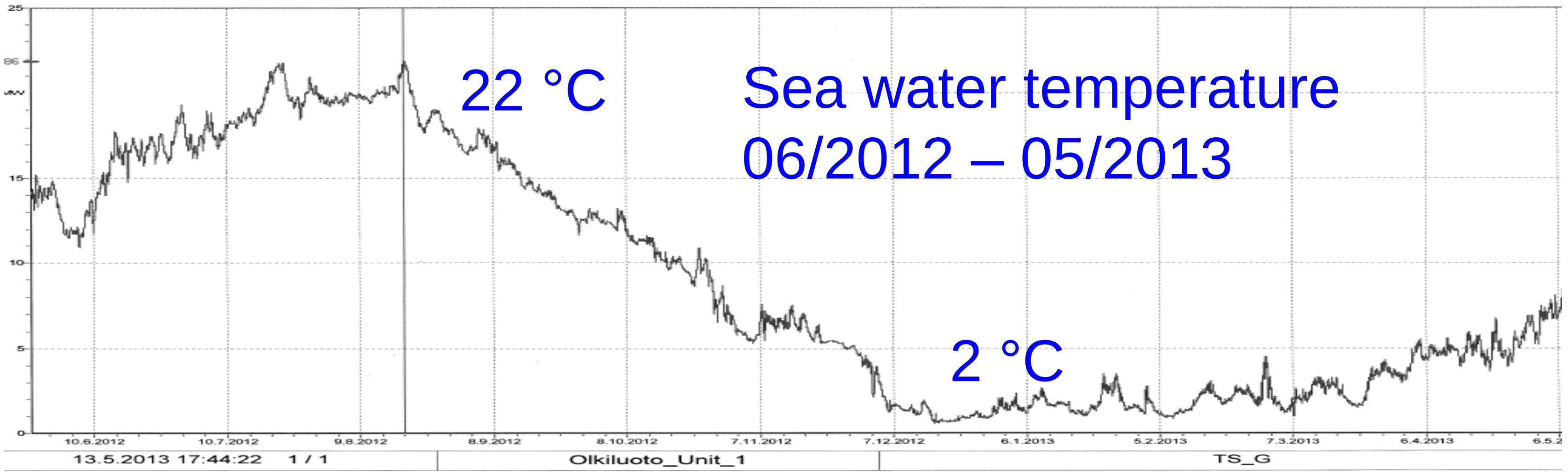
The next figure shows the arrangement of the OL1/OL2 Units with rotor train, foundation and condenser.

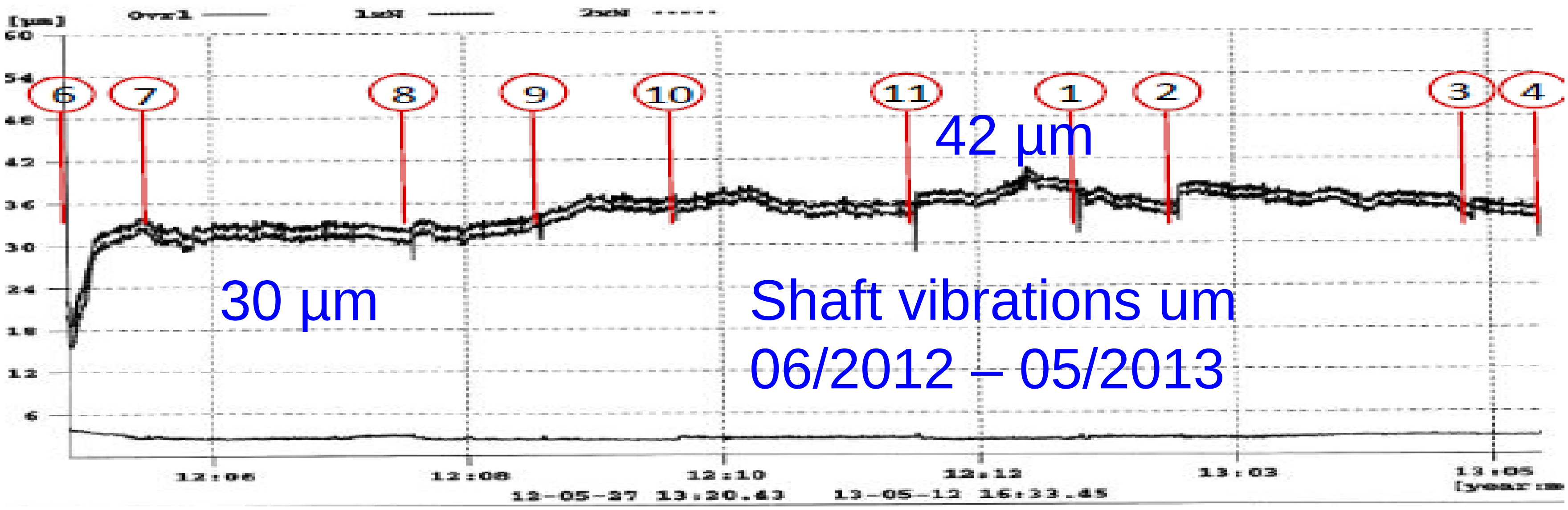
Bearings 3 and 5 are mounted on the condenser, other bearings on the foundation. In case of changes of the seawater temperature condenser temperature and pressure change as well, leading to a relative thermal condenser deformation. Due to this bearings 3 and 5 are moving relative to the shaft train and the static bearing forces will be different. They have an influence on the dynamic characteristics of the oil film and the lateral vibrations.

Lat. Vibrations due Change of Seawater temperature



Lat. Vibrations due **Change of Seawater temperature**





Lat. Vibrations due Change of Seawater temperature

Vibration Problem Mitigation

Avoid water films streaming down on the LP-rotor by protecting the rotor with sheet metal (sealing).
Change Active Power.
Check influences of different process parameters, e.g. condenser temperature and pressure, active power, on the static movement of the shaft axis relative to the seals.
Investigate heat input in oil seal system.

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Turbine and Generator Vibrations

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Vibration Problem Areas – Grouping and Analysis

Lateral Vibrations in Shaft Trains due to

- Unbalance
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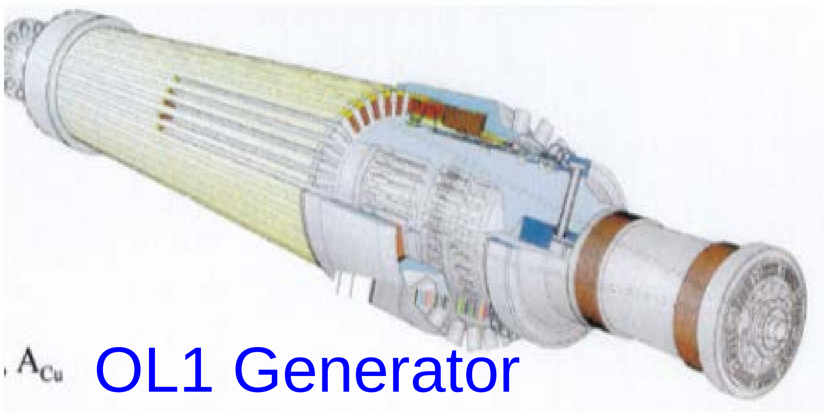
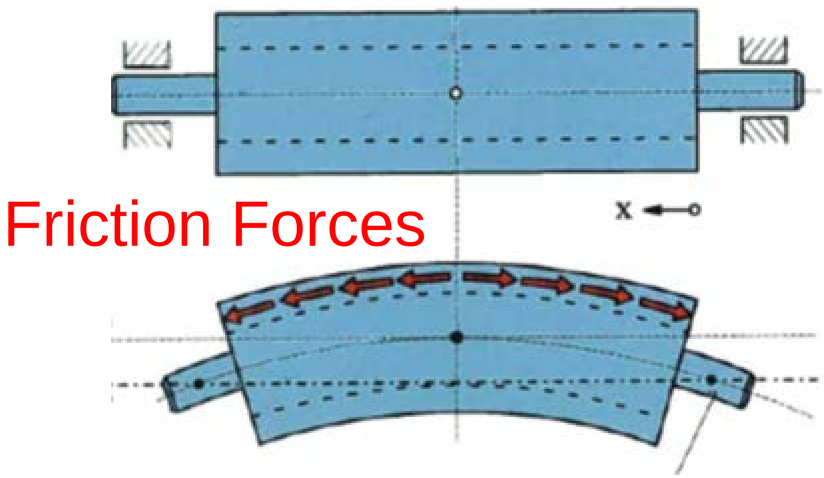
- Other Excitation sources (Friction, Instability,…)

Lateral Vibrations in Shaft Trains

Grouping	Analysis	Mitigation
Lateral Vibrations due to Unbalance	Run up and Run down curves. Critical Speeds (peaks). Damping. Short term and long term behav.	Balancing with Influence coefficients. Improve damping. Shift resonances by tuning.
Lateral Vibrations due to Heating-Cyclic Vibrations	Amplitude and phase versus time. Determine change of amplitudes and period. Polar plot. Rot.Vector.	Avoid rubbing by adjusting seal position.Pressure control in oil seal syst. Improve damping. Estimate Heat input.
Lateral Vibrations due Friction in Generators	Heat runs. Influence of temperatures, pressure and speed on vibrations (Geno).	Avoid unsymmetry in circumference for friction, pressure, temperature. Control winding temperature.

Lateral Vibrations in Shaft Trains **due to Friction**

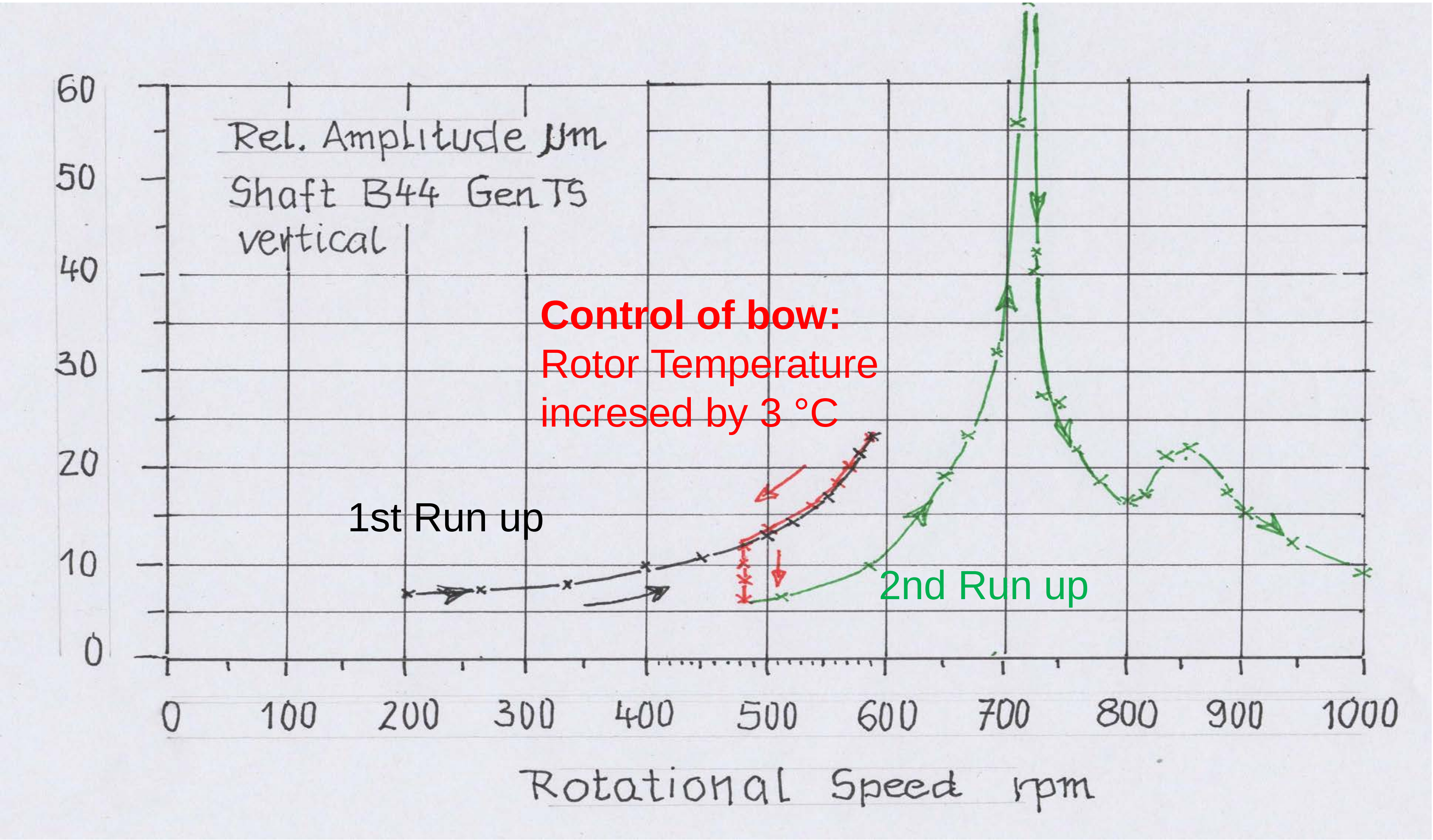




Friction Forces between the cupper windings and the generator steel rotor depend on temperature differences, the rotational speed, the mounting pressure and the friction coefficient between cupper and steel. In case of unsymmetrically distributed friction forces in circumference direction a friction induced rotor bow (unbalance) may lead to high 1X lateral vibrations of the generator rotor.

Lateral Vibrations in Shaft Trains due to Friction

Observed Friction Induced Vibrations and Mitigation

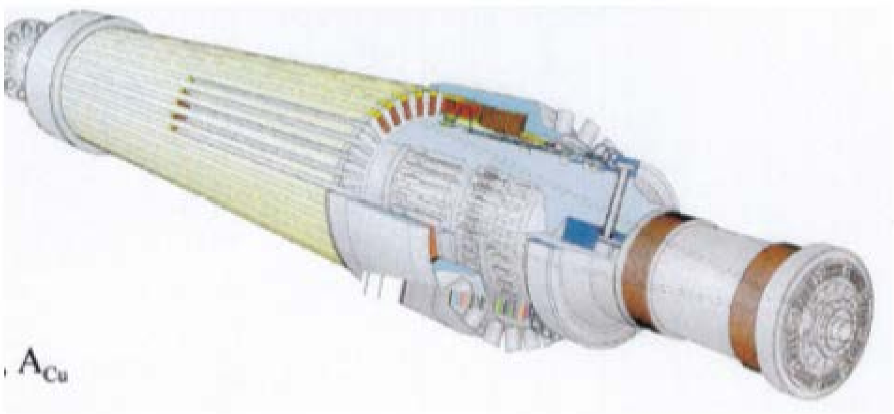


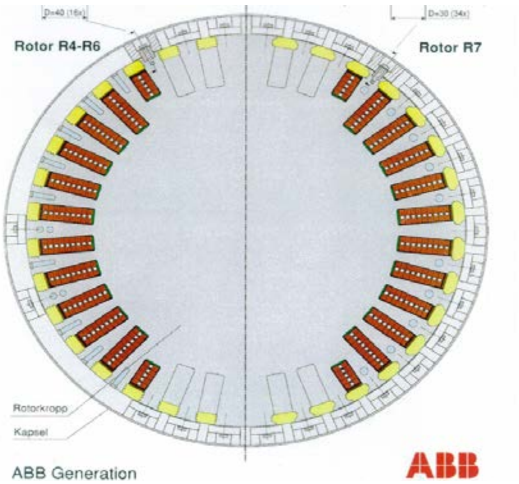
Lateral Vibrations in Shaft Trains

Grouping	Analysis	Mitigation
Lateral Vibrations due to Changes in Sea Water temperature	Investigate vibration versus time depending on condenser temperature, pressure and power	Protect rotor by sheet metal against water. Reduce active Power. Check process param. Adjust seals.
Lateral Vibrations due to Instability	Investigate Frequency spectra and look for half frequency components, e.g. from bearings or seals	Change bearing parameters, improve damping.Decrease power in case of HP seal instability.
Lateral Vibrations due to Unequal Moments of Inertia	Investigate lateral 2X and 1X vibration components in the range of .5 to 1.0 of 1st Geno Critical	Slots in 2 pole Generator rotor. Improve damping

Lat. Vibrations due to Unequal Moments of Inertia

Physical Description

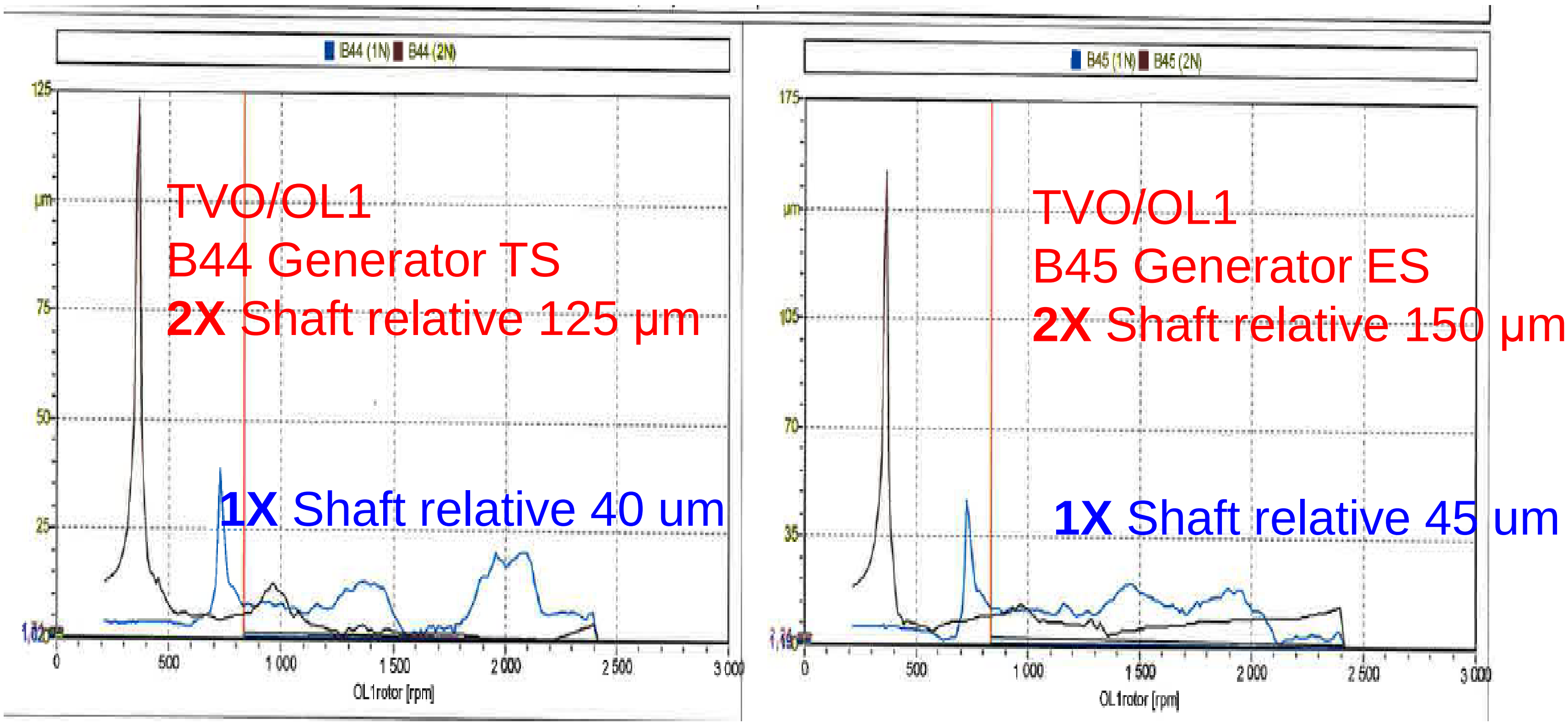




A two pole turbogenerator with unequal Moments of Inertia has different bending stiffnesses in two directions. When the shaft rotates the weight of the disk is lifted two times per one revolution. For the rotational frequency Ω besides the 1X unbalance excitation a frequency of excitation with 2X will also be observed (see weight resonance at next figure)

Lat. Vibrations due to Unequal Moments of Inertia

Observed 1x and 2x vibrations and Mitigation



With slots in the generator the different moments of inertia can be equalized. With that the effect of the 2X vibrations can be reduced (weight resonance).

Turbine and Generator Vibrations

Torsional Vibrations in Shaft Trains due to

- different Excitation sources

Stator Vibrations due to

- Electromagnetic Excitation

Identification of Vibration Problems

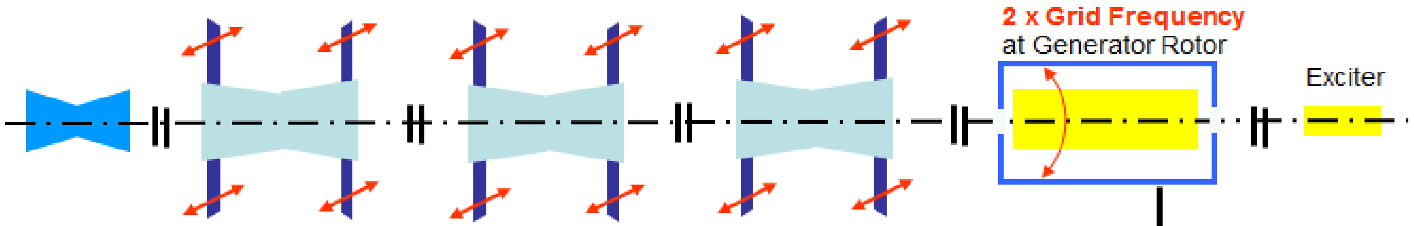
Conclusions

Torsional Vibrations in Shaft Trains

Grouping	Analysis	Mitigation
Torsional Vibrations due to Grid Unsymmetry (2X Excitation) and Electrical Faults.	Calculate Torsional Natural Frequencies. Transient Analysis of Electrical Faults, Shear Stresses. Encoder measurement	Keep Torsional Natural Frequencies outside limit range (ISO 22266). Monitoring and Lifetime Assessment.
Torsional Vibrations due to Sub Synchronous Resonance	Determination of low (subsynchronous) Torsional Natural Frequencies and allowable angular displacements.	SSR protection System: **S**ub **S**ynchronous Damping Controller (SSDC)
Torsional Vibrations with Coupled Blade Vibrations	Blade Vibration Measurements (BVM) on Blades.	De-activate partial vacuum breaking during run down.

Torsional Vibrations due to Grid Unsymmetry

Physical Description



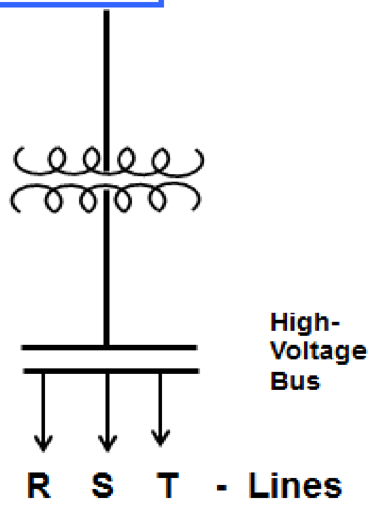
Excitation from the electrical Grid (RST Lines) due to non-symmetrical electrical Grid Loading

Excitation Frequency is 2 x Grid Frequency (100 or 120 Hz)

Calculate Torsional Natural Frequencies of Shaft Line

Calculate Coupled Mode Shape of Shaft and Blade

Check the Design Criteria (ISO 22266)

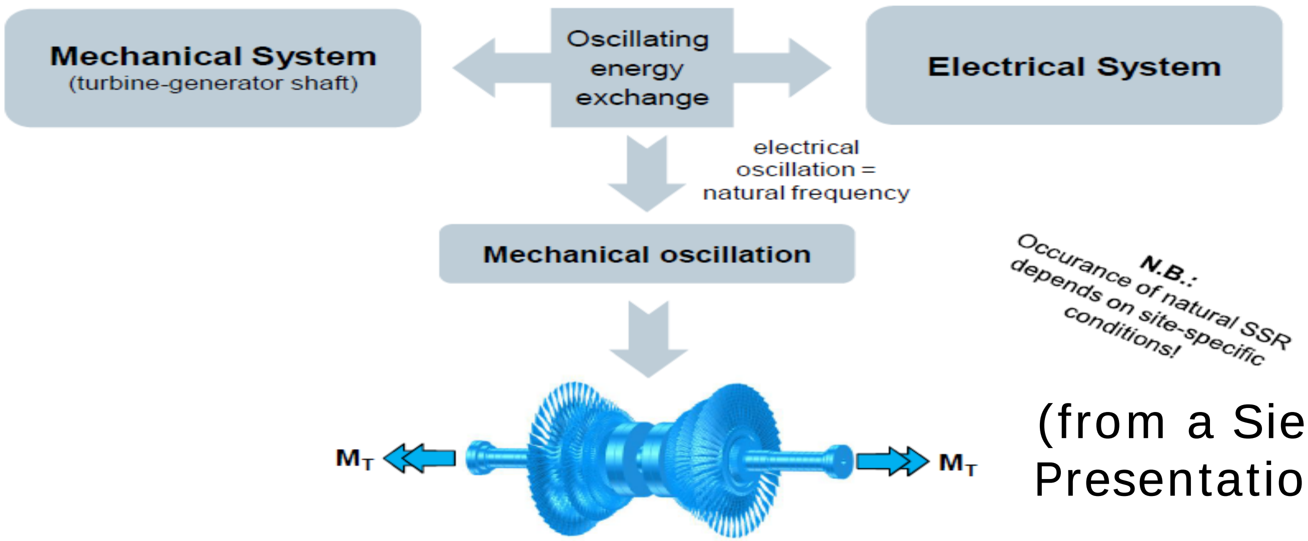


Analysis: Calculate Torsional Natural Frequencies

Mitigation: Natural Frequencies should be outside a limit frequency range (ISO 22266).

Torsional Vibrations due to Sub Syn. Resonance

Physical Description



(from a Siemens Presentation)

Analysis: Calculate Sub Synchronous Torsional Natural Frequencies & allowable angular displacements

Mitigation: Protection System Sub Synchronous Damping Controller (SSDC).

Turbine and Generator Vibrations

Torsional Vibrations in Shaft Trains due to

- different Excitation sources

Stator Vibrations due to

- Electromagnetic Excitation

Identification of Vibration Problems

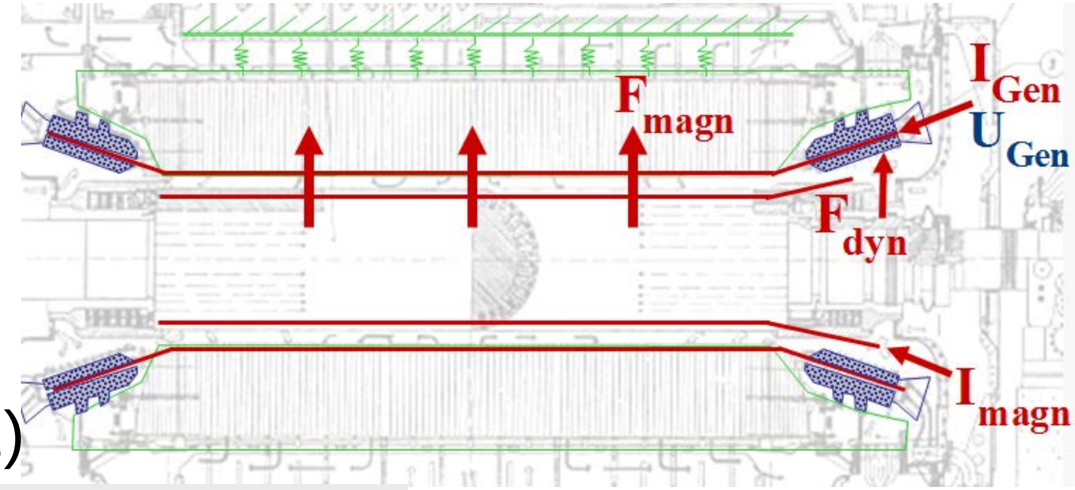
Conclusions

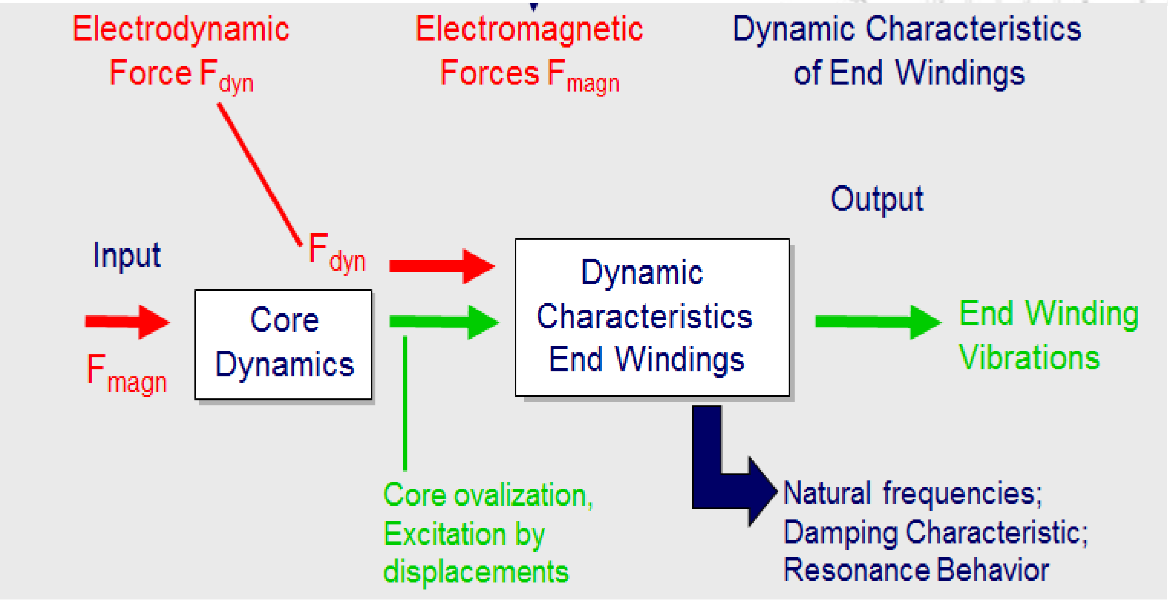
Stator Vibrations in Generator

Grouping	Analysis	Mitigation
2X End Winding Vibrations in Generator Stator due to **Electro-Magnetic Forces**	Experimental investigation of mechanical and electrical influence parameters.	Avoid mechanical resonances close to 100 Hz. Mass and Stiffness tuning. Add damping
2X Stator Core Axial Vibrations due to **Electro-Magnetic Forces**	Measurement of axial core vibrations.	Consolidation of the stator core by inserted wedges.
2X Stator Cooling Pipe Vibrations due to **Electro-Magnetic Forces**	Vibration measurements at cooling pipes in 3 directions.	Avoid resonances close to 100 Hz. Tuning by masses. Add damping.

Stator End Winding Vibrations due to EM Forces

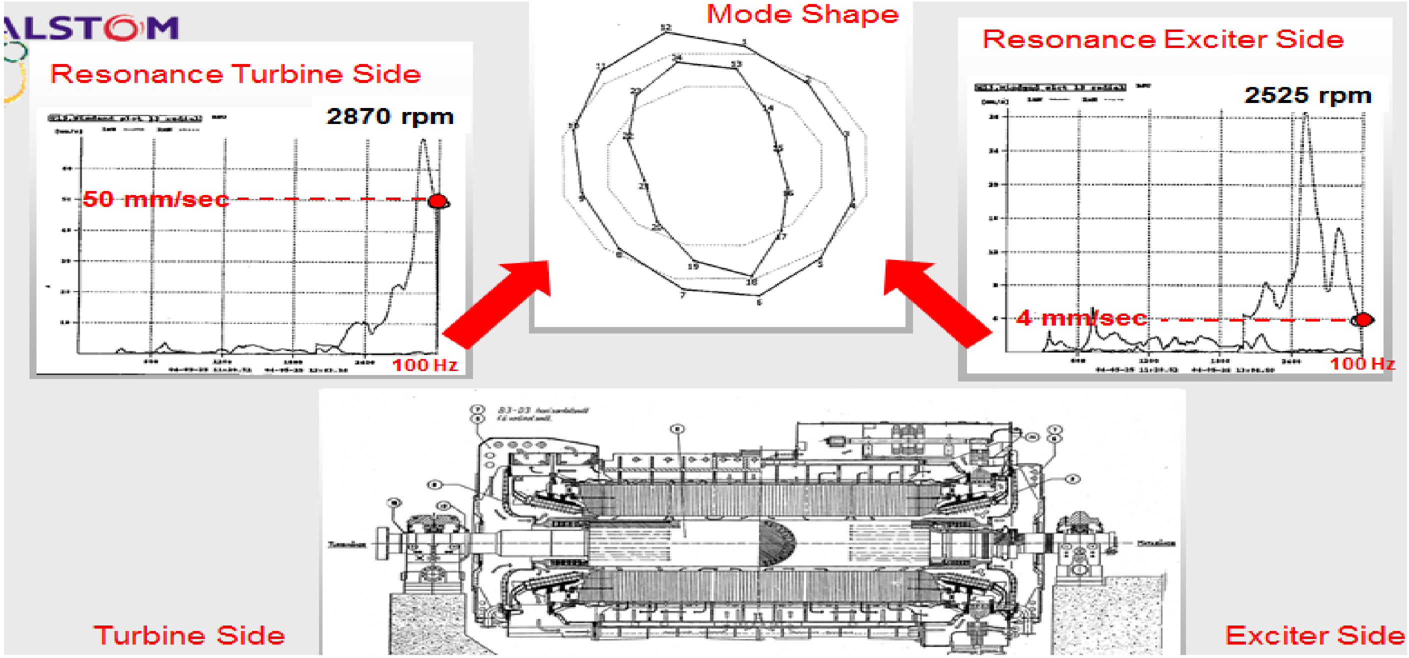
Physical Description:
Electrodynamic and Electromagnetic Forces excite the Stator End Windings with 2x Grid Frequency (100 or 120 Hz)





End Winding Vibrations depend on electrical and mechanical parameters !

Stator End Winding Vibrations due to EM Forces



Analysis: Numerical and experimental Analysis for End Winding Vibrations. Influence of electrical and mechanical Parameters.

Mitigation: Avoid mechanical Resonances close to 100 Hz (or 120 Hz). Mass and Stiffness tuning for End Windings.

Turbine and Generator Vibrations

Torsional Vibrations in Shaft Trains due to

- different Excitation sources

Stator Vibrations due to

- Electromagnetic Excitation

Identification of Vibration Problems

Conclusions

Definition of different **Alarms** for **Lateral Vibration Problems**

ALARM 1 **Slow increase** of **1-X Lateral vibrations to amplitude limit values.** Usually also change of phase.

ALARM 2 **Sudden increase** of **1-X Lateral vibrations to amplitude limit values or over amplitude limit values.**
Usually also change of phase.

ALARM 3 **Change of 1-X Lateral vibration vector in polar diagram with changing amplitude** (increase, decrease or stable) and **continous rotation of vector.**
Period may be 1 hour to 10 hours. Check ISO limits.

ALARM 4 **Increase of a frequency component at 1/2-X** in the frequency spectrum (subsychronous lateral vibration). **1-X Lateral vibration** is also in the spectrum.

Definition of different **Lateral Vibration Problems**

PROBLEM 1 **Slow change (increase) of Unbalance**
(e.g. due to thermal effects with a **thermal bow** or due to slowly increasing **Mechanical Unbalance**)

PROBLEM 2 **Sudden change (increase)** of **Mechanical Unbalance**
(e.g. due to Blade loss or due to moving parts in rotating systems)

PROBLEM 3 **Cyclic or Spiral Vibrations.** Superposition of an **Original Mechanical Unbalance** with a **Rotating Thermal Unbalance** (Rubbing at a Hot Spot, e.g. at Exciter Brushes or in Seals and Bearings of Turbines.).

PROBLEM 4 **Change of Oil Film Bearing Coefficients** (e.g. due to oil film temperature, Static Bearing Loads, Clearance, etc.)

Definition of different **Lateral Vibration Problems**

PROBLEM 5 **Friction Induced Mechanical Bow (Unbalance) in Turbo-Generators.** This may lead to strong **1-X Lateral** Vibrations.

PROBLEM 6 **Change of Sea Water Temperature with Condenser Deformation and change of Static Bearing Position.** Due to a change of the journal static position also the Bearing Dynamics and the **1-X Lateral vibration** changes.

Diagram 1: Identification of Lateral Vibration Problems

	ALARM 1	ALARM 2	ALARM 3	ALARM 4
PROBLEM 1	Part 1 Chapter 5.1			Part 1 Chapter 5.1
PROBLEM 2		Part 1 Chapter 5.1		
PROBLEM 3			Part 1 Chapter 5.2	
PROBLEM 4	Part 1 Chap. 5.1.1&3			Part 1 Chap. 5.1.1&3
PROBLEM 5		Part 1 Chapter 5.3		
PROBLEM 6	Part 1 Chapter 5.4			

Turbine and Generator Vibrations

Torsional Vibrations in Shaft Trains due to

- different Excitation sources

Stator Vibrations due to

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Identification of Vibration Problems

Conclusions

Conclusions

This lecture presented for the different vibration groups a physical description of the specific vibration problem, described the applied analysis techniques, reported about the observed vibration types in the power plants and suggested mitigation activities, which were used to solve the vibration problem.

The study can be very helpful, in order to transfer knowledge to new personnel, to support planned changes of turbine trains and to find fast solutions when vibration problems occur in turbine trains.

Conclusions

It can be concluded, that

for each specific vibration problem a good knowledge about the physical relations is an important base for a good solution of the vibration problem

the used experimental tools in the power plants (transducers, signal processing units, analyzers) are necessary for the vibration analysis and for the control of the success of measures.

the cooperation with the turbine manufacturer can often be very helpful in order to support mitigation activities by means of their experience and the well developed numerical tools.

Vorlesungen Mechatronik im Wintersemester

TECHNISCHE UNIVERSITÄT DARMSTADT

ENERGIFORSK Vibration Group
Seminar: Vibrations in Nuclear Applications
04. October 2016, Stockholm

Turbine and Generator Vibrations

Analysis and Mitigation

Prof. Dr.-Ing. Rainer Nordmann

MiM