Vorlesungen Mechatronik im Wintersemester

Energiforsk Seminar: Lectures in the Power Plants Ringhals, Oskarshamn and Forsmark, March 2022

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Vibrations of Turbines and Generators in Power Plants

Lecture II Lateral Vibrations in Turbogenerators

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Lateral Vibrations in Turbogenerators

- Lateral Vibrations in Turbogenerators
- FE- Modelling for Lateral Vibrations in Turbogenerators
- FE-Model used for the Design and as Digital Twin for the Operation
- Monitoring during Operation by means of Measurements
- Evaluation of Lateral Vibrations (ISO-Standards, DIAM, Digital Twin)
- Vibration Control: Mitigation of Lateral Vibrations

Lateral Vibrations in Turbogenerators

Steam Turbines, Generator and Pipe System in the Plant

Pipe System

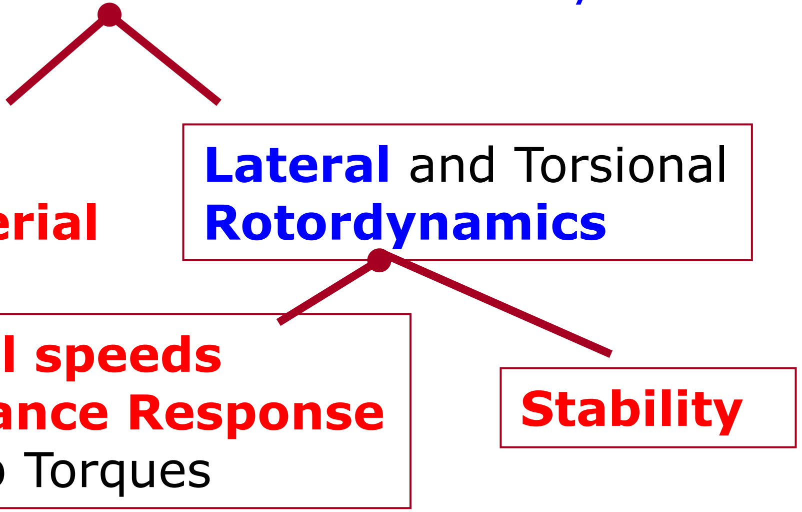
Generator

Low Pressure Turbines LPT

High Pressure Turbine HPT

Lateral Vibrations in Turbogenerators

Different Disciplines of Physics



Disciplines : Thermodynamics **Mechanics** Electrodynamics

Stresses
Strength of material

Lateral and Torsional
Rotordynamics

Critical speeds
Unbalance Response
Air Gap Torques

Stability

Lateral Vibrations in Turbogenerators

Lateral Vibrations of Shaft Trains

Machine with Rotating Shaft

Lateral Vibrations perpendicular to the Shaft Axis (Bending)

Lateral Vibrations in Turbogenerators

Lateral Vibrations of Shaft Trains

Which Phenomena are of Practical Relevance?

Lateral Vibrations: **Lateral Vibrations perpendicular to the Shaft axis with Bending along the Shaft line. Physical Effects: Inertia (masses), Siffness and Damping of System Components (Shaft, Bearings).**

Dynamic Characteristics: Natural Frequencies, Critical Speeds, Natural Modes, Stability, Amplitudes and Phase angles of the Vibration Response due Excitations

Excitation: Mechanical and thermal Unbalances,
Bow (Unbalance) due to Coupling Errors,
Excitation due to Instabilities in Fluid Bearings and Seals

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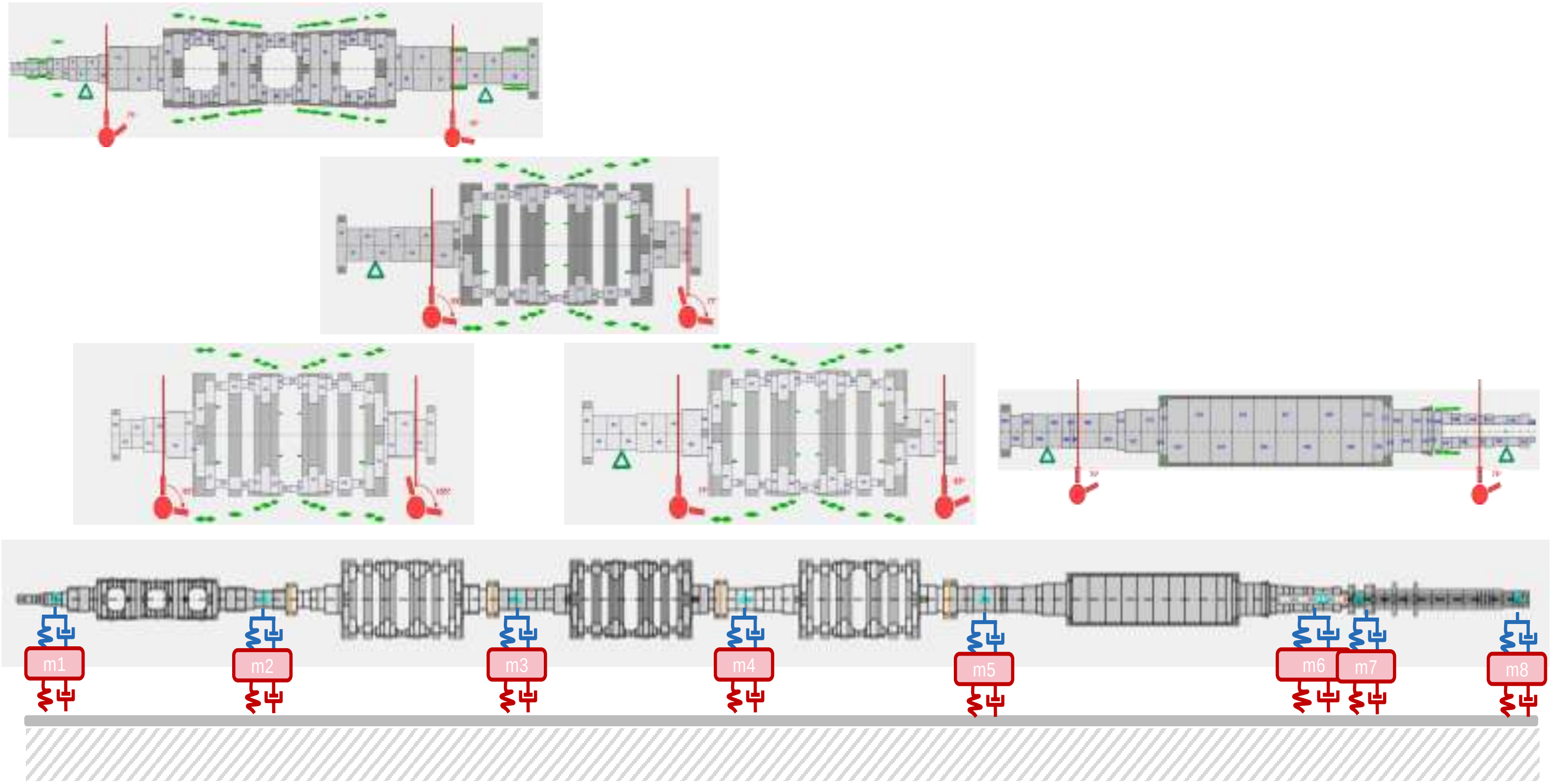
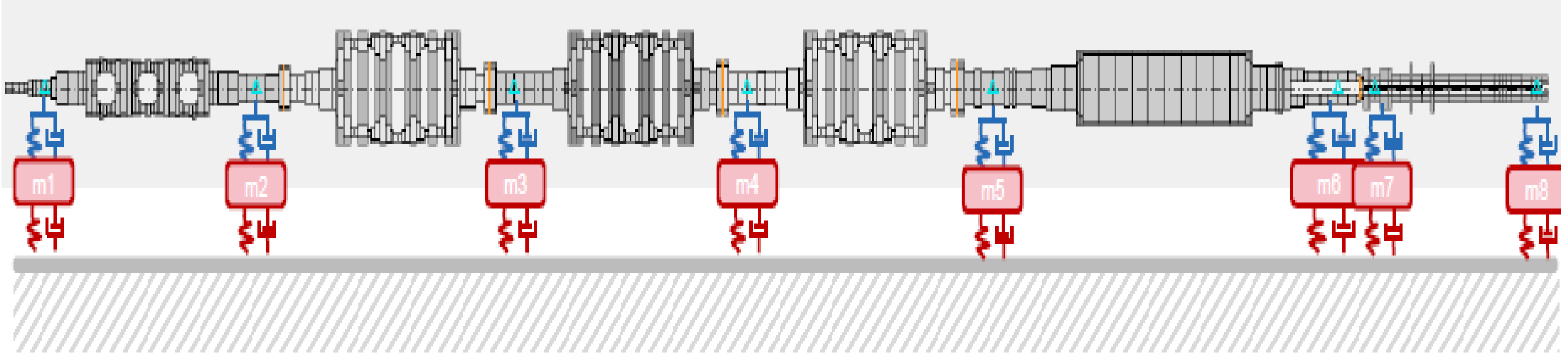
FE-Modelling for Lateral Vibrations in Turbogenerators

Mass and Stiffness Distribution along the Shaft Train



FE Modelling for Lateral Vibrations in Turbogenerators

Model and Equations of Motion



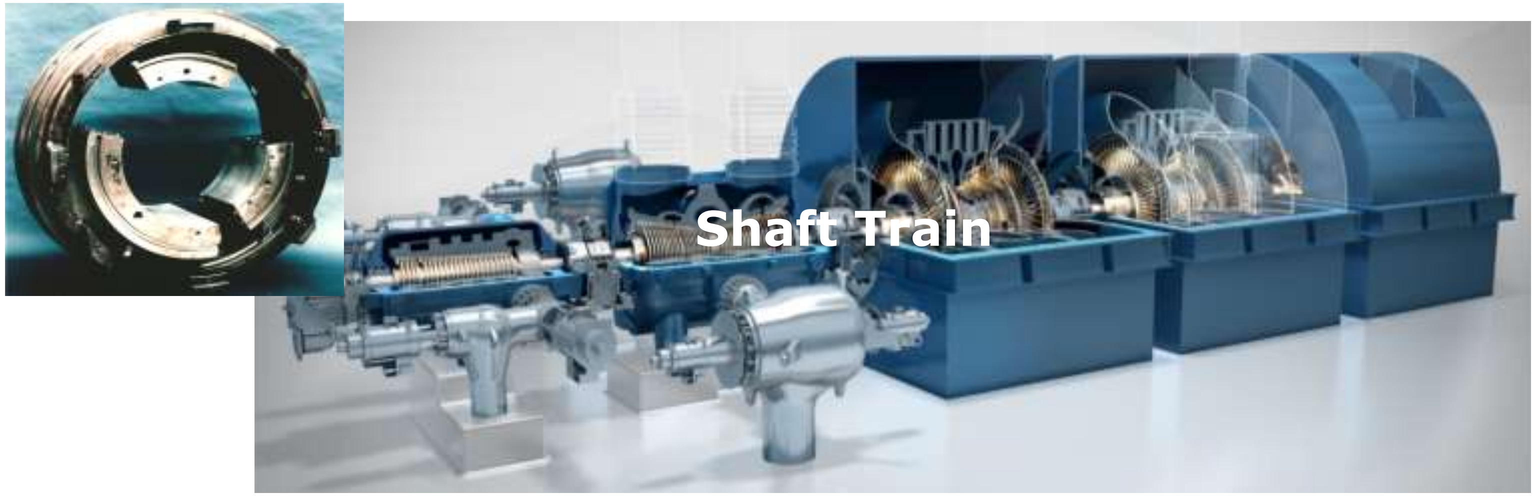
$$\mathbf{M}\,\ddot{x}(t)+(\mathbf{D}(\Omega)+\mathbf{G}(\Omega))\,\dot{x}(t)+\mathbf{K}(\Omega)\,\mathbf{x}(t)=\mathbf{F}(t)$$

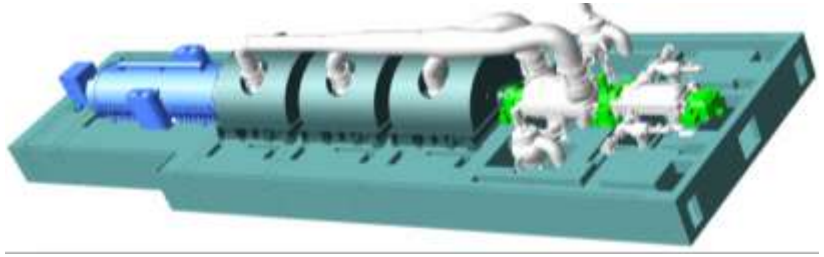
The **Equations of Motion** for **Lateral Vibrations** of the **Turbogenerator** contain the stiffness, damping and inertia information of the shaft train and the bearings. But it is also important, that the supports - **pedestals and foundation** - are included.

FE-Modelling for Lateral Vibrations in Turbogenerators

Different Interactions have an Influence on the Vibrations

Rotor-Fluid Interaction: Oil Film Bearings, Seals





Rotor-Structure Interaction: Casing, Foundation

FE-Modelling for Lateral Vibrations in Turbogenerators

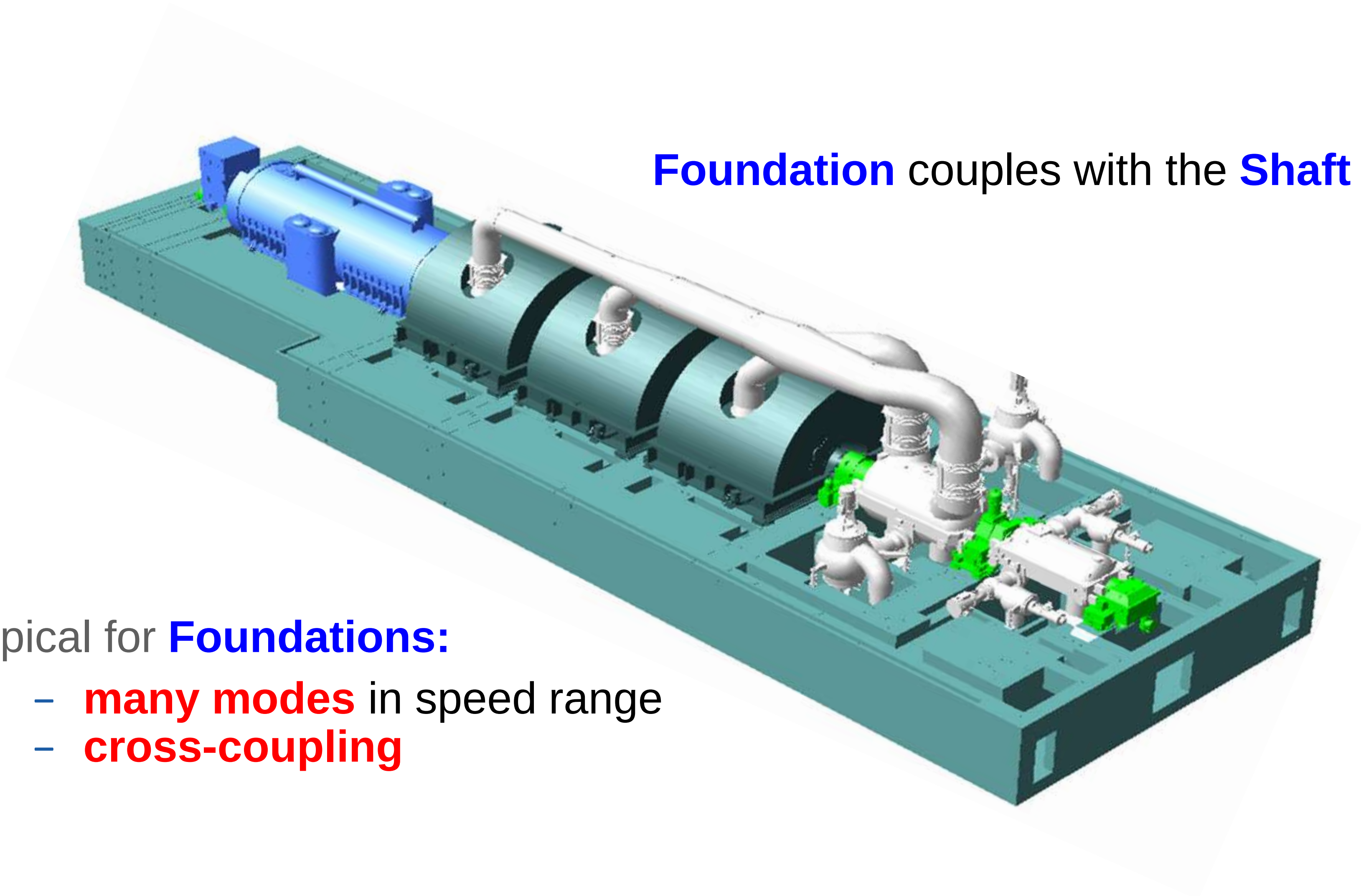
Different Interactions have an Influence on the Vibrations

Consequences for Modelling

- **Multiphysics** – in-depth understanding necessary
- Tools from different Disciplines (Mechanics, Electric, Fluid) necessary
- **Mechanical** & **Electrical** Departments need to interact and cooperate
- **Testing & Validation** essential to validate models and identify key parameters.

FE-Modelling for Lateral Vibrations in Turbogenerators

Different Interactions have an Influence on the Vibrations



Foundation couples with the **Shaft train**

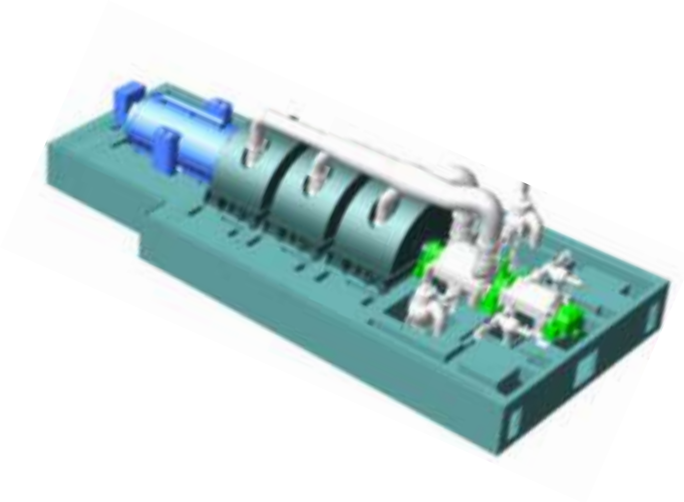
Typical for **Foundations:**

- **many modes** in speed range
- **cross-coupling**

FE-Modelling for Lateral Vibrations in Turbogenerators

Different Interactions have an Influence on the Vibrations

3D-FE
Modal Analysis
for the Foundation



Procedure

Estimation of mode shapes and natural frequencies of the foundation without the rotor (FRF for bearing locations)

Input for Rotordynamics:

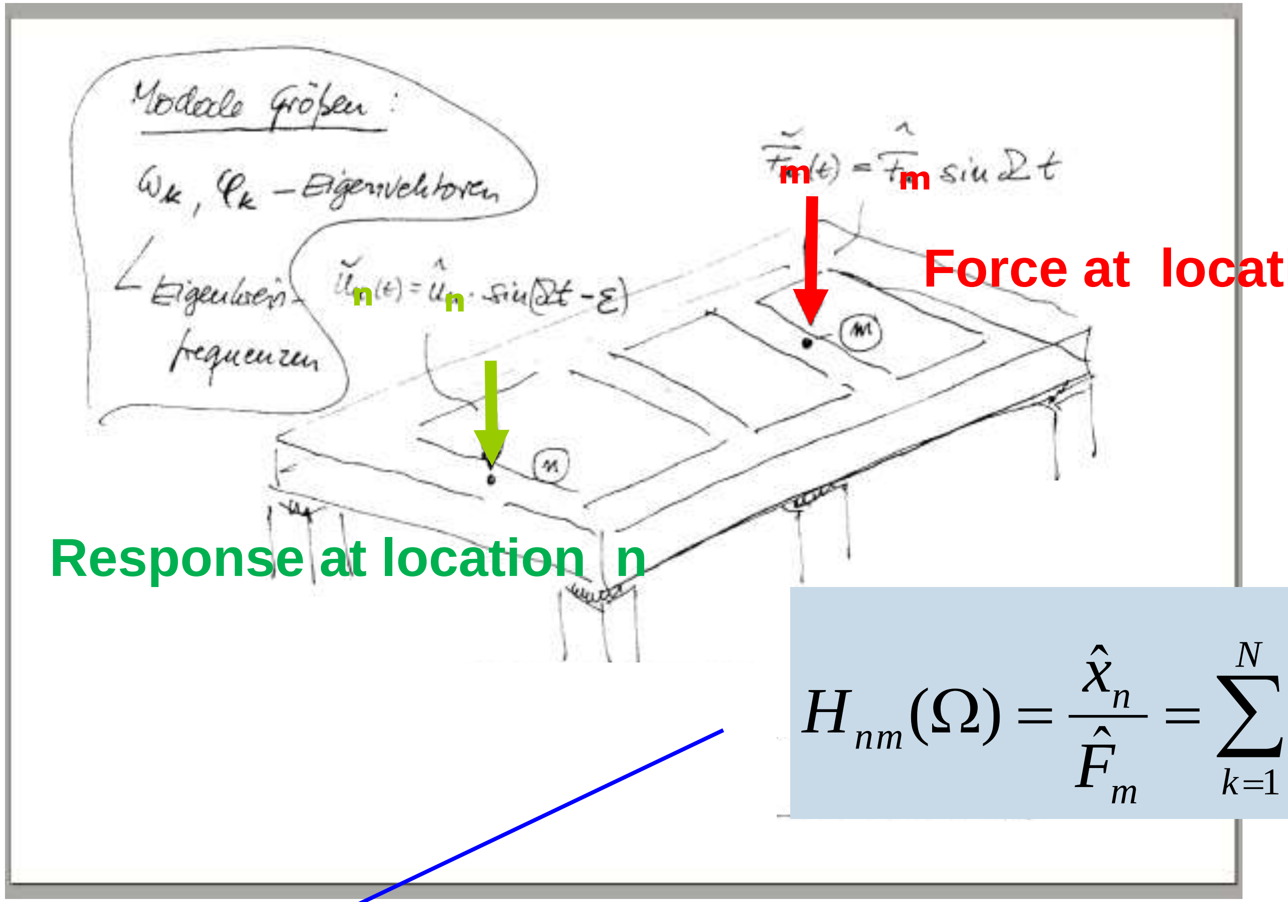
→Components of the mode shapes at the bearing locations (interaction)

→Natural Frequencies

→Modal Damping

FE-Modelling for Lateral Vibrations in Turbogenerators

Different Interactions have an Influence on the Vibrations



Force at location m

Response at location n

$$H_{nm}(\Omega) = \frac{\hat{x}_n}{\hat{F}_m} = \sum_{k=1}^{N} \frac{\varphi_{mk} \cdot \varphi_{nk}}{(\omega_k^2 - \Omega^2) + i \cdot 2\omega_k D_k \Omega}$$

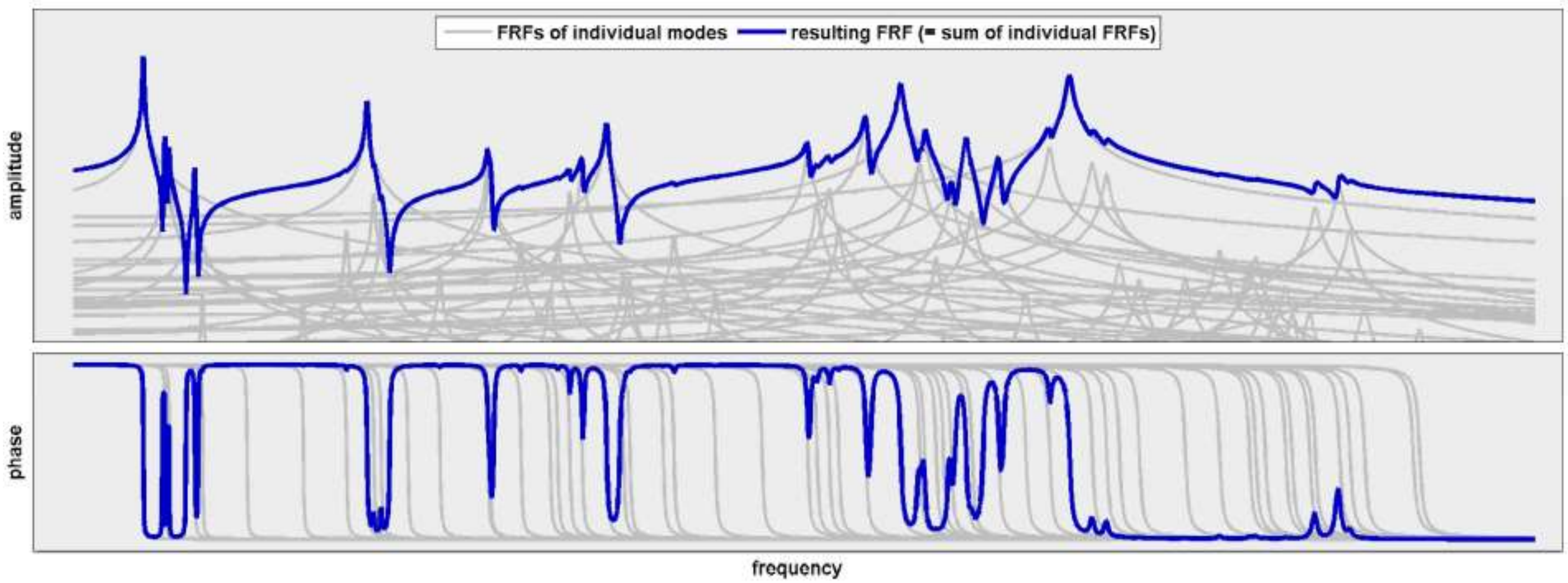
Frequency Response Functions of **Foundation/Pedestal** introduced at the coupling points (Bearigs) to the Shaft Train

FE-Modelling for Lateral Vibrations in Turbogenerators

Rotor-Structure-Interaction with Pedestal and Foundation

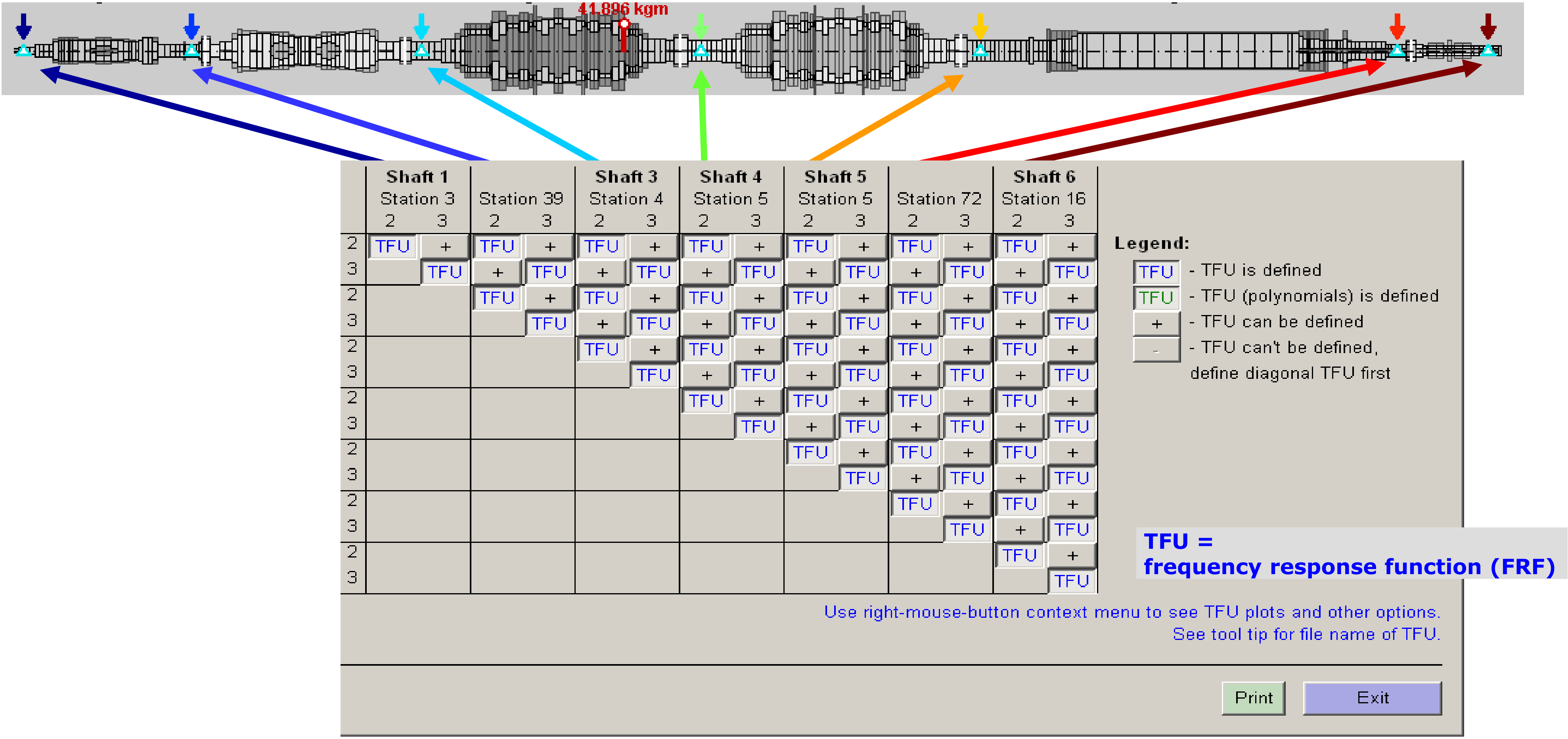
Frequency Response Functions can come from

- 3D FEM Calculations (Natural frequencies, Mode shapes)
- FRF- Measurements



FE-Modelling for Lateral Vibrations in Turbogenerators

Rotor-Structure-Interaction with Pedestal and Foundation



	Shaft 1				Shaft 3		Shaft 4		Shaft 5				Shaft 6	
	Station 3		Station 39		Station 4		Station 5		Station 5		Station 72		Station 16	
	2	3	2	3	2	3	2	3	2	3	2	3	2	3
2	TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU	+
3		TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU
2			TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU	+
3				TFU	+	TFU	+	TFU	+	TFU	+	TFU	+	TFU
2					TFU	+	TFU	+	TFU	+	TFU	+	TFU	+
3						TFU	+	TFU	+	TFU	+	TFU	+	TFU
2							TFU	+	TFU	+	TFU	+	TFU	+
3								TFU	+	TFU	+	TFU	+	TFU
2									TFU	+	TFU	+	TFU	+
3										TFU	+	TFU	+	TFU
2											TFU	+	TFU	+
3												TFU	+	TFU
2													TFU	+
3														TFU

Legend:

TFU - TFU is defined
TFU - TFU (polynomials) is defined
\+ - TFU can be defined
\- - TFU can't be defined, define diagonal TFU first

TFU = frequency response function (FRF)

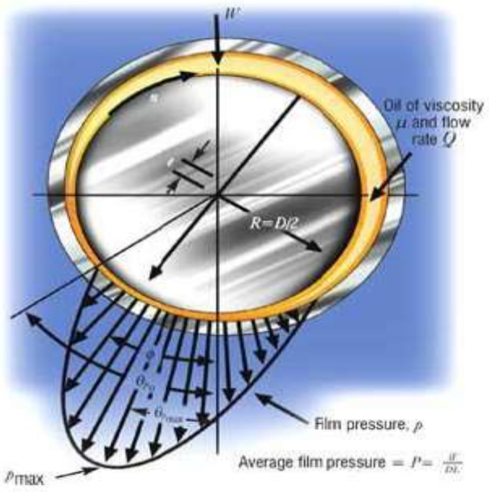
Use right-mouse-button context menu to see TFU plots and other options.
See tool tip for file name of TFU.

Coupling of FRF of Pedestal & Foundation with Rotor Train

FE-Modelling for Lateral Vibrations in Turbogenerators

Fluid-Rotor-Interaction in Oil Film Bearings

Oil Film bearings



Force-Motion-Relations

Stiffness- and damping coefficients of the Oil Film Bearings

$$F_x = k_{xx}x + k_{xy}y + d_{xx}\dot{x} + d_{xy}\dot{y}$$

$$F_y = k_{yx}x + k_{yy}y + d_{yx}\dot{x} + d_{yy}\dot{y}$$

FE-Modelling for Lateral Vibrations in Turbogenerators

Fluid-Rotor-Interaction in Oil Film Bearings

The **Stiffness and Damping coefficients** can be determined by numerical calculations (Reynolds-equations, CFD) or by experiments. For a bearing with a special geometry the coefficients depend on the **Sommerfeld number** or on the static displacement.

Fluid film bearings have usually **anisotropic behavior** :

$k_{xx} \neq k_{yy}$ and $d_{xx} \neq d_{yy}$

The coupling coefficients differ from each other

$k_{xy} \neq k_{yx}$ and $d_{xy} \neq d_{yx}$

A measure for **instability sensitivity** is the difference: ($k_{xy} – k_{yx}$). Damping Coefficients d_{xx} and d_{yy} are good for stability. Coefficients can be found in tables or diagrams.

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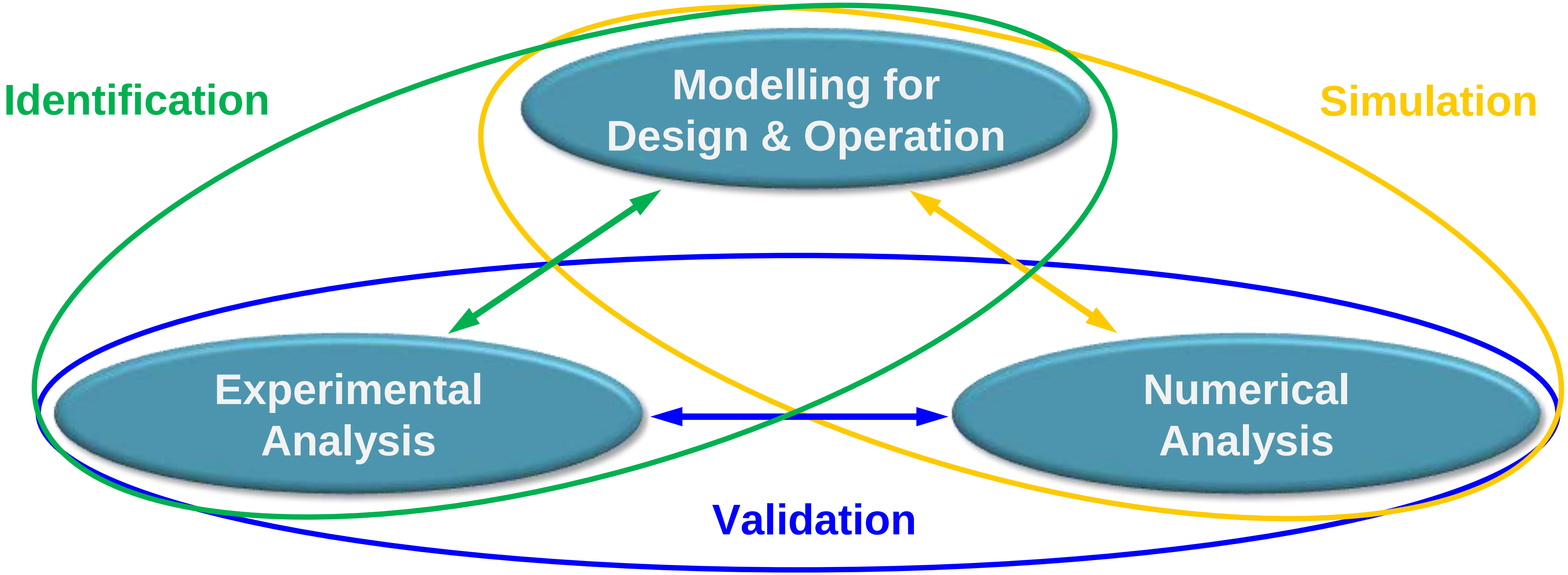
FE- Model used for the Design and as Ditigal Twin for the Operation

Assessment of Lateral Vibrations – Design Process and during Operation



When the **Simulation Results** are validated by **Experimental Analysis,** **the** **Model** can also be used as a **Digital Twin** for the **Operation.**

FE- Model used for the Design and as Ditigal Twin for the Operation

Assessment of Lateral Vibrations in the Design Process

Lateral Vibrations:

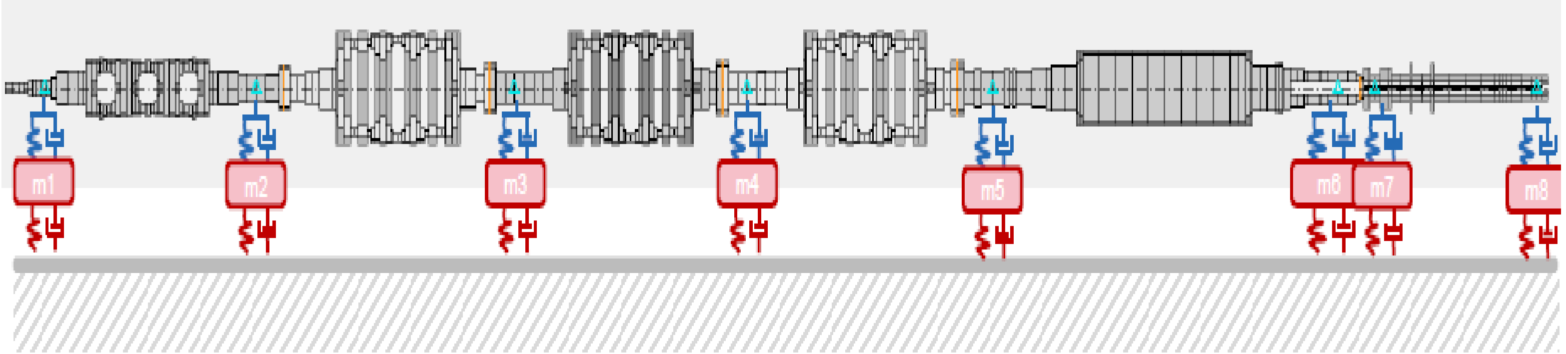
- Bending vibrations of the Shaft Train, mainly due to Unbalance
- Strong Fluid-Structure (FSI) and Rotor-Structure Interaction (RSI)
- Gyroscopic Effects due to Rotation
- Speed dependent dynamic characteristics (e.g. Oil Film Bearings)
- Shaft models are very good, Uncertainties mainly in FSI and RSI

Assessment of Lateral Vibrations:

- Eigenvalues and Mode Shapes, Resonances
- Unbalance Response, Critical Speeds (Run up and Run down curves)
- Stability Behavior
- Bearing Loads and Losses

FE- Model used for the Design and as Ditigal Twin for the Operation

Assessment of Lateral Vibrations in the Design – **Eigenvalues & Stability**



Eigenvalue Problem for Turbogenerator

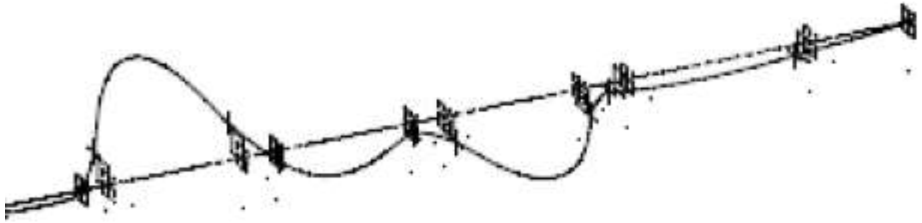
$$(\lambda^2 \mathbf{M} + \lambda(\mathbf{D}(\Omega) + \mathbf{G}(\Omega)) + \mathbf{K}(\Omega))\cdot \mathbf{x} = \mathbf{0}$$

Complex Eigenvalues **:** $\lambda = \alpha + j\,\omega$

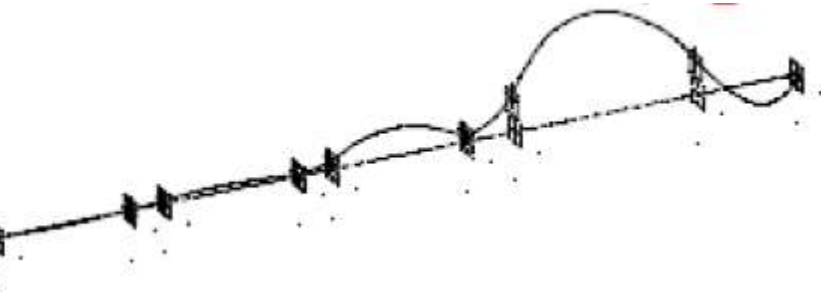
Information for damping (stability) and natural frequencies

FE- Model used for the Design and as Ditigal Twin for the Operation

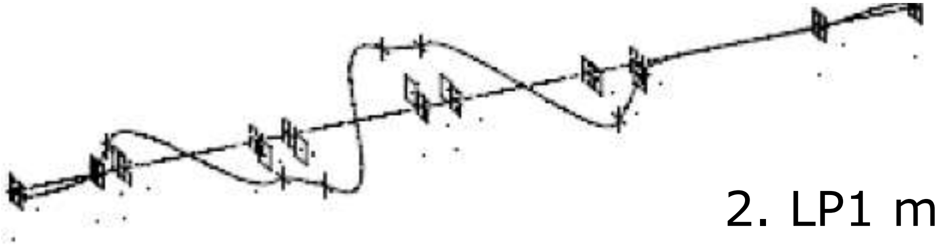
Assessment of Lateral Vibrations in the Design - **Eigenmodes**



1. LP1 mode at 10.7 Hz
Modal Damping 1,1 %



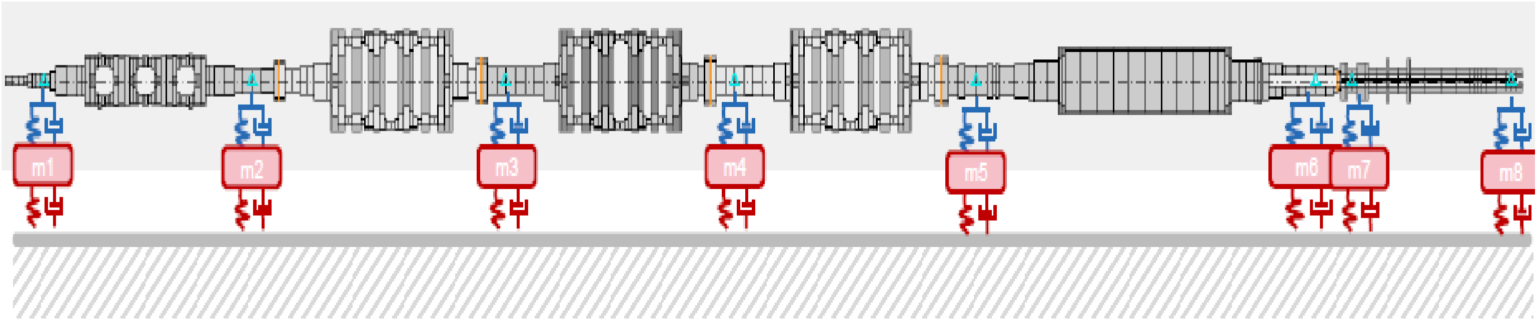
1. Generator mode at 11.0 Hz
Modal Damping 0,9 %



2. LP1 mode at 27.6 Hz
Modal Damping 9 %

FE- Model used for the Design and as Ditigal Twin for the Operation

Assessment of Lateral Vibrations in the Design – **Unbalance Response**



Complex Equations for **Unbalance Response**

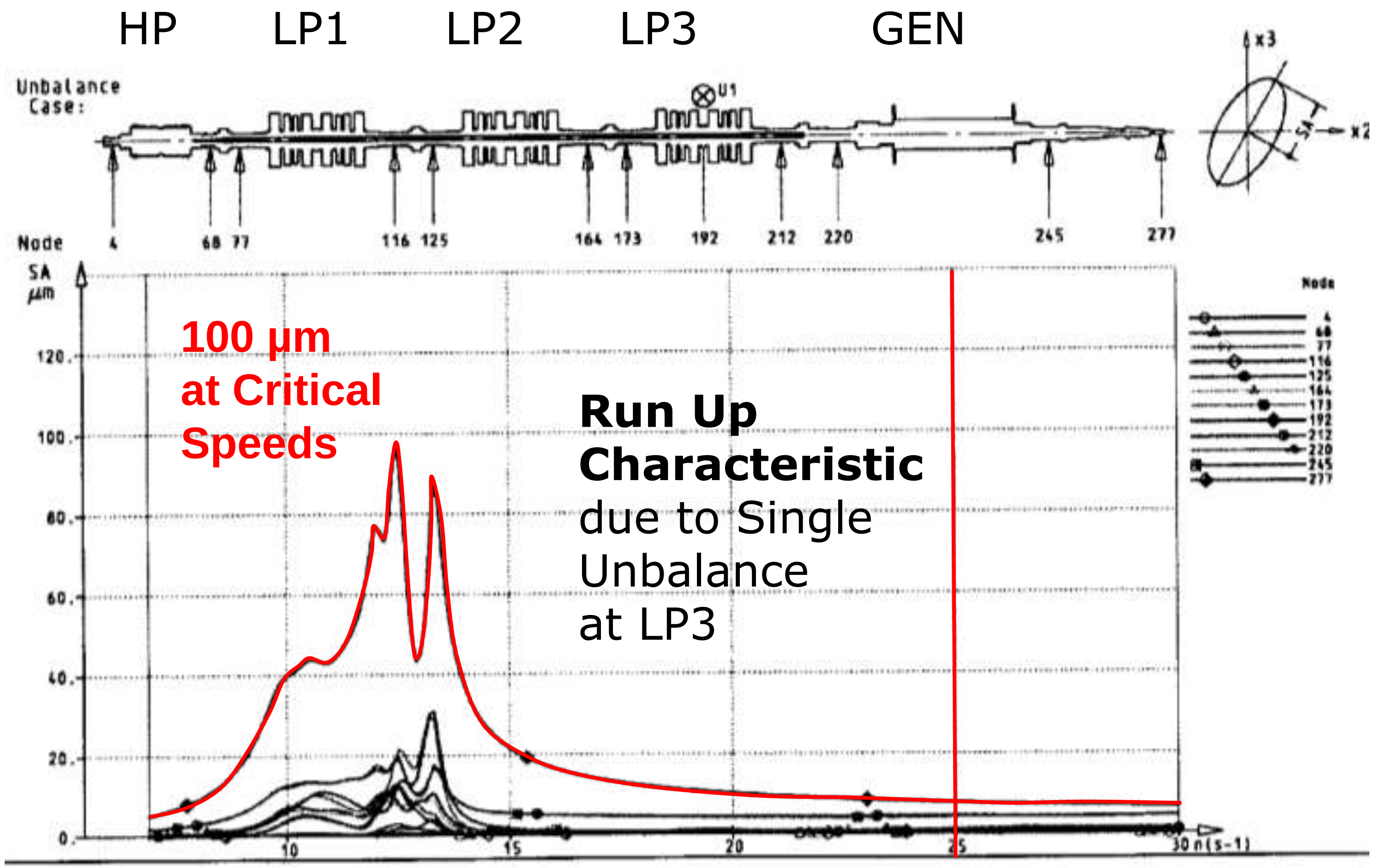
$$((\mathbf{K}(\Omega) - \Omega^2\,\mathbf{M}) + j\cdot\Omega\,(\mathbf{D}(\Omega) + \mathbf{G}(\Omega))\cdot\tilde{\mathbf{x}} = \mathbf{U}\cdot\Omega^2\cdot\tilde{\mathbf{F}}$$

$$\tilde{X}_i = \tilde{X}_{i\,\mathrm{Re}} + j\cdot\tilde{X}_{i\mathrm{Im}}$$

Complex System Response
contains Amplitude and Phase

FE- Model used for the Design and as Ditigal Twin for the Operation

Assessment of Lateral Vibrations in the Design – **Unbalance Response**



100 µm at Critical Speeds

Run Up Characteristic due to Single Unbalance at LP3

25 Hz

Lateral Vibrations in Turbogenerators

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Monitoring during Operation by means of Measurements

Absolute Vibration velocities and Relative Shaft Vibrations

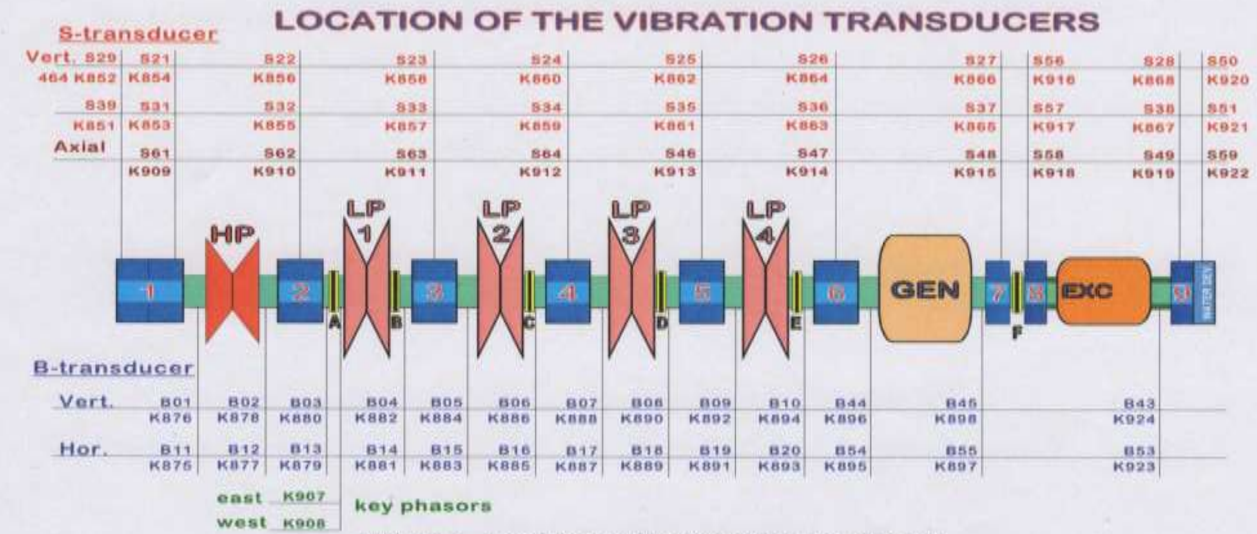


Figure 1. Location of the vibration transducers.

For Monitoring of High Performance Turomachinery Absolute Vibration Velocities in mm/sec and/or Relative Shaft vibrations in µm at defined locations (Bearings) are measured.

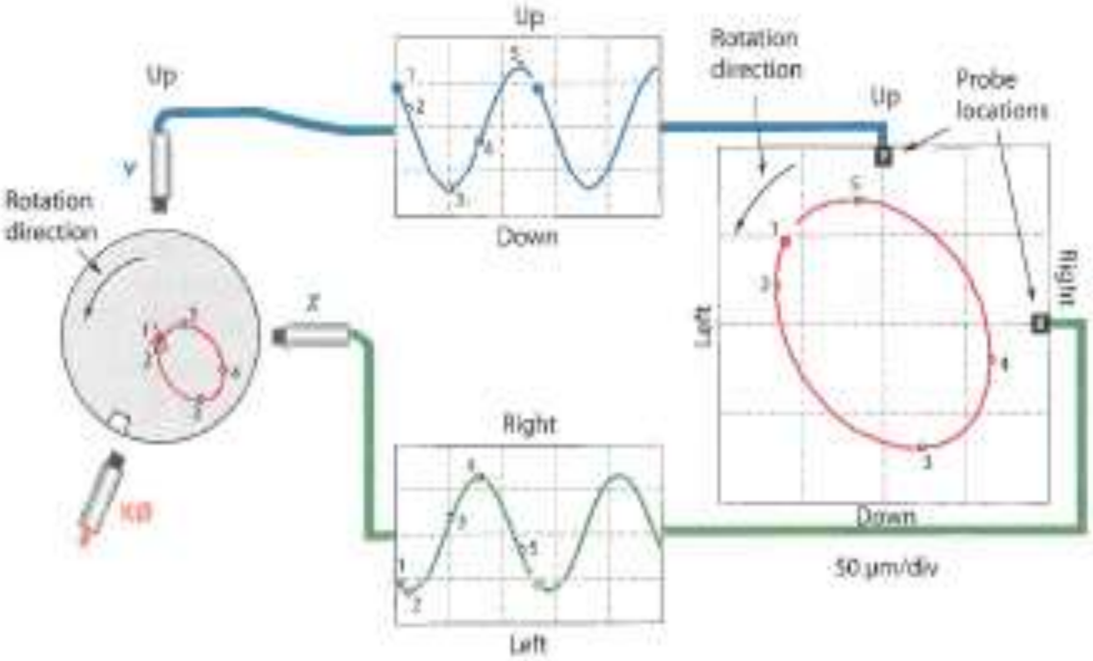
Evaluation of the measured Vibrations by means of Guidelines ISO Standards

Monitoring during Operation by means of Measurements

Relative Shaft Vibrations

Relative Shaft Vibrations in horizontal and vertical direction. By Superposition of the two signals Orbits can be determined. They present shaft motions in the measurement plane.

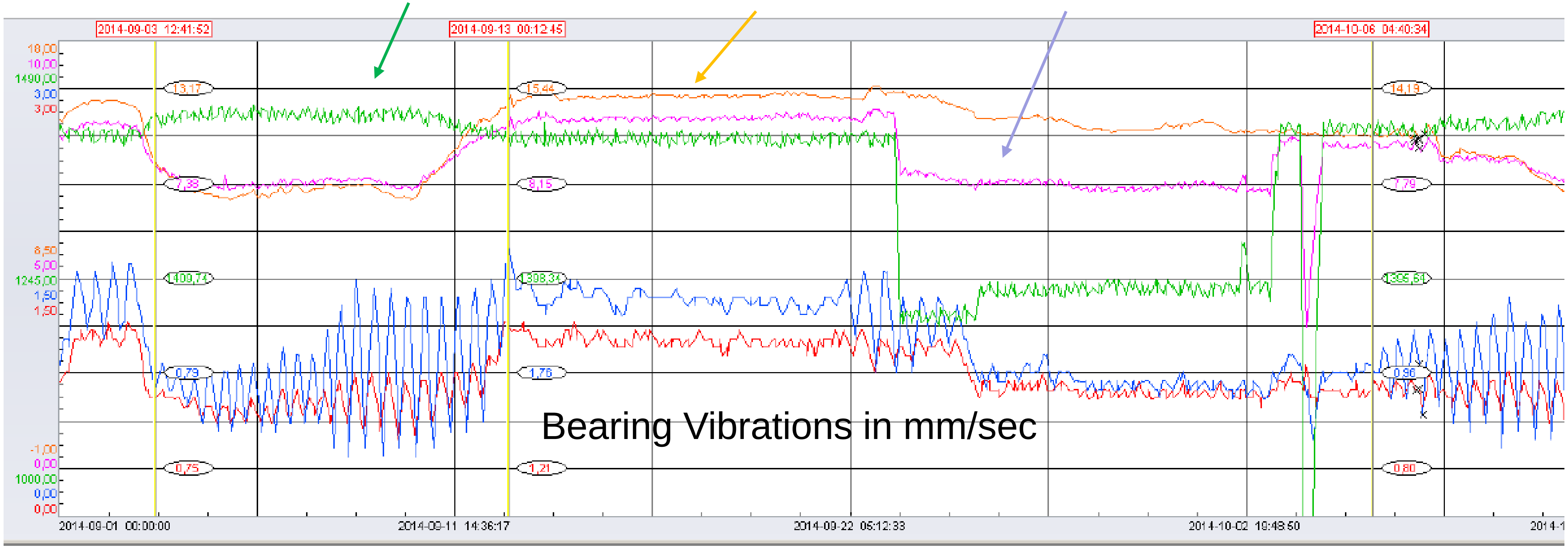
The Orbit characteristic in the time domain helps to identify the dynamic behavior of the Machine.



Monitoring during Operation by means of Measurements

Bearing Vibrations and other related Machine quantities

Lateral Vibrations are measured together with other Machine quantities in order to identify possible sources of Vibrations.



Power MW

Temperature

Pressure

Bearing Vibrations in mm/sec

Monitoring during Operation by means of Measurements

Transformation from the Time domain to the Frequency domain

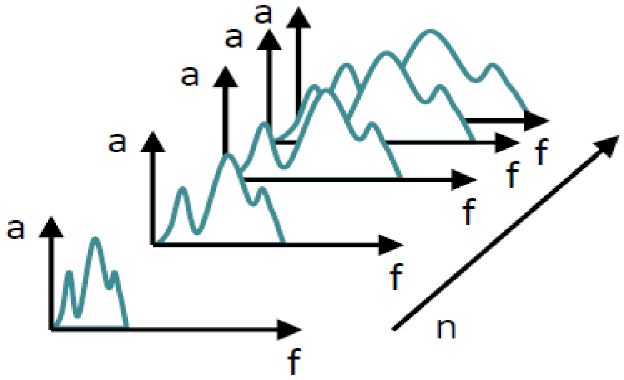
For a better interpretation of Vibration signals the **Transformation** from the Time domain into the **Frequency domain** is very important.

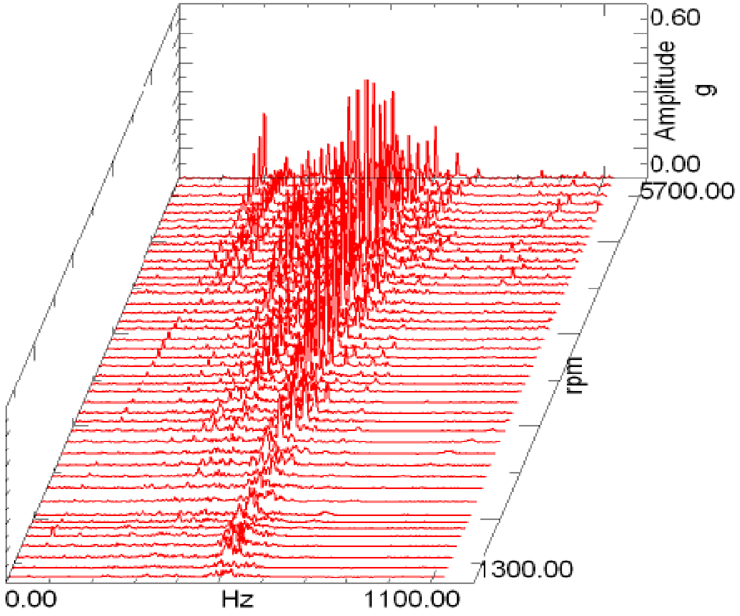
The **Fast Fourier Transformation** (FFT) is a very effective tool for this process.
As a result **Frequency Spectra** are obtained in the Frquency domain

$$X(\Omega) = F\ \{x(t)\} = \int_{-\infty}^{\infty} x(t) e^{-i\Omega t}\, dt$$

Different presentations of Vibrations in the **Frequency domain** are possible.

Monitoring during Operation by means of Measurements
Frequency Spectra in the Waterfall Diagram

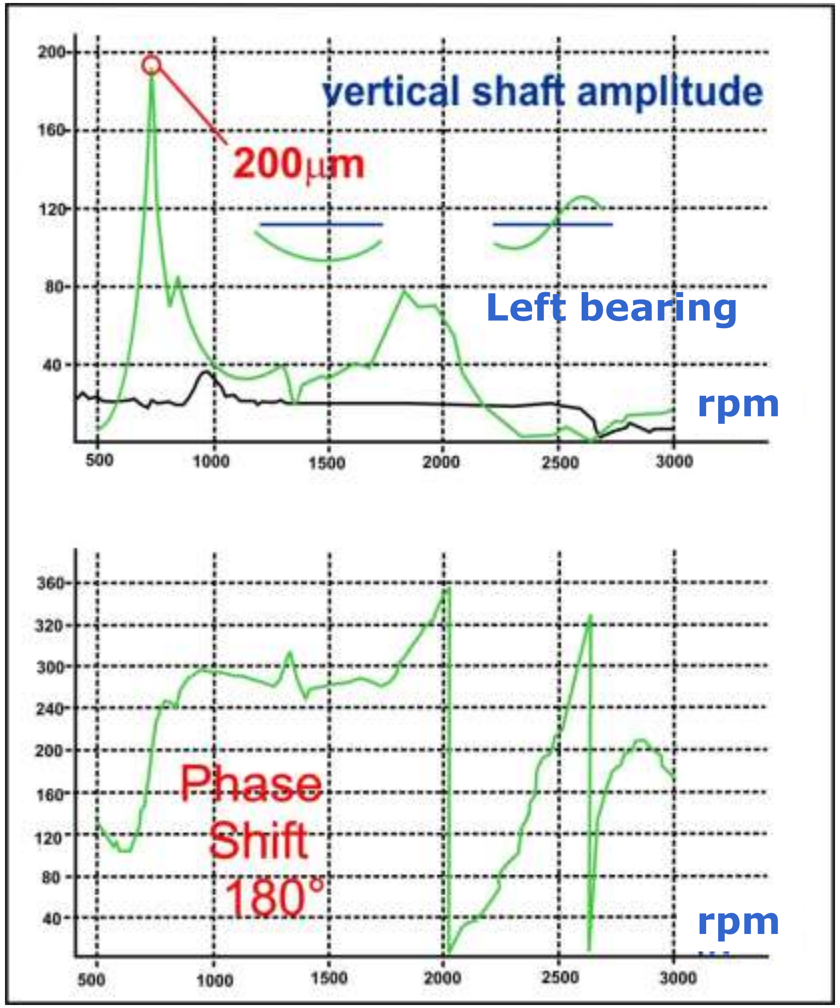


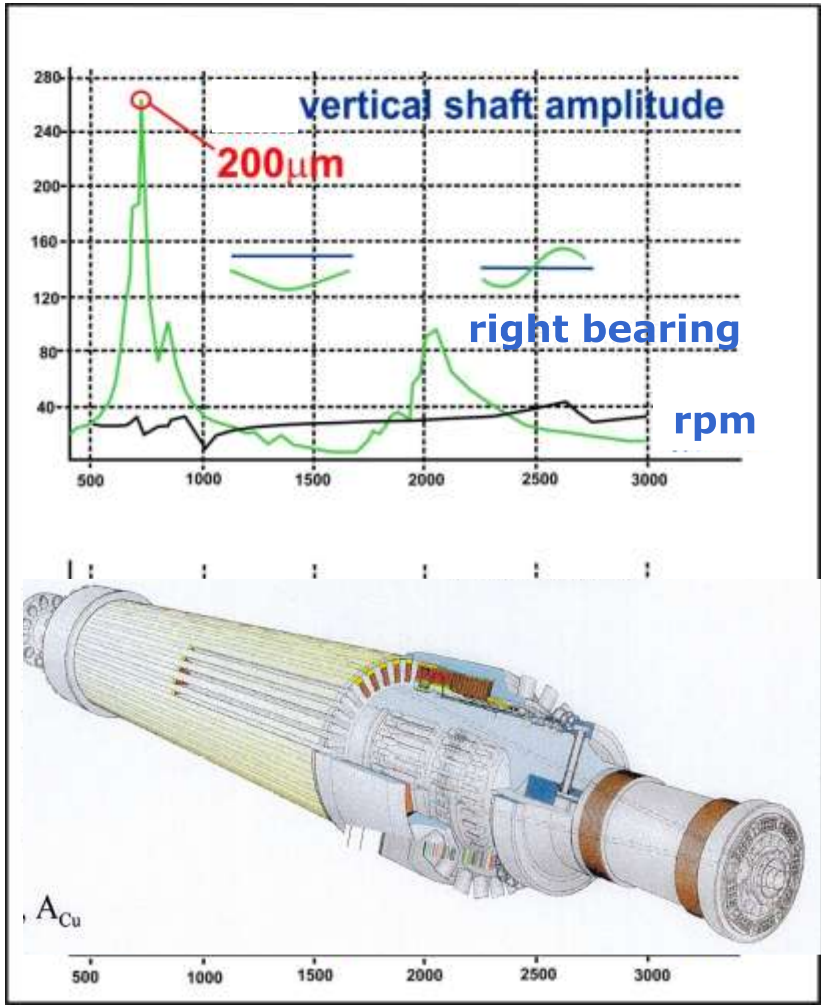


In a **Waterfall Diagram** Frequency **Spectra** are shown for different **Speeds of rotation** in rpm. In each single spectrum Amplitudes of vibration are presented versus the frequency of vibration .

Monitoring during Operation by means of Measurements

Run up and Run down Charactreistics of Lateral Vibrations





Monitoring during Operation by means of Measurements

Frequency Spectra with Forward and Backward frequencies

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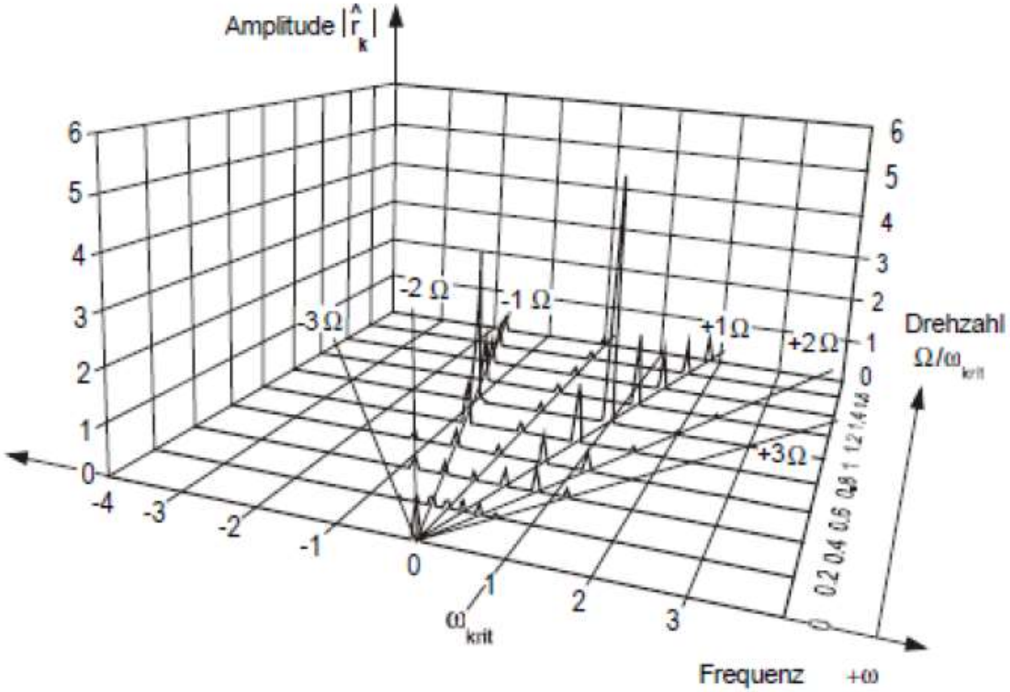

Frequency Spectra with **Forward**- and **Backward frequencies**. Both are very helpful to analyze Vibrations and to diagnose Failures.

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Evaluation of Lateral Vibrations (ISO Standards, DIAM, Digital Twin)

ISO Standards for Turbogenerators with Steam Turbines and Generators

Measured Vibration values on both the rotating shafts and on nonrotating parts like Bearing Housings (Pedestals) are the base for an **Evaluation** of the **dynamic behavior** of Turbogenerators with Steam turbines and Generators. Measurements at these locations characterize the state of the vibration of the machine reasonably well.

The used **Evaluation Criteria** are based on experience with those machines over years and can quite well be used for assessing the **Vibratory State** and the **Severity** of the **Vibrations**.

For the evaluation the measured Vibration values are compared with **Limit Values**, which are subdivided in different zones, characterizing the Machine State. Vibrations should not exceed the defined limits in order to guarantee **allowable deformations** and **stresses**

More details regarding the evaluation and the vibration values are described in **ISO Standards**, e.g. **ISO 20816** for Steam Turbines and Generators.

Evaluation of Lateral Vibrations (ISO Standards, DIAM, Digital Twin)

DIAM Project: Detection, Investigation, Analysis, Mitigation)

Another procedure for the Detection and Evaluation of Lateral Vibrations of Turbogenerators has been investigated in an Energiforsk project, called **DIAM – A Matrix Tool for Turbine and Generator Vibrations.**

The basic idea of this project can be explained by a **Matrix M1**, which expresses relations between **Detections of Vibration** (horizontal in M1) and **Vibration Phenomena** or the Cause of Vibration (vertical in M1).

Probability numbers (0 to 5) in the Matrix determine, how strong the relations between Detections and Phenomena are.

Introducing the detected vibrations of a Turbogenerator in the Matrix M1 most probable Vibration Phenomena will be shown based on the probability numbers.

Evaluation of Lateral Vibrations (ISO Standards, DIAM, Digital Twin)

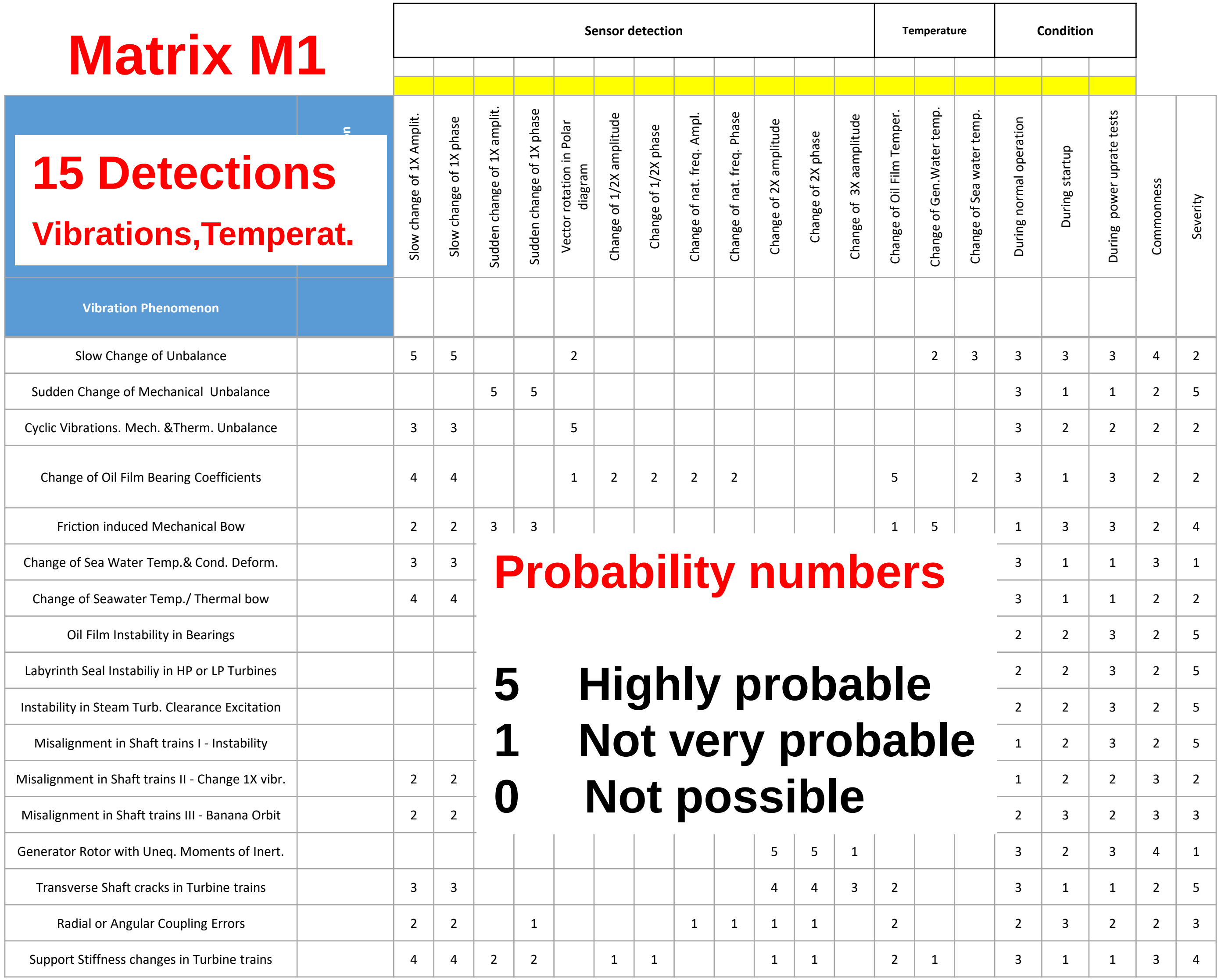
DIAM Project: Detection, Investigation, Analysis, Mitigation)

Matrix M1

15 Detections

Vibrations,Temperat.

18 Vibration Phenomena



	Sensor detection												Temperature			Condition				
Vibration Phenomenon	Slow change of 1X Amplit.	Slow change of 1X phase	Sudden change of 1X amplit.	Sudden change of 1X phase	Vector rotation in Polar diagram	Change of 1/2X amplitude	Change of 1/2X phase	Change of nat. freq. Ampl.	Change of nat. freq. Phase	Change of 2X amplitude	Change of 2X phase	Change of 3X aamplitude	Change of Oil Film Temper.	Change of Gen.Water temp.	Change of Sea water temp.	During normal operation	During startup	During power uprate tests	Commonness	Severity
Slow Change of Unbalance	5	5			2									2	3	3	3	3	4	2
Sudden Change of Mechanical Unbalance			5	5												3	1	1	2	5
Cyclic Vibrations. Mech. &Therm. Unbalance	3	3			5											3	2	2	2	2
Change of Oil Film Bearing Coefficients	4	4			1	2	2	2	2				5		2	3	1	3	2	2
Friction induced Mechanical Bow	2	2	3	3									1	5		1	3	3	2	4
Change of Sea Water Temp.& Cond. Deform.	3	3														3	1	1	3	1
Change of Seawater Temp./ Thermal bow	4	4														3	1	1	2	2
Oil Film Instability in Bearings																2	2	3	2	5
Labyrinth Seal Instabiliy in HP or LP Turbines																2	2	3	2	5
Instability in Steam Turb. Clearance Excitation																2	2	3	2	5
Misalignment in Shaft trains I - Instability																1	2	3	2	5
Misalignment in Shaft trains II - Change 1X vibr.	2	2														1	2	2	3	2
Misalignment in Shaft trains III - Banana Orbit	2	2														2	3	2	3	3
Generator Rotor with Uneq. Moments of Inert.										5	5	1				3	2	3	4	1
Transverse Shaft cracks in Turbine trains	3	3								4	4	3	2			3	1	1	2	5
Radial or Angular Coupling Errors	2	2		1				1	1	1	1		2			2	3	2	2	3
Support Stiffness changes in Turbine trains	4	4	2	2		1	1			1	1		2	1		3	1	1	3	4

Probability numbers

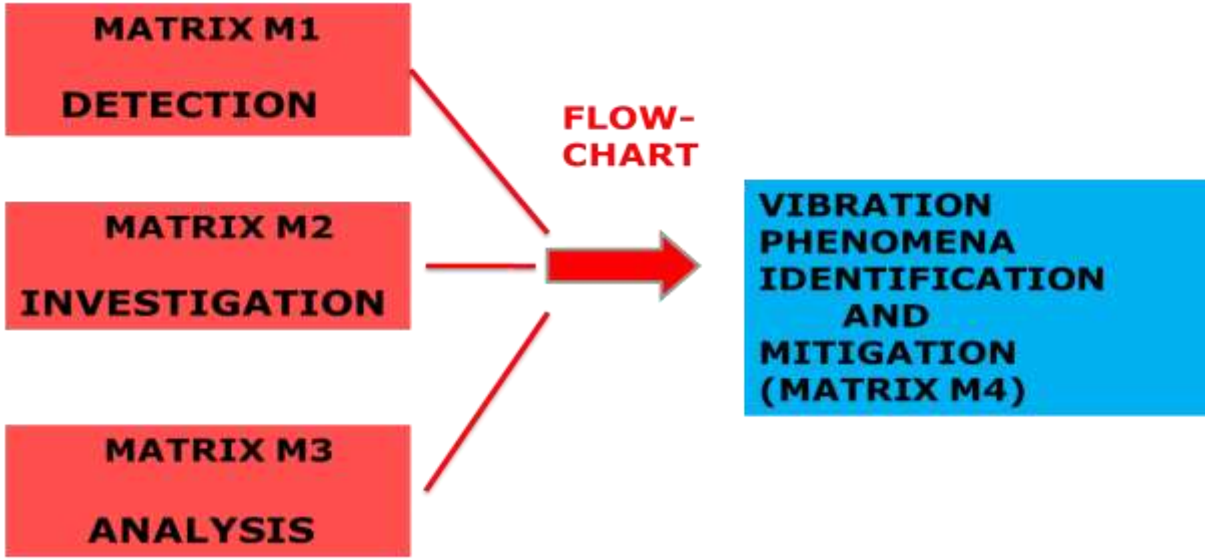
5	**Highly probable**
1	**Not very probable**
0	**Not possible**

Evaluation of Lateral Vibrations (ISO Standards, DIAM, Digital Twin)

DIAM Project: Detection, Investigation, Analysis, Mitigation)

After this first step further **Investigations** (Matrix M2) and deeper **Analysis** (Matrix M3) can follow in order to confirm the possible **Vibration Phenomena** by further probabilities. In this step **Digital Twins** can support the procedure

In a Matrix M4 – the **Mitigation** Matrix - suggestions are presented, by which measures the vibration problem can be solved.



MATRIX M1

DETECTION

MATRIX M2

INVESTIGATION

MATRIX M3

ANALYSIS

FLOW-
CHART

VIBRATION
PHENOMENA
IDENTIFICATION
AND
MITIGATION
(MATRIX M4)

Lateral Vibrations in Turbogenerators

- Lateral Vibrations in Turbogenerators
- FE- Modelling for Lateral Vibrations in Turbogenerators
- FE-Model used for the Design and as Digital Twin for the Operation
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- Vibration Control: Mitigation of Lateral Vibrations

Vibration Control: Mitigation of Lateral Vibrations

Passive and Active Vibration Control Measures

Vibration Control Measures	Without Energy Conversion	With Energy Conversion		
	Passive		semi-Active	Active
Reduction of Excitation				
System Tuning				
Damping				
Vibration Absorber				
Isolation of disturbance				
Isolation to protect the receiver				

Conventional Solution

Extended Solutions

Increase of:
Effectiveness, Complexity,
more Solution Variants

Vibration Control: Mitigation of Lateral Vibrations

Reduction of Excitation - Balancing

Vibration Control Measures	Without Energy Conversion	With Energy Conversion	
	Passive	**semi-Active**	**Active**
Reduction of Excitation	**Balancing**		
System Tuning			
Damping			
Vibration Absorber			
Isolation of disturbance			
Isolation to protect the receiver			

Conventional Solution

Extended Solutions

Increase of:
Effectiveness, Complexity,
more Solution Variants

Vibration Control: Mitigation of Lateral Vibrations

Reduction of Excitation: Balancing in a Spin Pit

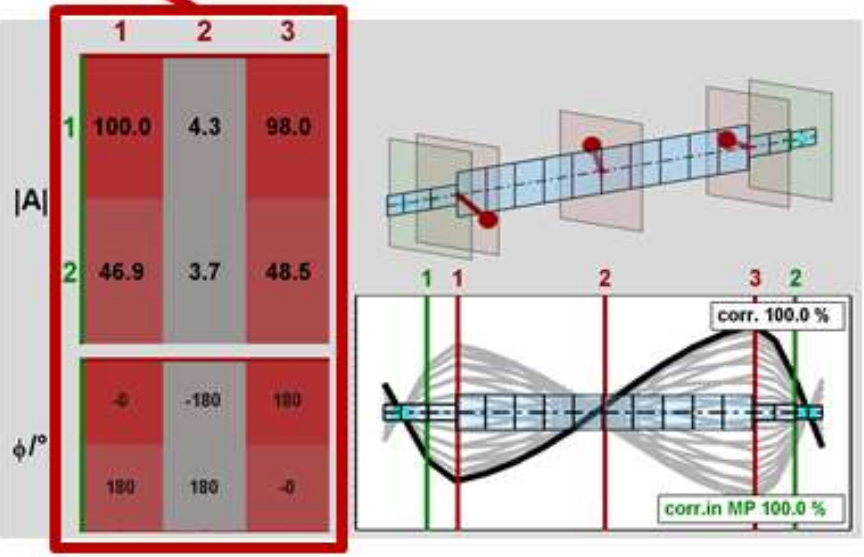
Balancing of LPT - Rotor

Vibration Control: Mitigation of Lateral Vibrations

Reduction of Excitation: Balancing with Influence Coefficients

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

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



		1	2	3
|A|	1	100.0	4.3	98.0
	2	46.9	3.7	48.5
ϕ/°		-0	-180	180
		180	180	-0

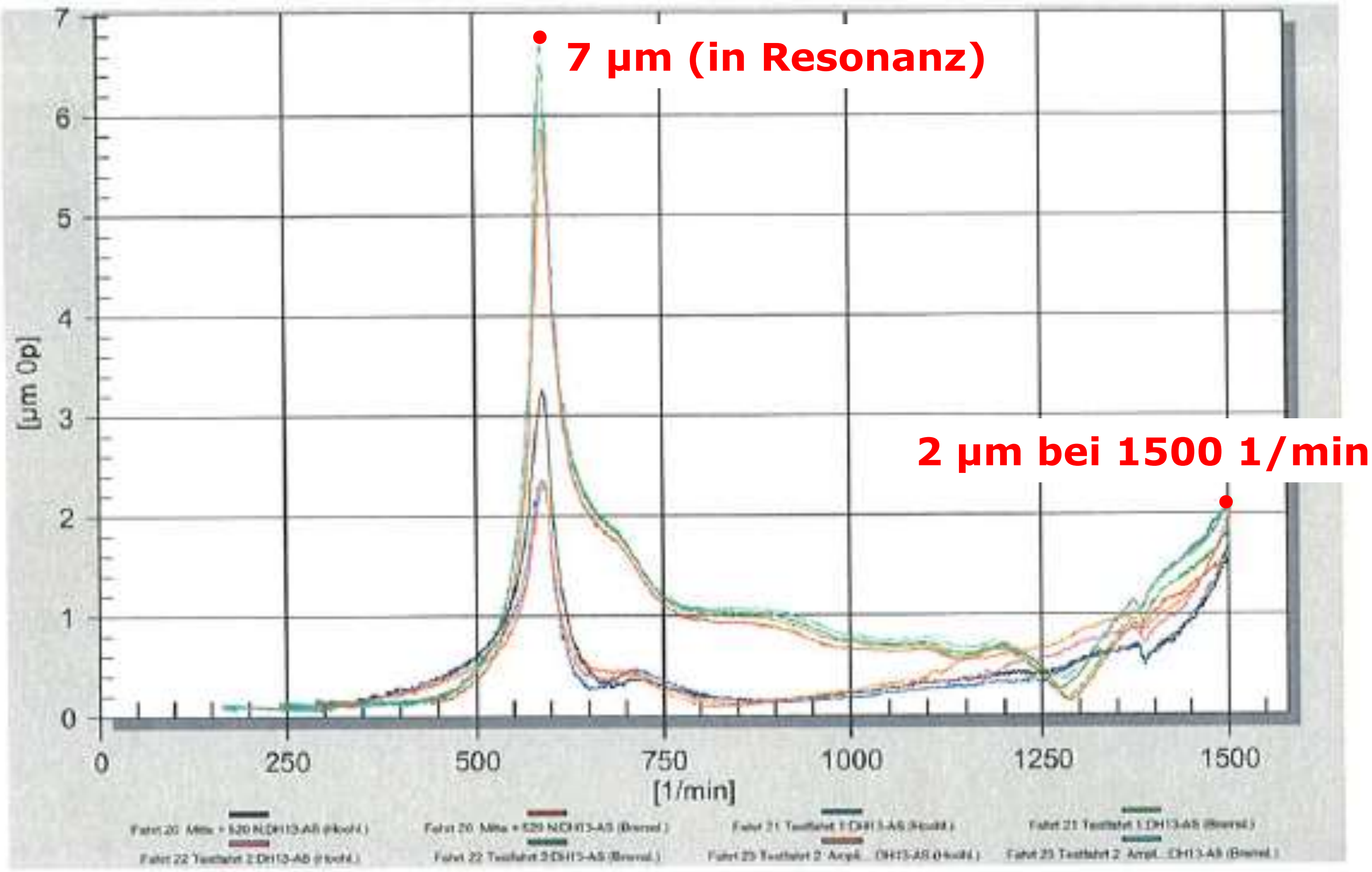
Example

2 measurement planes (in one direction)

3 compensation planes

Vibration Control: Mitigation of Lateral Vibrations

LPT- Steam Turbine Rotor after Balancing in a Spin Pit



7 µm (in Resonanz)

2 µm bei 1500 1/min

Vibration Control: Mitigation of Lateral Vibrations

Reduction of Excitation: **Active** Balancing

Vibration Control Measures	**Without Energy Conversion**	**With Energy Conversion**		
	Passive		**semi-Active**	**Active**
Reduction of Excitation				**Balancing**
System Tuning				
Damping				
Vibration Absorber				
Isolation of disturbance				
Isolation to protect the receiver				

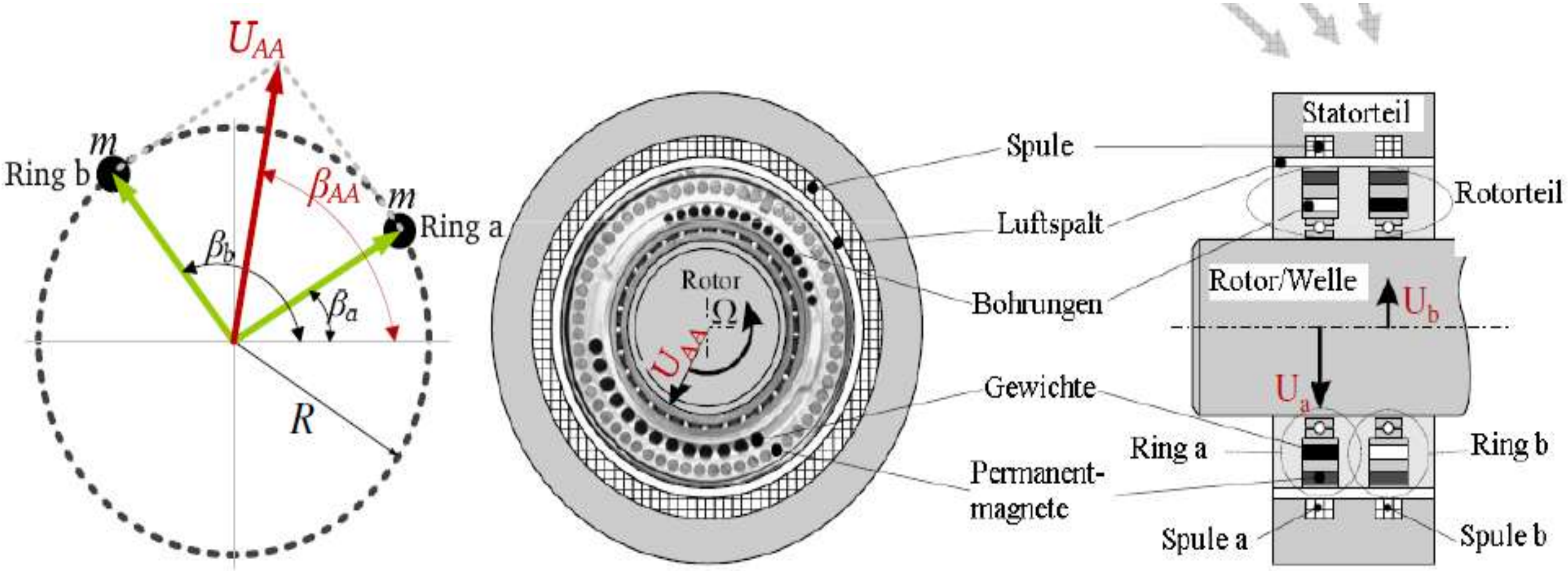
Conventional Solution

Extended Solutions

Increase of:
Effectiveness, Complexity,
more Solution Variants

Vibration Control: Mitigation of Lateral Vibrations

Reduction of Excitation: Active Balancing



Active Balancing Device
used in Machine tools

Vibration Control - Mitigation of Lateral Vibrations

System Tuning by Mass and Stiffness, Damping

Vibration Control Measures	Without Energy Conversion	With Energy Conversion	
	Passive	semi-Active	Active
Reduction of Excitation			
System Tuning	Mass, Stiffness		
Damping	Damping		
Vibration Absorber			
Isolation of disturbance			
Isolation to protect the receiver			

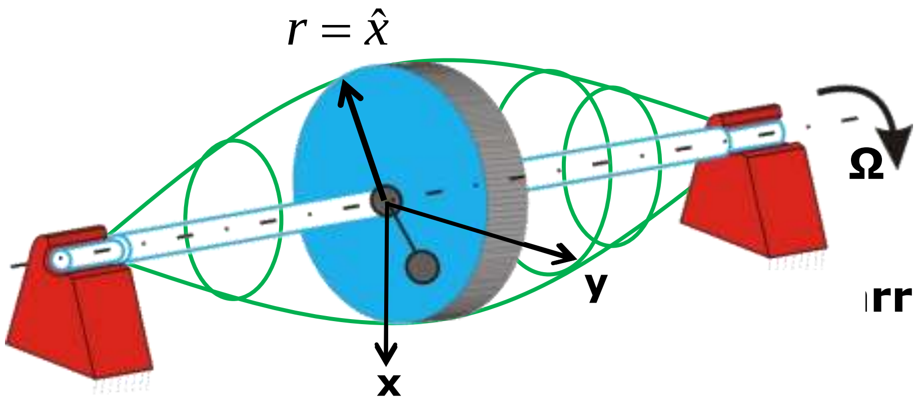
Extended Solutions

Increase of:
Effectiveness, Complexity,
more Solution Variants

Vibration Control - Mitigation of Lateral Vibrations

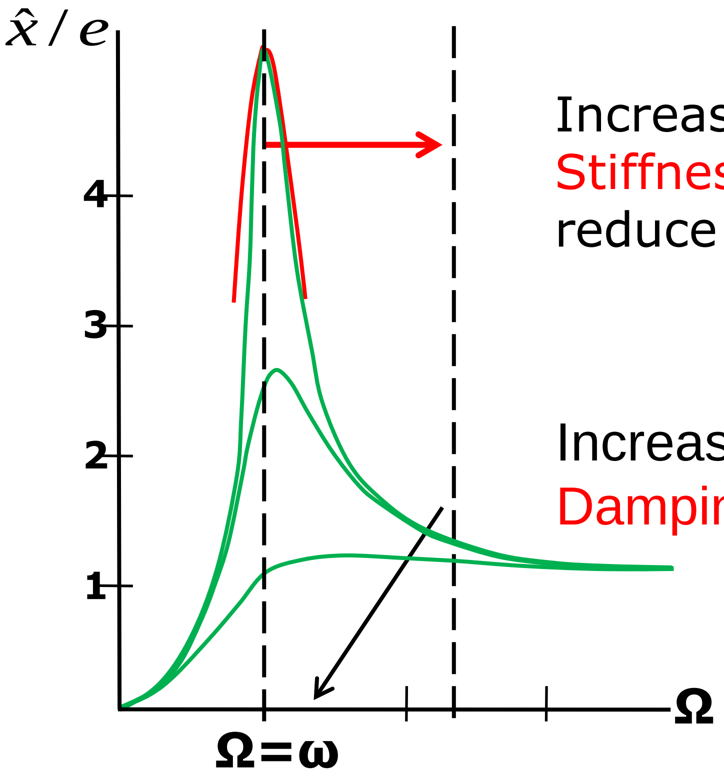
System Tuning by Mass and Stiffness, Damping

Shaft Vibrations



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

Amplitude



Increase
Stiffness or
reduce mass!

Increase
Damping

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Vorlesungen Mechatronik im Wintersemester

Energiforsk Seminar: Lectures in the Power Plants Ringhals, Oskarshamn and Forsmark, March 2022

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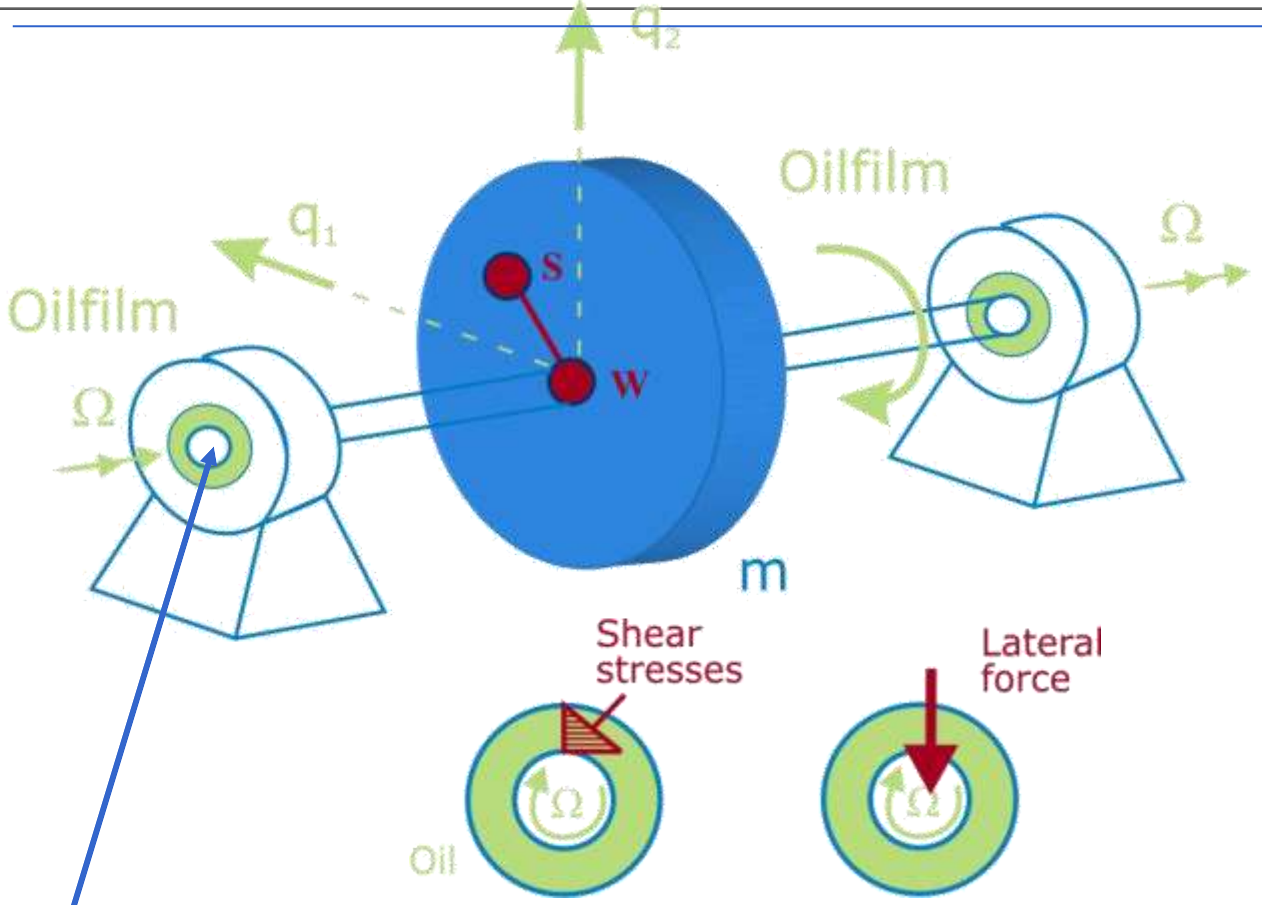
Vibrations of Turbines and Generators in Power Plants

Lecture II Lateral Vibrations in Turbogenerators

Rainer Nordmann
Technische Universität Darmstadt and Fraunhofer Institute LBF

Vibration Phenomena:
Selfexcited Vibrations



Rotational Energy of Shaft →

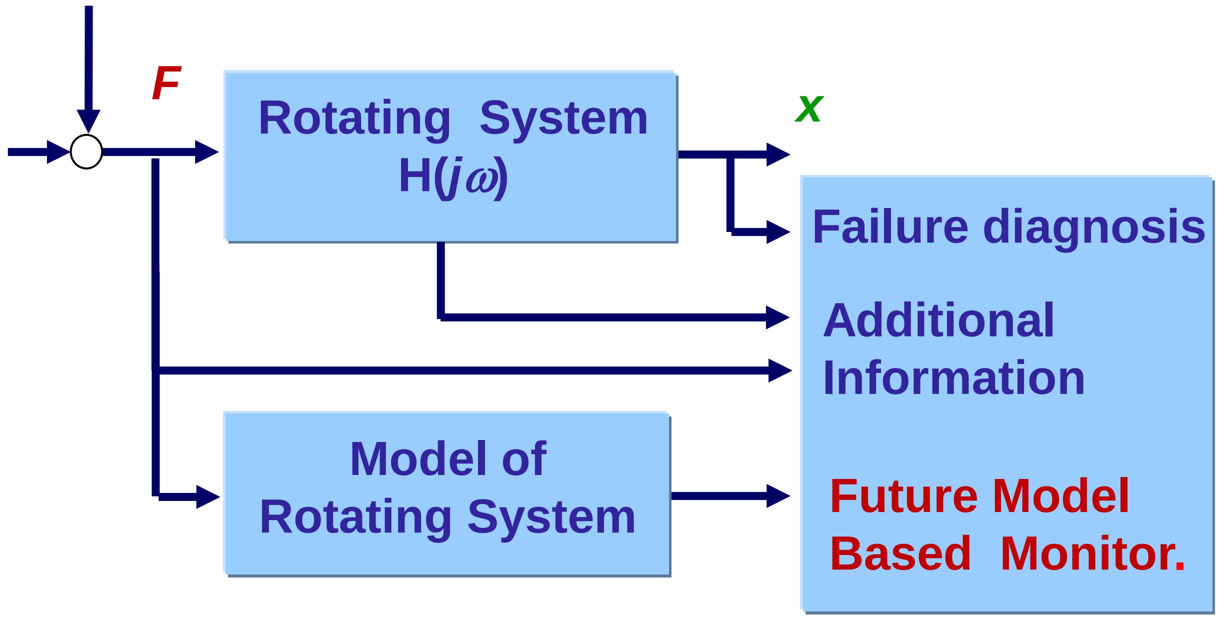
Energy in Oilfilm due to shear stresses →

Stabilizing or Destabilizing Lateral Oilfilm forces →

Lateral shaft vibrations q_1, q_2

Feedback

Future Model Based Monitoring & Diagnosis
Failure Diagnosis by means of FRF H(jω)



F

Rotating System
H($j\omega$)

x

Failure diagnosis

Additional Information

Future Model Based Monitor.

Model of Rotating System

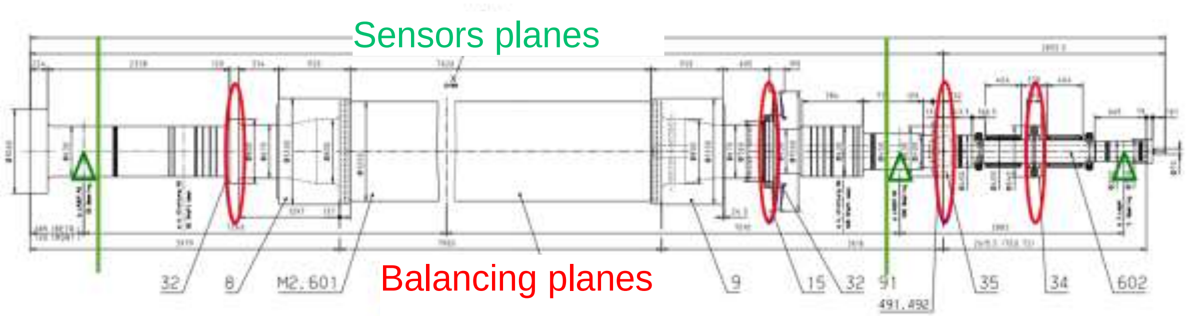
$$H(j\omega)\ F\ (j\omega) = x\ (j\omega)$$

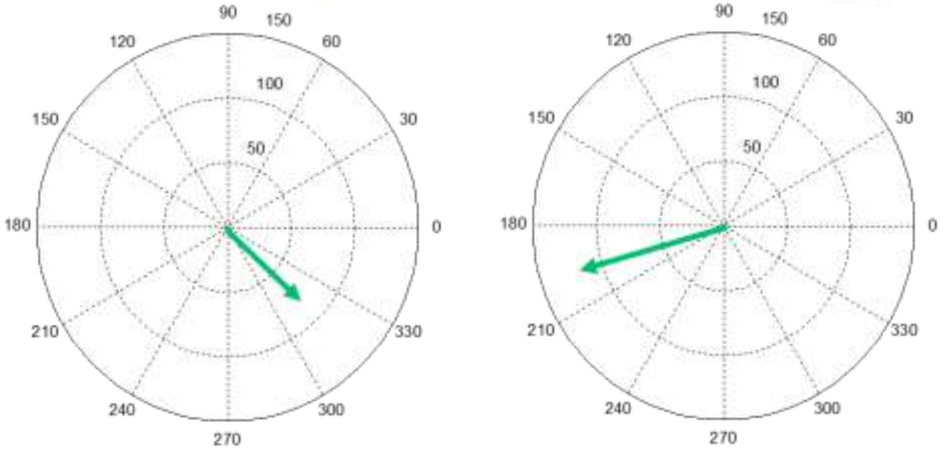
Parameter-Estimation

Question:

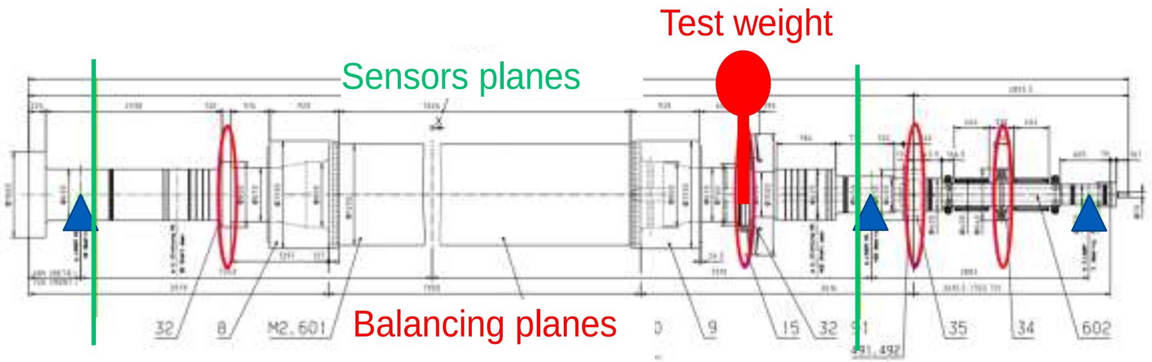
How strong is the influence of failures on the FRF H($j\omega$)?

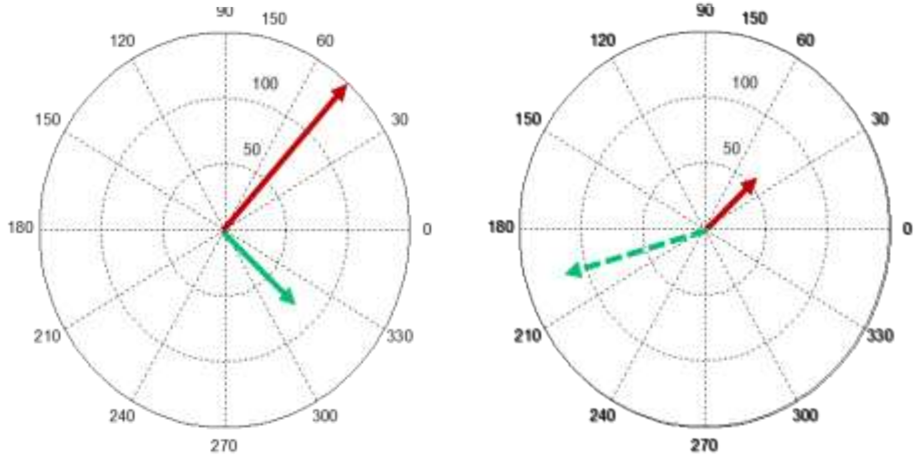
Determination of Influence Coefficients





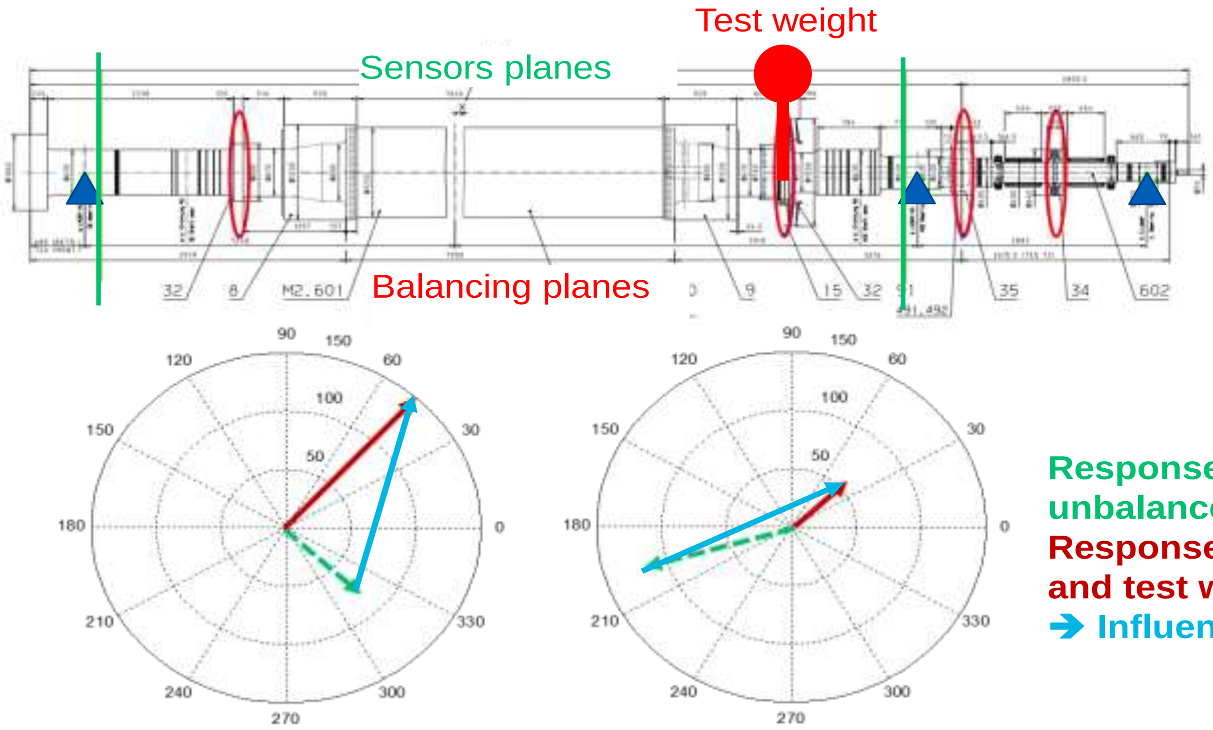
Vibration response amplitude to «residual» unbalance distribution @ e.g. 3000rpm





Response to «residual» unbalance @ e.g. 3000rpm

Response to resid. unbalance and test weight



Response to «residual» unbalance @ e.g. 3000rpm

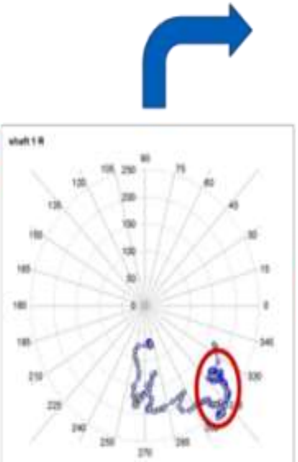
Response to resid. unbalance and test weight

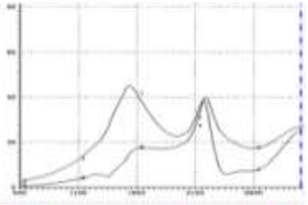
➔ Influence of test weight

The Balancing Process by means of Influence Coefficients

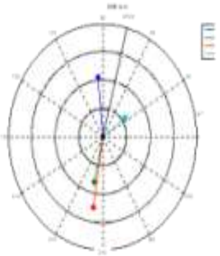
Classic balancing approach

Excessive vibration – Balancing needed

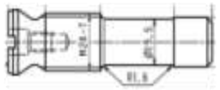




Unit run-up and coast down (*n)

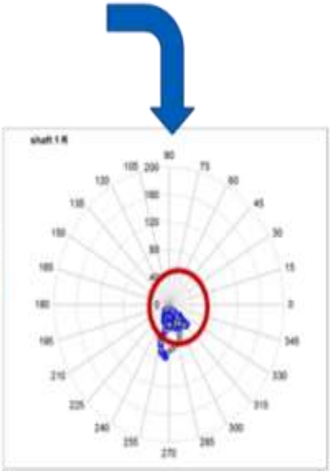


Measured influence coefficients



Selection of bolt weight and position for **final balancing**

Balancing completed – Acceptable vibration



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