Vorlesungen Mechatronik im Wintersemester

Vibrations in Nuclear Applications
Energiforsk Stockholm, November 9th 2023

TECHNISCHE UNIVERSITÄT DARMSTADT

Pump Vibration Problems in Power Plants

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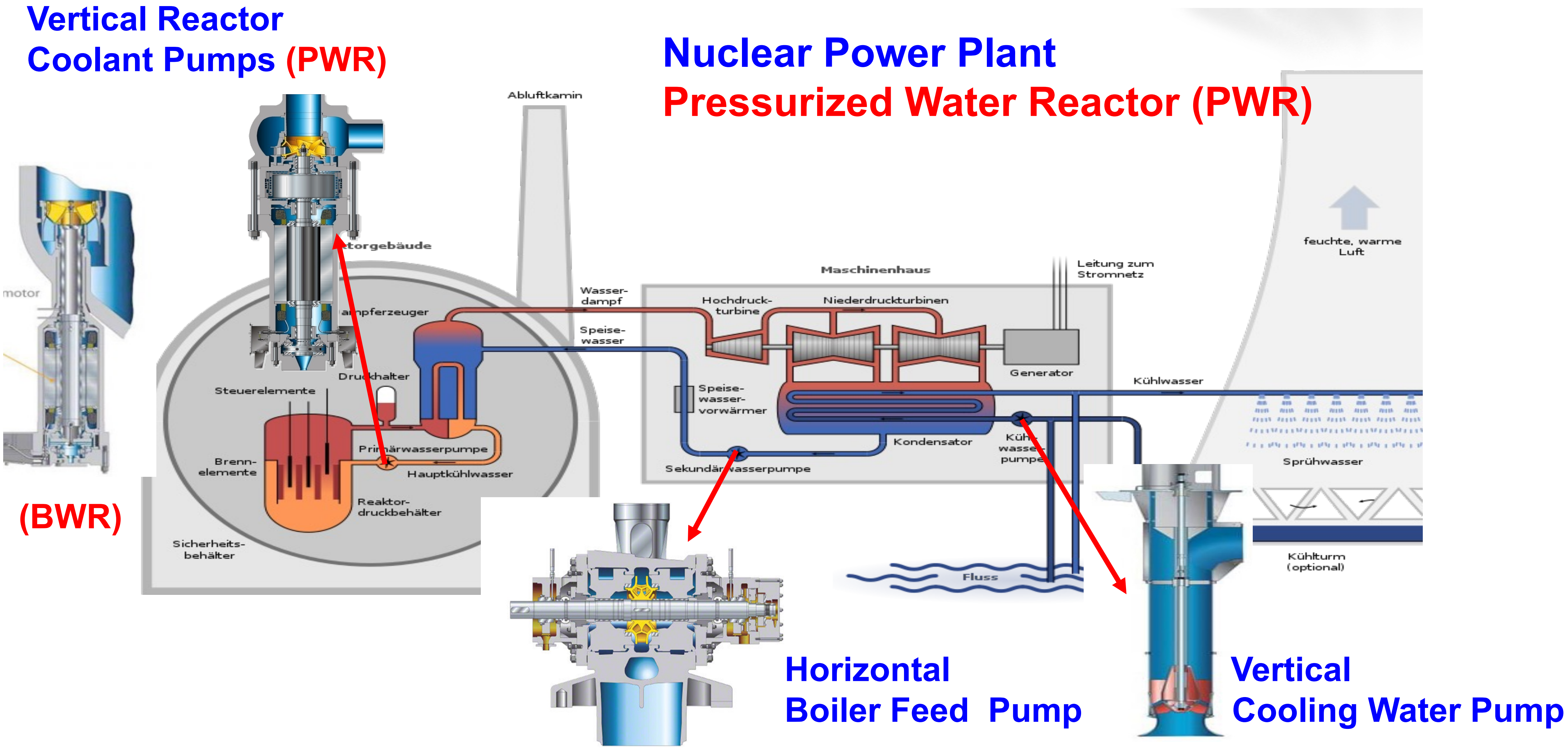
Pump Vibrations in Power Plants

- Different Vertical and Horizontal Pumps in Power Plants
- A typical Vertical Pump System for a Nuclear Power Plant
- Vibration Phenomena in Pump Systems
- Modeling of Pump Systems to predict Vibration Phenomena
- Monitoring of Pump Systems for Vibration Control
- Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces
- Vibrations of Vertical Pumps due to Unbalance and Instability

Different Vertical and Horizontal Pumps in Nuclear Power Plants



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A typical Vertical Pump System for a Nuclear Power Plant

Source: KSB Handbook

Vertical Reactor Coolant Pump

with

Impeller and Guide Vane

Flywheel

Electric Motor Drive

Three Radial Fluid Bearings

Axial Fluid Bearing

Pump Casing

A typical Vertical Pump System for a Nuclear Power Plant

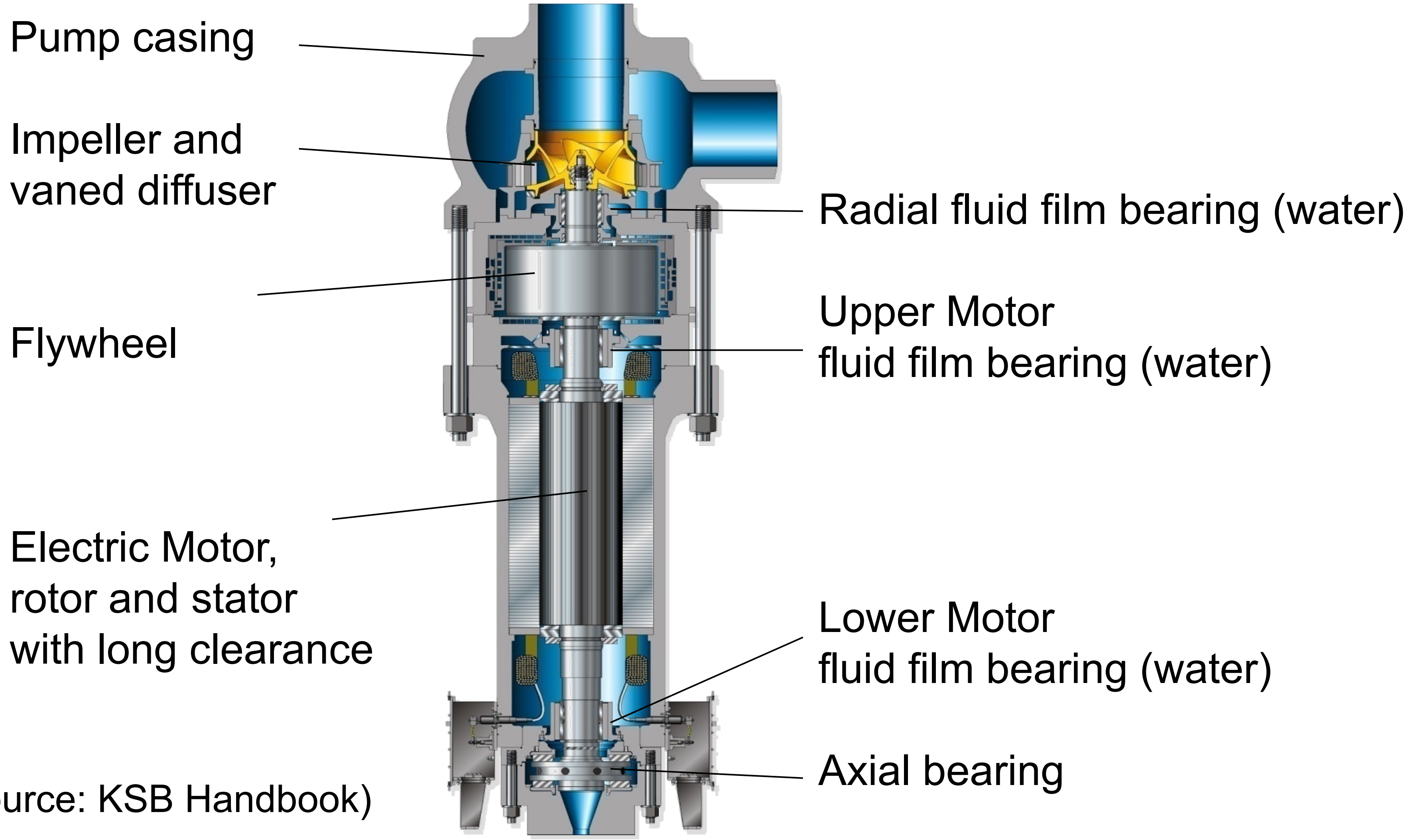
Source: KSB Handbook

Vertical Reactor Coolant Pump

Pump Characteristics

Power	kW
Capacity	m^3/h
Head	m
Pressure	bar
Temperature	°C
Rotational Speeds	rpm

A typical Vertical Pump System for a Nuclear Power Plant



(Source: KSB Handbook)

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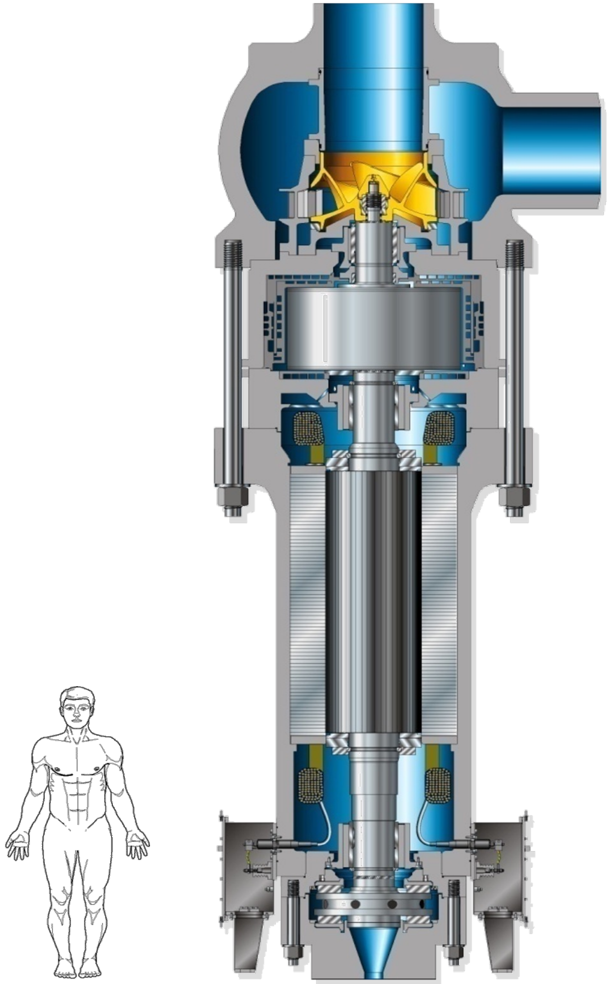
Vibration Phenomena in Pump Systems
Overview



Vibrations of Vertical Pumps
Fluid Dynamics & Mechanics

Stresses
Material Strengths

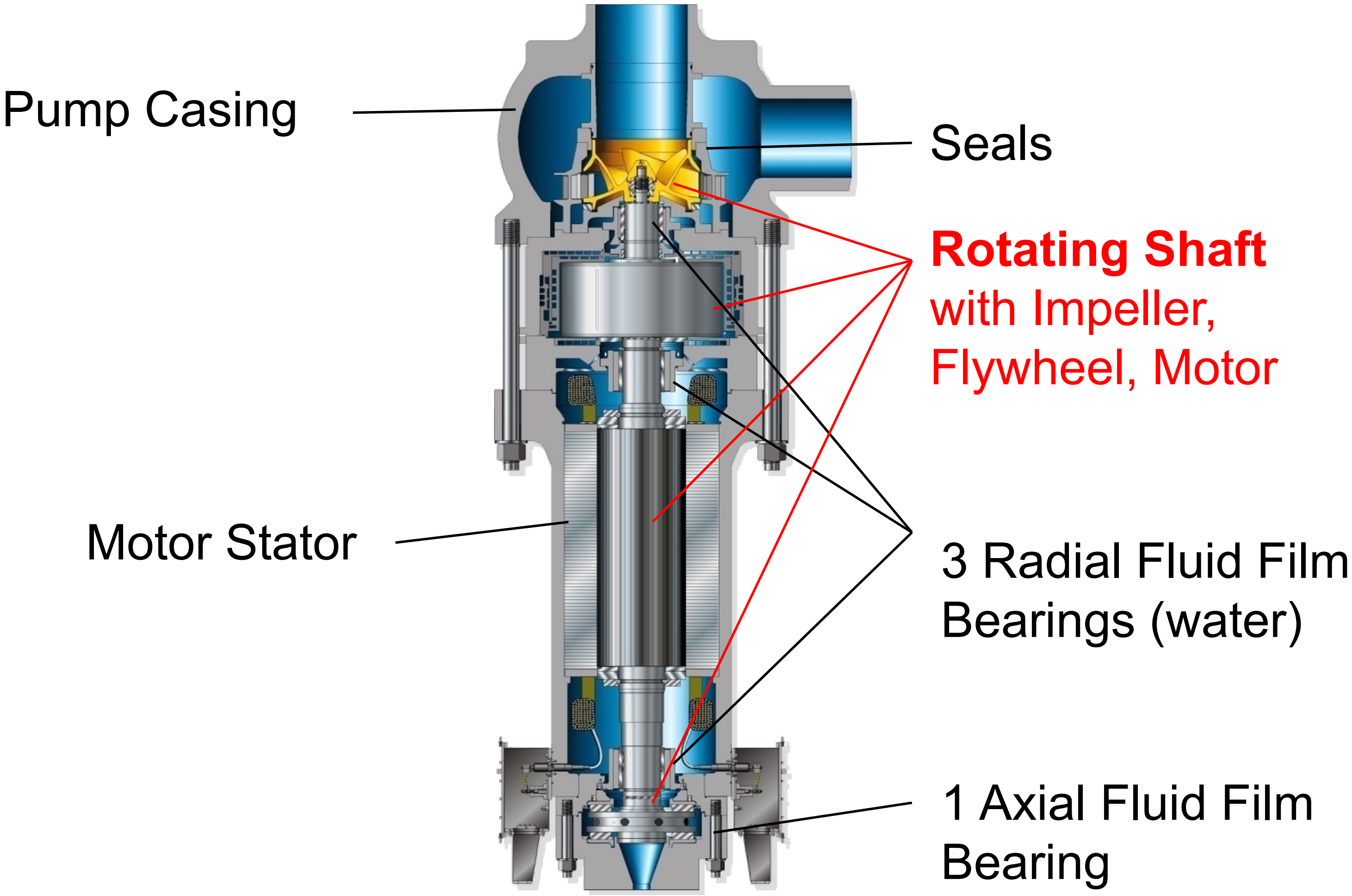
Rotordynamics with
Interaction Effects

Unbalance Vibrations,
Critical Speeds,
Vibrations due to
Rotor Fluid Interactions and
Rotor Structure Interactions

Rotor
Instability,
Whirl and
Whip

Vibration Phenomena of Pump Systems

Important System Components regarding Vibrations



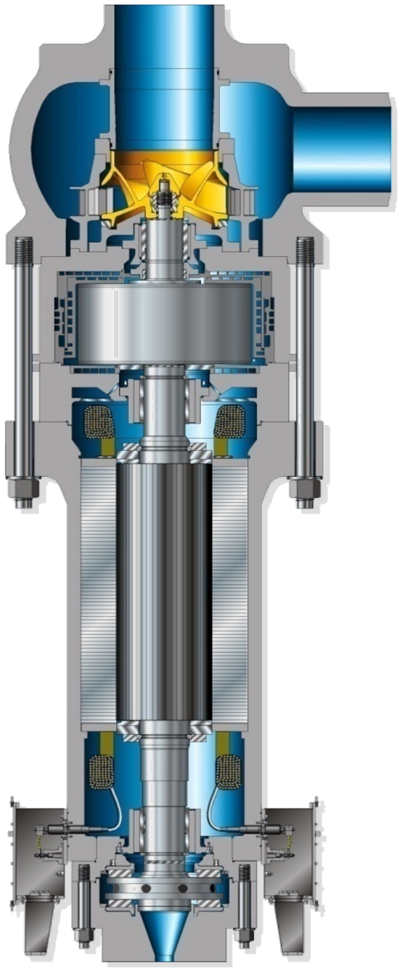
Vibration Phenomena of Pump Systems

Excitation and Reaction Forces for Lateral Vibrations

Impeller Fluid Forces

Unbalance Forces

Electromagnetic Forces



Radial Fluid Bearing Forces

Excitation Forces

Reaction Forces

Vibration Phenomena of Pump Systems
Motivation for **Rotordynamic** Investigations?

- How is the influence of **time dependent forces (moments)** on the dynamic behavior of a Pump System?

- Which **motions of vibration** and which **internal stresses** act on the rotating and on the non-rotating machine parts of the Pump?

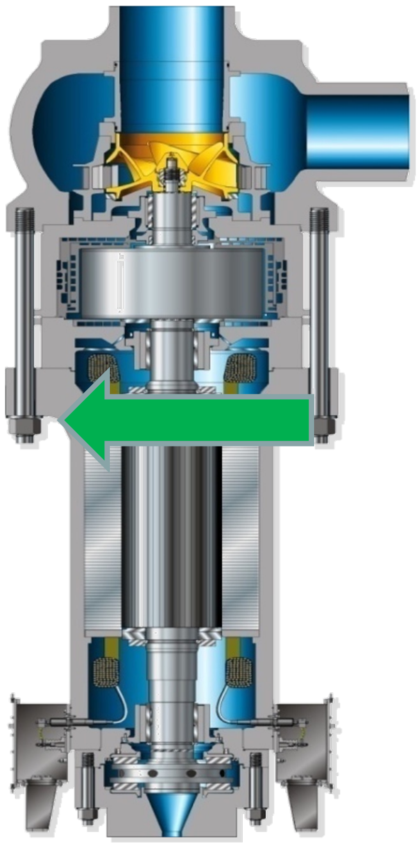
- Are critical conditions **(Resonances, Critical Speeds, Instabilities)** possible?

- **Can vibrations destroy machine parts?**
  Rubbing, shaft cracks, bearing failures, large deformations,…

- Which **Interactions** have to be considered?
  Fluid Structure Interactions FSI (Impeller, bearings, seals),
  Rotor Structure Interaction RSI (Pump casing, foundation)
  Electromechanical Interaction in the motor drive

Vibration Phenomena of Pump Systems

Lateral Vibrations



Lateral Vibrations: perpendicular to the shaft axis with bending along the shaft line.
Physical Effects: Inertia (masses), stiffness and damping of the system components.

Dynamic Characteristics: Lateral natural frequencies, critical speeds, natural modes, stability, Frequency Response Functions (FRF)

Excitations:
Unbalance forces, excitation with rotational frequency,
Fluid forces at the impeller with vane passing frequency
Electromagnetic forces at the motor
Self excited vibrations, Instability in bearings and seals

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Modelling of Pump Systems to Predict Vibration Phenomena

Equations of Motion - Input Output Relations

Vibrations of Pump System = **Dynamics of Pump System** x **Excitation of Pump Sytem**

Output	Pump System	Input
Lateral Vibrations	▪ Matrices M, D, G, K or ▪ Natural frequencies ▪ Damping ▪ Mode shapes	▪ Unbalance (Exc. Ω) ▪ Fluid forces (Exc. $n\Omega$) ▪ E-Magnetic forces ▪ Self - Excitation

Modelling of Pump Systems to Predict Vibration Phenomena

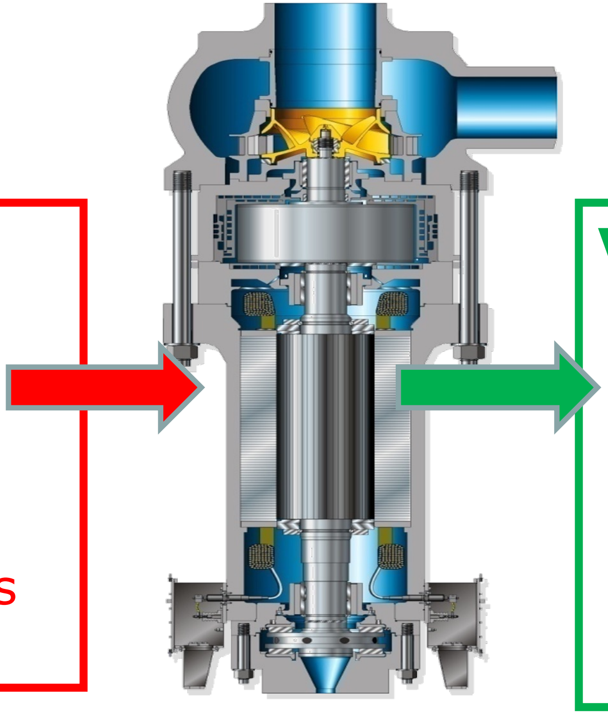
Equations of Motion, Input Output Relations

Excitations F(t)

Unbalance Forces

Fluid Forces

Electromagnetic Forces



Vibration Response x(t)

Unbalance Response

Fluid Forces Response

Response to Emagnetic Forces

Dynamic Characteristics of the Pump System:

Physical Parameters: Mass, Damping & Stiffness of Shaft, Fluid Bearings, Seals

Modal Parameters: Natural frequencies, Damping, Natural modes,

Modelling of Pump Systems to Predict Vibration Phenomena

Stiffness and Damping Coefficients of Fluid Film Bearings and Seals

The Forces of **Fluid Film Bearings** and **Seals** can be presented by **stiffness and damping coefficients k_{ij} and d_{ij}** in linear form:

$$F_z(t) = k_{zz}z + k_{zy}y + d_{zz}\dot{z} + d_{zy}\dot{y}$$

$$F_y(t) = k_{yz}z + k_{yy}y + d_{yz}\dot{z} + d_{yy}\dot{y}$$

They depend on the **geometry** (diameter, width, clearance) of the Bearings and Seals, on the **physical fluid data** (density, viscosity, temperature) and on the **operating conditions** (rotational speed, pressure, temperature, ..).

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Modelling of Pump Systems to Predict Vibration Phenomena

Stiffness and Damping Coefficients of Fluid Film Bearings and Seals

The **stiffness and damping coefficients** of Fluid film bearings and Seals can be determined by **Numerical calculations** (CFD) or by **Experiments**.
Example: For a bearing with a special geometry the coefficients depend on the Sommerfeld number So. Fluid film bearings have anisotropic behavior :

$$kzz \neq kyy \quad \text{and} \quad dzz \neq dyy$$

The coupling coefficients differ from each other (unsymmetry):

$$kzy \neq kyz \quad \text{and} \quad dzy \neq dyz$$

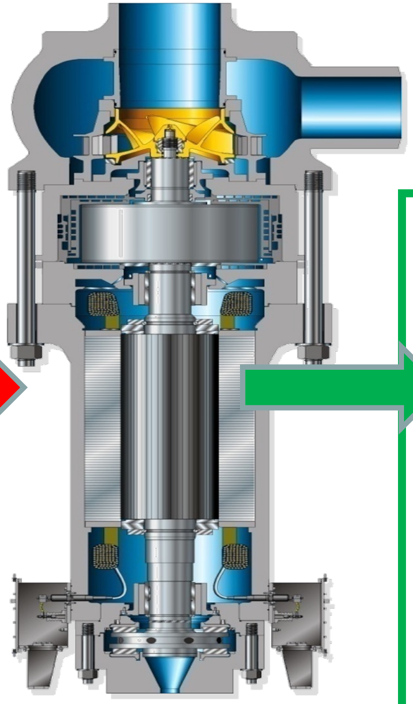
A measure for **instability sensitivity** is the difference: $(kzy - kyz)$.

Modelling of Pump Systems to Predict Vibration Phenomena

Equations of Motion, Input Output Relations

Excitations F(t)

- Unbalance Forces
- Fluid Forces
- Electromagnetic Forces



Vibration Response x(t)

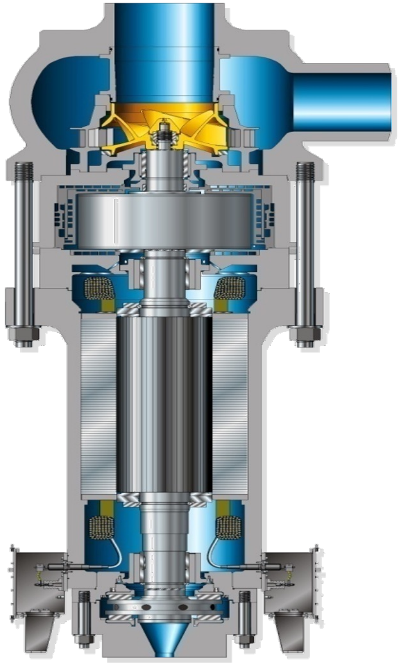
- Unbalance Response
- Fluid Forces Response
- Emagnetic Forces Respose

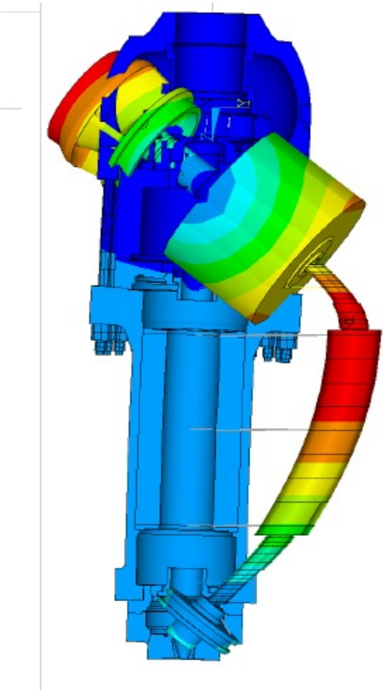
$$\mathbf{M}\,\ddot{x}(t) + (\mathbf{D}(\Omega) + \mathbf{G}(\Omega))\,\dot{x}(t) + \mathbf{K}(\Omega)\,x(t) = \mathbf{F}(t)$$

The Equations of Motion of the Pump contain the stiffness & damping & mass information of the shaft and the bearings and seals. The dynamic influences of the **casing** and the **piping** can be included.

Modelling of Pump Systems to Predict Vibration Phenomena

Natural Vibrations: Eigenvalues and Mode Shapes





Natural frequency ω

Damping α

Bending mode

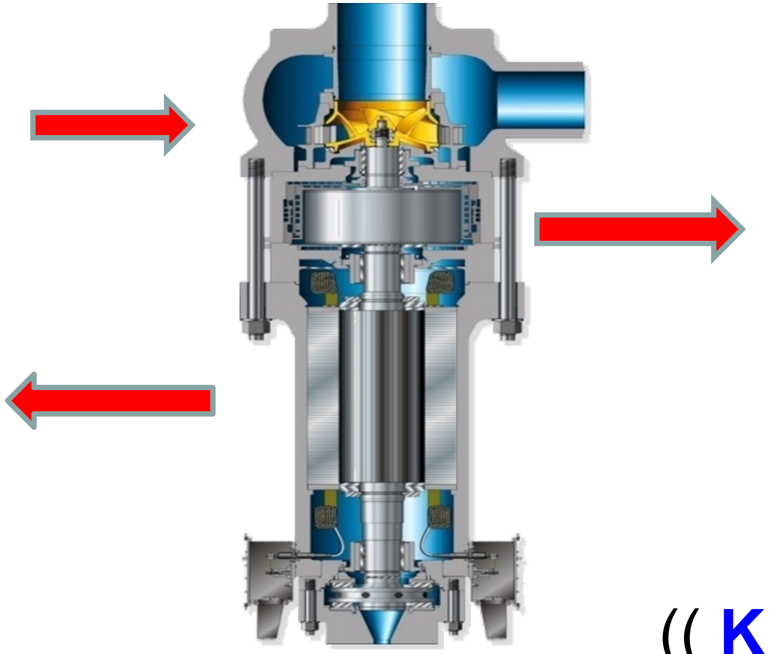
$$\left(\lambda^2 \mathbf{M} + \lambda(\mathbf{D}(\Omega) + \mathbf{G}(\Omega)) + \mathbf{K}(\Omega)\right) \cdot \mathbf{x} = \mathbf{0}$$

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

Information for **natural frequencies ω** and **damping α** (stability)

Modelling of Pump Systems to Predict Vibration Phenomena

Lateral Vibrations due to **Unbalance Forces**



Unbalance forces act mainly at the main masses m: impeller, flywheel and motor. For each mass they are defined by amplitude $me\Omega^2$ and phase

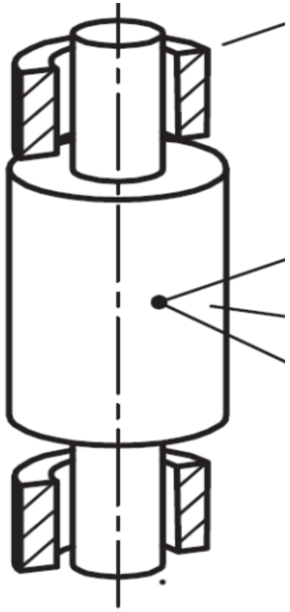
$$((\mathbf{K}(\Omega) - \Omega^2 \mathbf{M}) + j\Omega (\mathbf{D} (\Omega) + \mathbf{G} (\Omega)) \mathbf{x} = \mathbf{U} \Omega^2 \mathbf{F}_i$$

Complex System response x_i contains amplitude and phase

Modelling of Pump Systems to Predict Vibration Phenomena

Lateral Vibrations due to Unbalance Forces and Instability

This prestudy investigates the lateral **vibrations of a rigid mass m with unbalance**, running with **angular velocity Ω in** cylindrical hydrodynamic **waterfilm bearings.** The shaft arrangement is vertical



Hydrodynamic circular waterfilm bearing 1

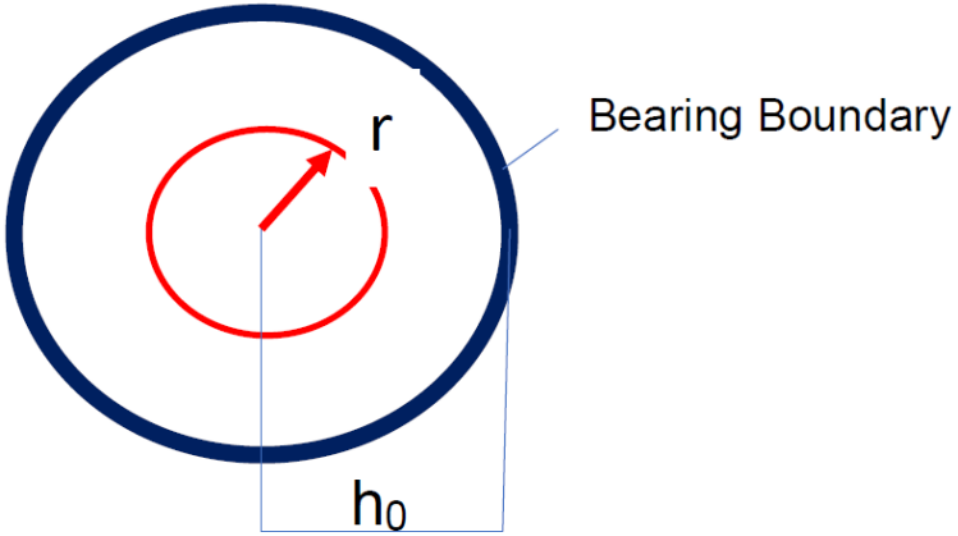
Mass of Impeller **m**

Mass eccentricity: ε

Hydrodynamic circular waterfilm bearing 2

Modelling of Pump Systems to Predict Vibration Phenomena
Lateral Vibrations due to **Unbalance Forces an Instability**

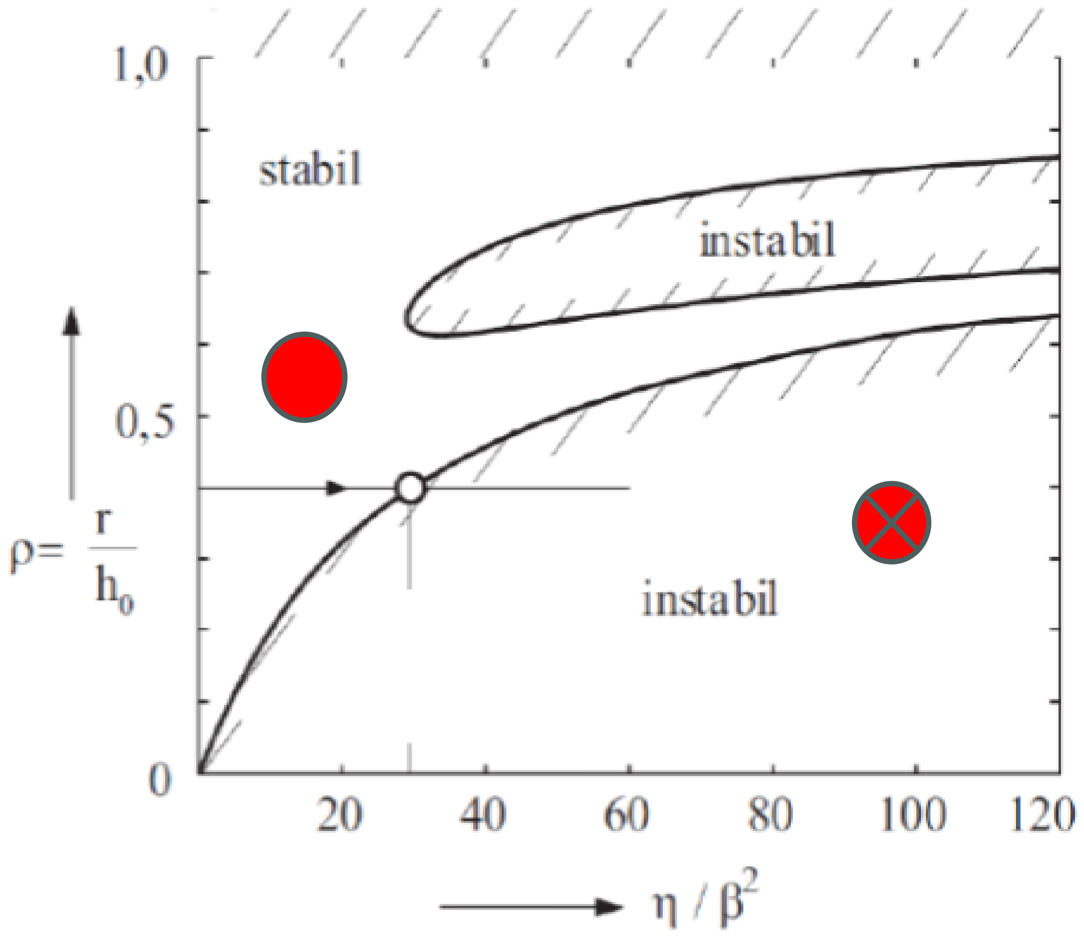
With a **nonlinear calculation** for the impeller mass m and the circular waterfilm bearing we can determine **the vibration amplitude r of an circular orbit** due to an **unbalance ε** acting at the impeller. **The frequency of the orbit is Ω.** The amplitude r can be related **to** the radial bearing clearance h_0, where ρ is between 0 and 1.



$$\rho = r / h_0 < 1$$

Modelling of Pump Systems to Predict Vibration Phenomena

Lateral Vibrations due to **Unbalance Forces and Instability**



This diagram shows, that **stable and unstable** motions are possible.

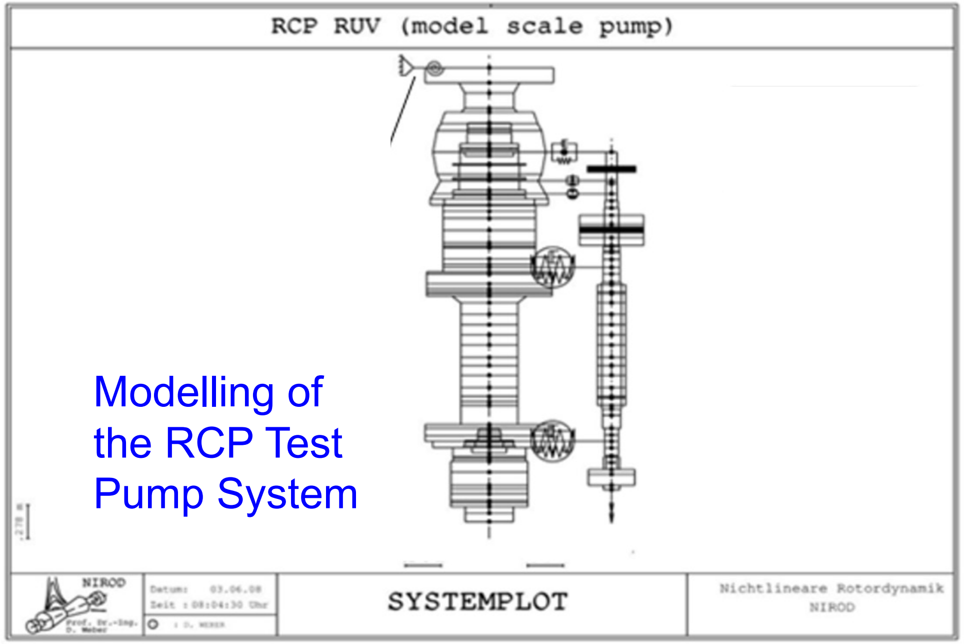
Are we in a stable or unstable range?

Subsynchronous vibrations will appear in the unstable range.

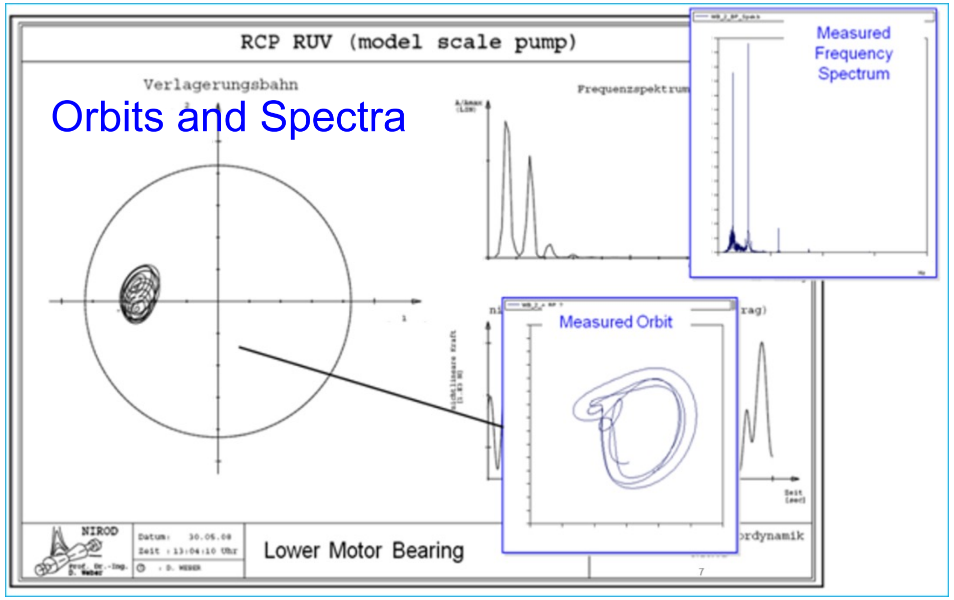
A final solution has to be found numerically.

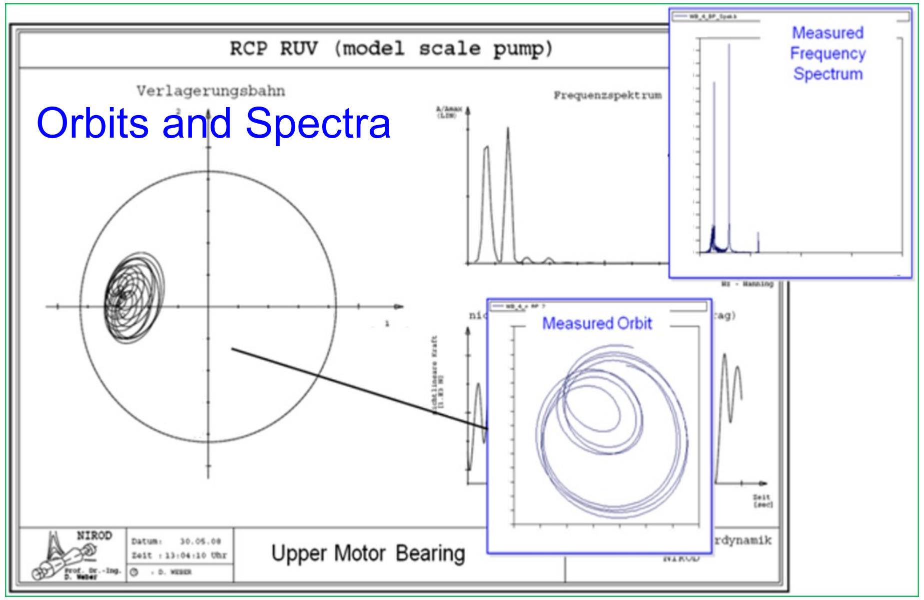
High Unbalance Forces stabelize!

Lateral Vibrations of a Test Pump System



Unbalance Vibrations with shaft rotational frequency **Ω** and **unstable vibrations** with ~ **Ω/2 (whirl).** Calculated and measured Orbits and Frequency Spectra at the lower and upper motor bearing.





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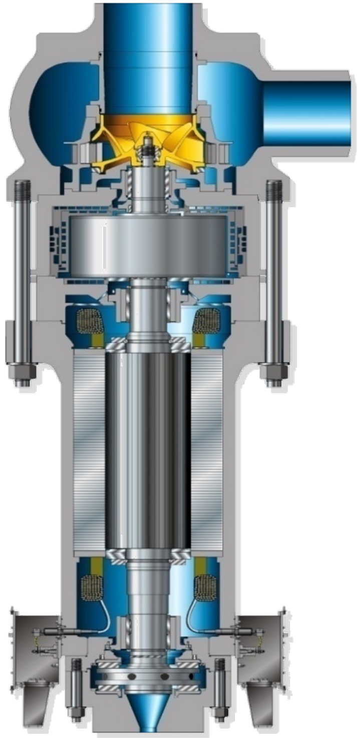
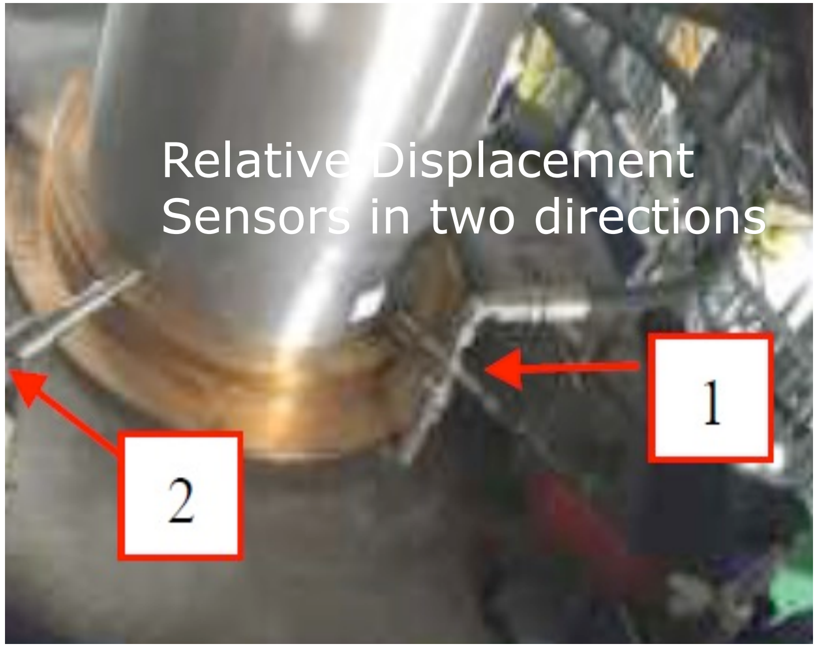
Monitoring of Pump Systems for Vibration Control

Monitoring by means of Relative Displacement Sensors

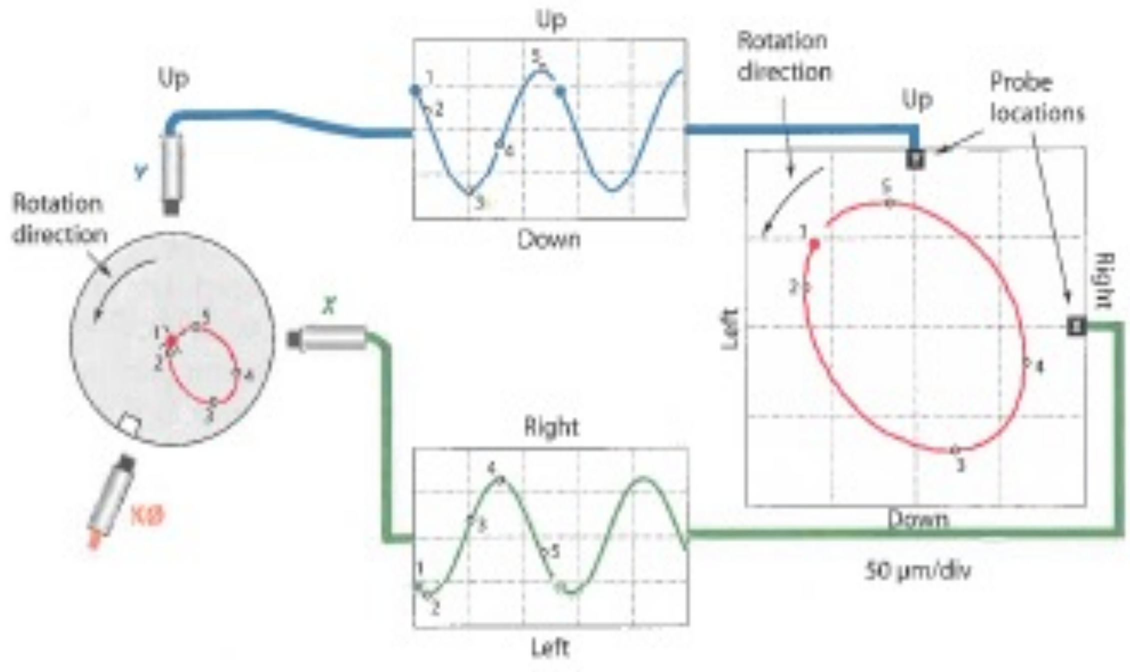




For Monitoring of Pump Systems **absolute vibration velocities in mm/sec** and/or **relative shaft vibrations in µm** at defined locations (Bearings) are usually measured. Vibrations are evaluated e.g. by ISO Standards or other Standards.

Monitoring of Vertical Pump Systems
Conventional Monitoring

Measurement of **relative shaft vibrations** in horizontal and vertical direction by means of displacement sensors. By superpositon of the two signals in one plane **Orbits** can be determined. They show the shaft motions in the measurement plane.



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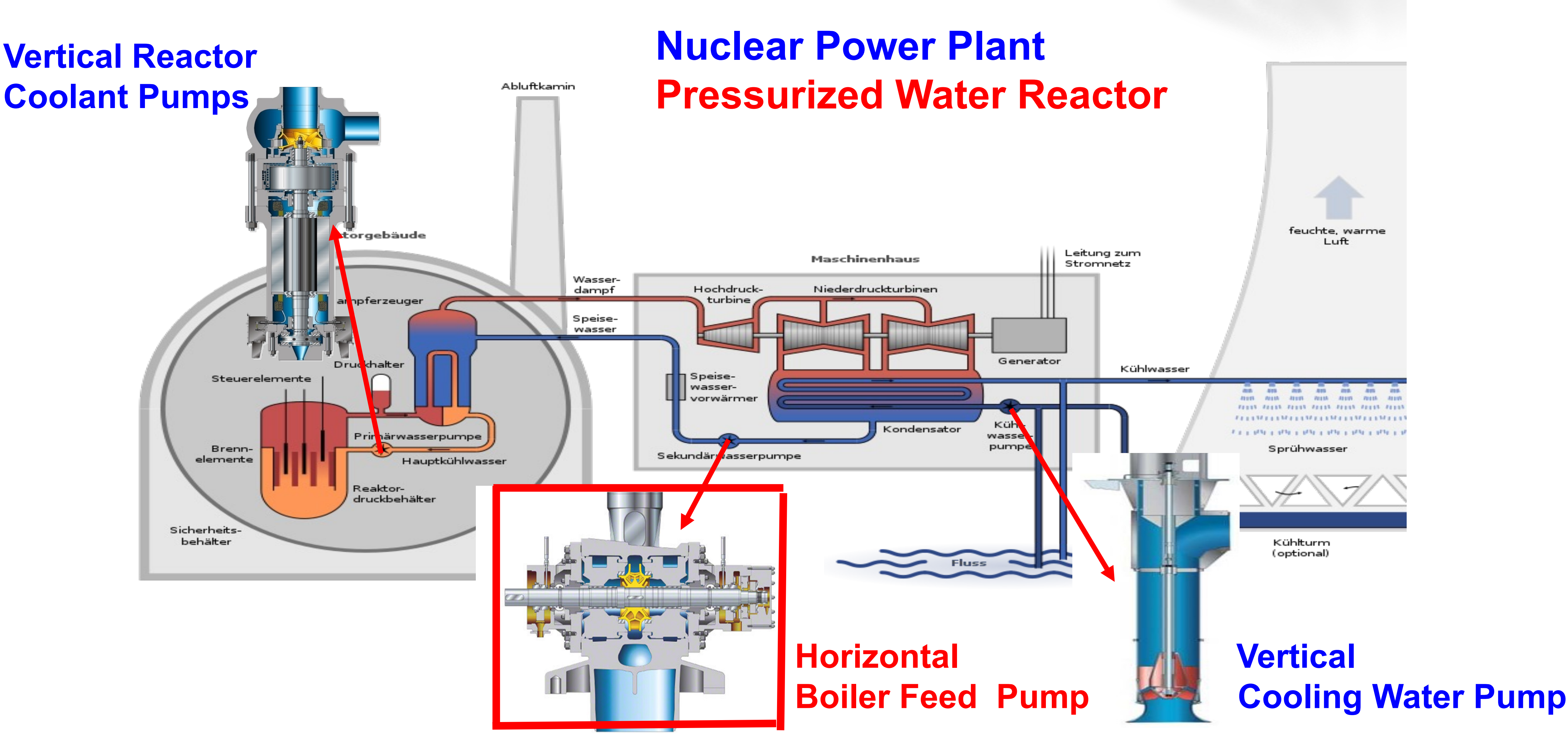
Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces



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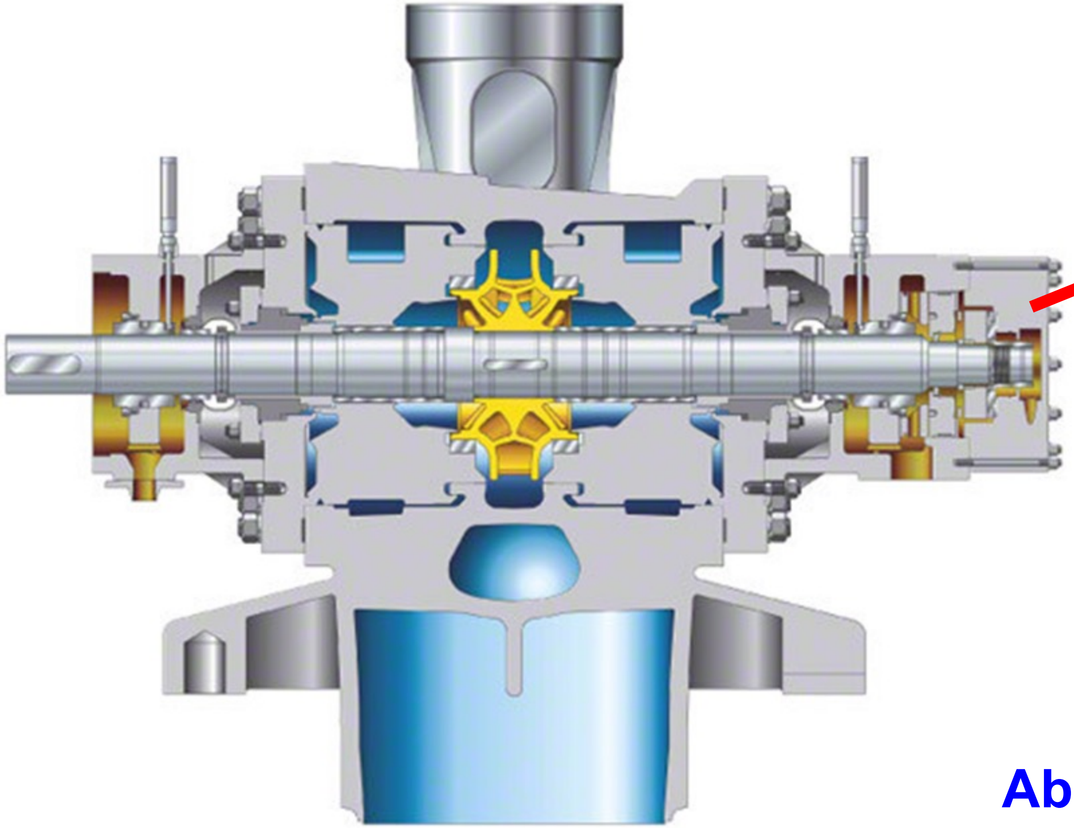
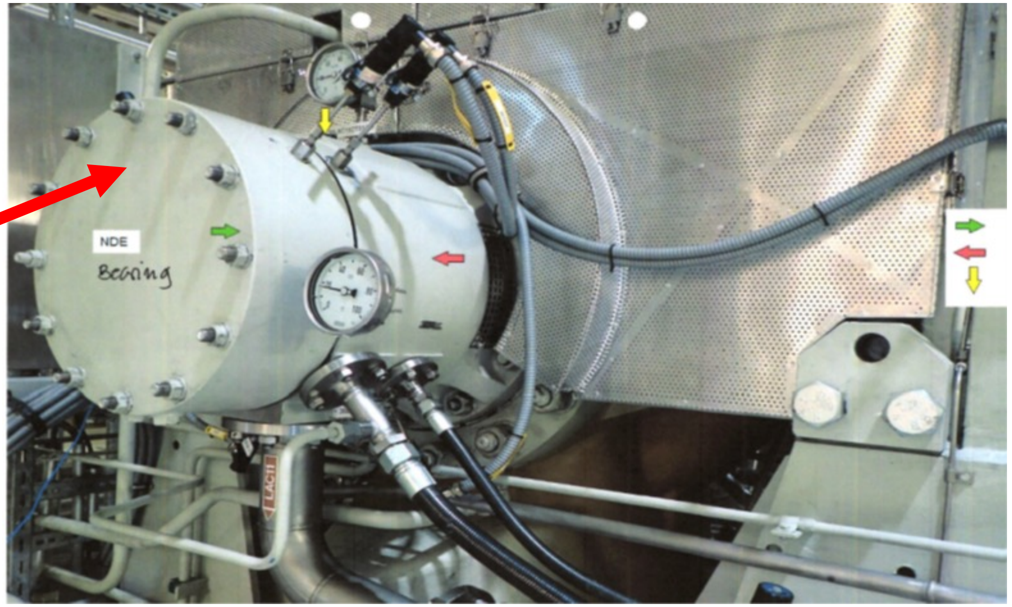
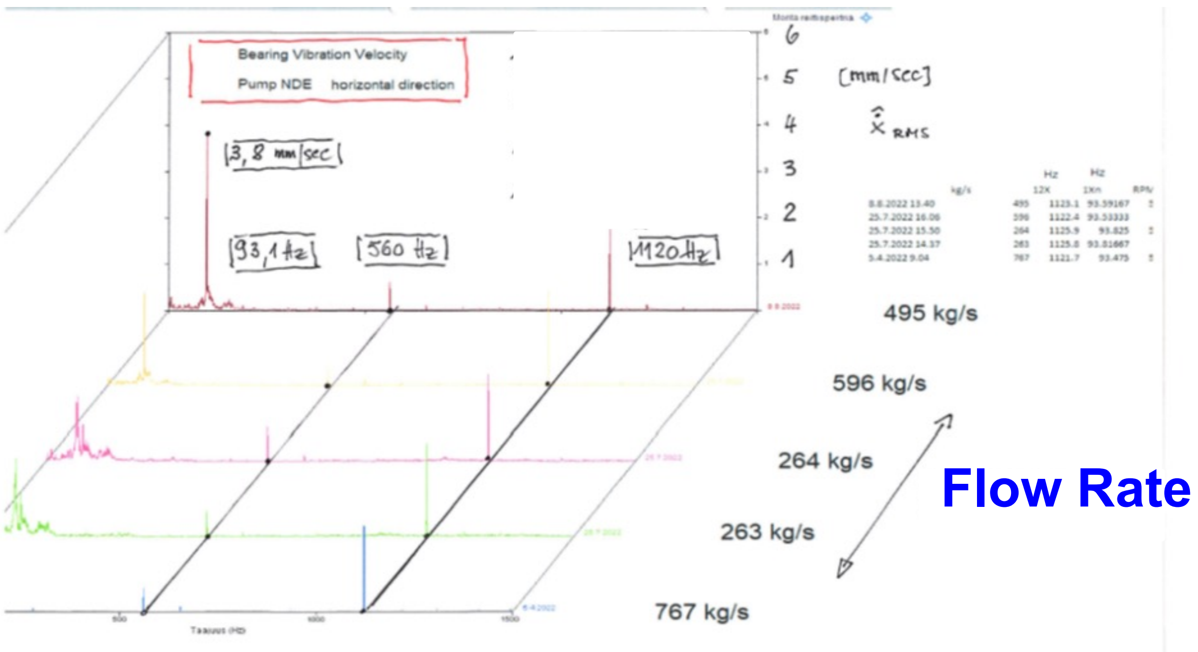




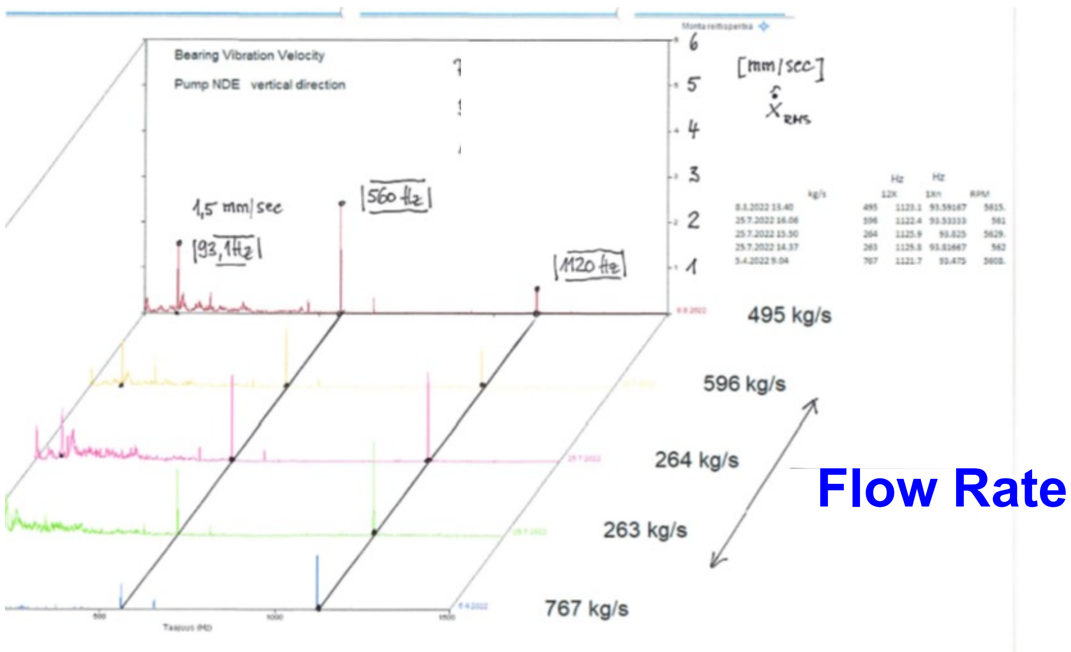
Absolute RMS Vibration velocities $\dot{x}_{RMS}$ were determined at the two **Bearing housings** in in horizontal, vertical and axial directions

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

NDE Bearing horizontal $\dot{x}_{RMS}$



NDE Bearing vertical $\dot{x}_{RMS}$

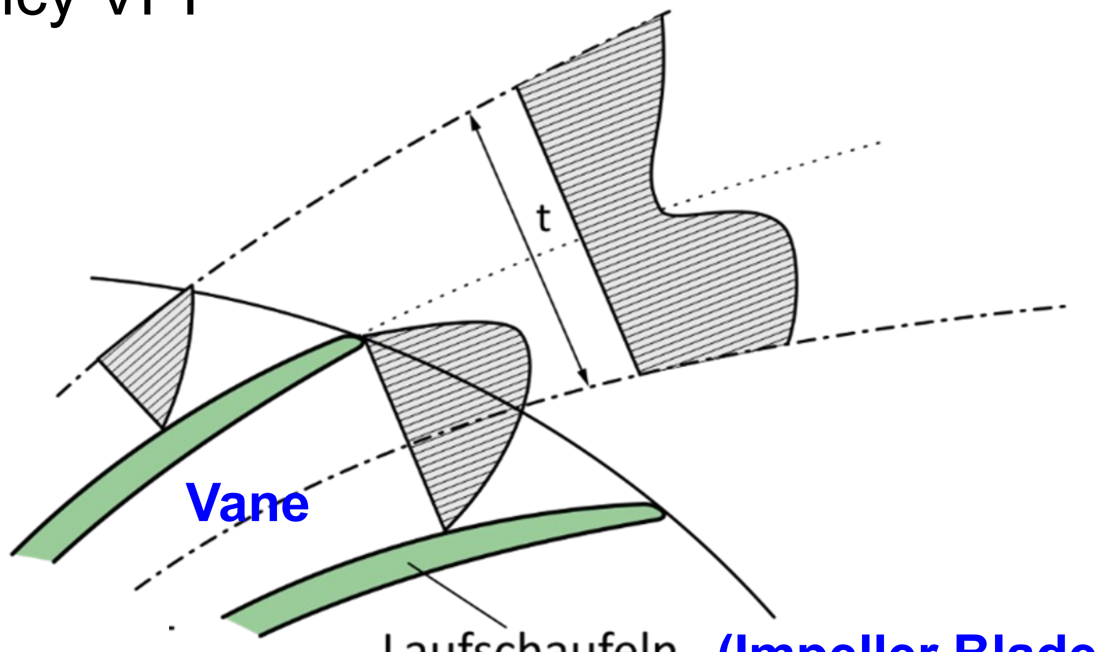


560 Hz 1120 Hz **560 Hz 1120 Hz** → **Frequency Hz**

How can the **vibrations** at **frequencies of 560 Hz** and **1120 Hz** be explained **?**

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Vane Pass Frequency VPF



The Fluid Structure Interaction creates **Fluid Forces** in the area between the **impeller** and **the volute** with the blade passing frequency **VPF = f_{rot} x N** and higher Harmonics of it.
$f_{rot} = \Omega / 2\pi$ is the rotational frequency of the pump shaft in Hz and N is the number of blades.

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Campbell Diagram with Excitation lines and Natural Frequencies

In case of the considred **Boiler Feed Pump**

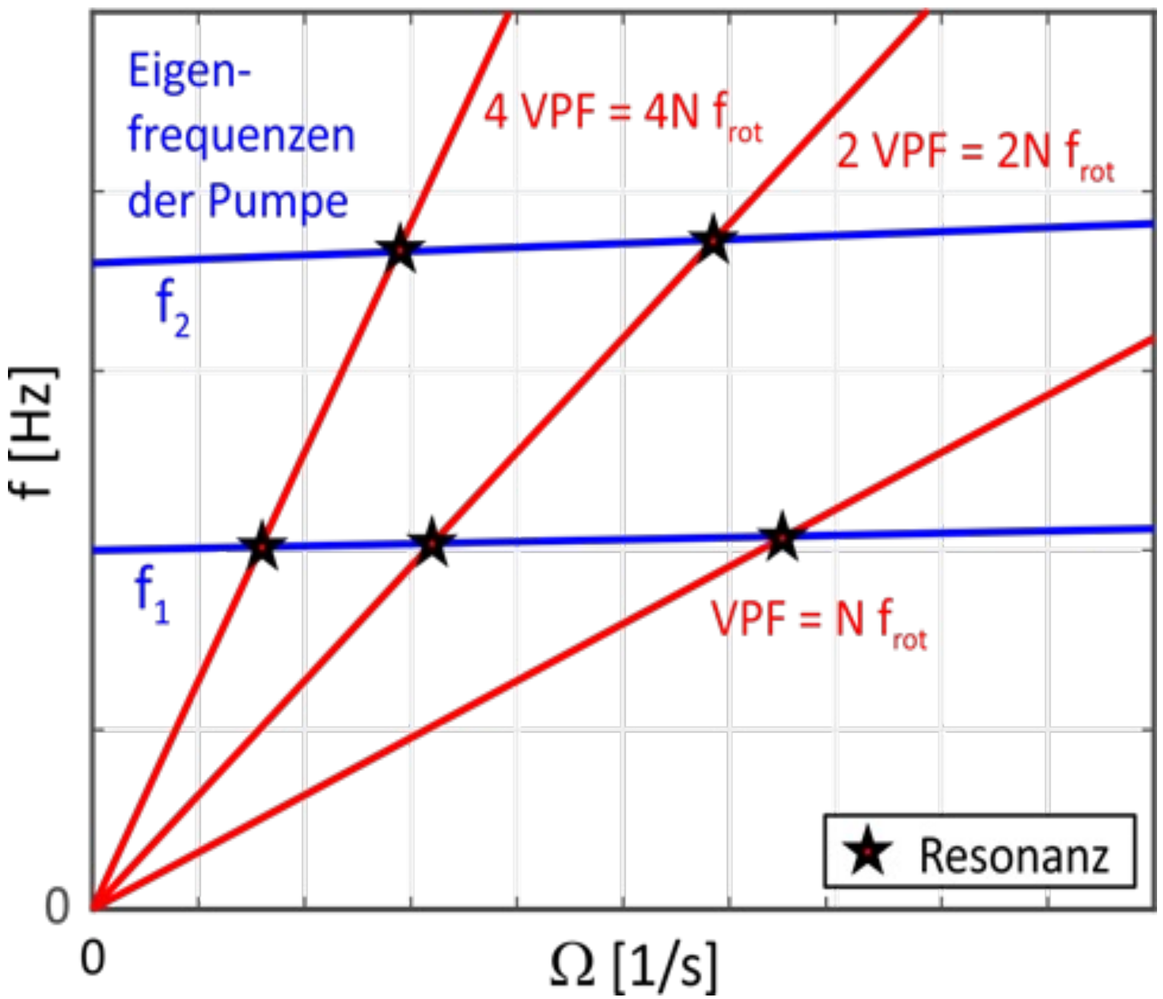
f_{rot} = 93,2 Hz and N = 6

and the **Vane Passing Frequency VPF** is

VPF = 560 Hz and 2 VPF = 1120 Hz

In a **Campbell Diagram** we can find possible **Resonances,** when the speed dependent **Excitation Frequencies VPF, 2 VPF, …** cross the speed dependent **lateral natural frequencies** (blue lines) of the pump system.

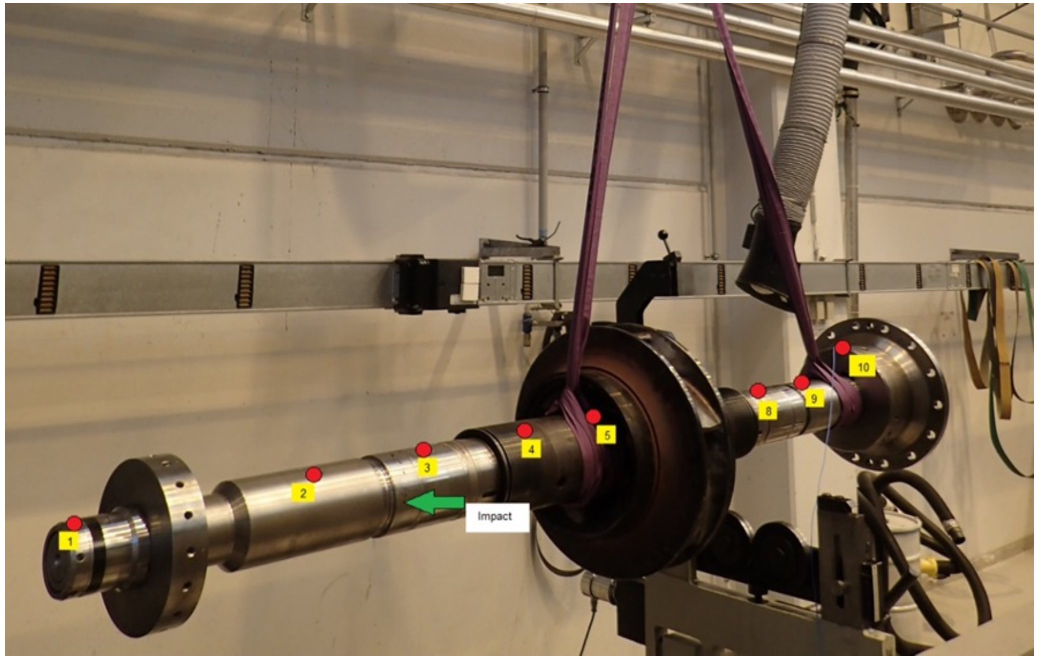
To find the **Resonances** the **lateral natural frequencies** have to be determined.



Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Determination of the Lateral Natural Frequencies by Exp. Modal Analysis

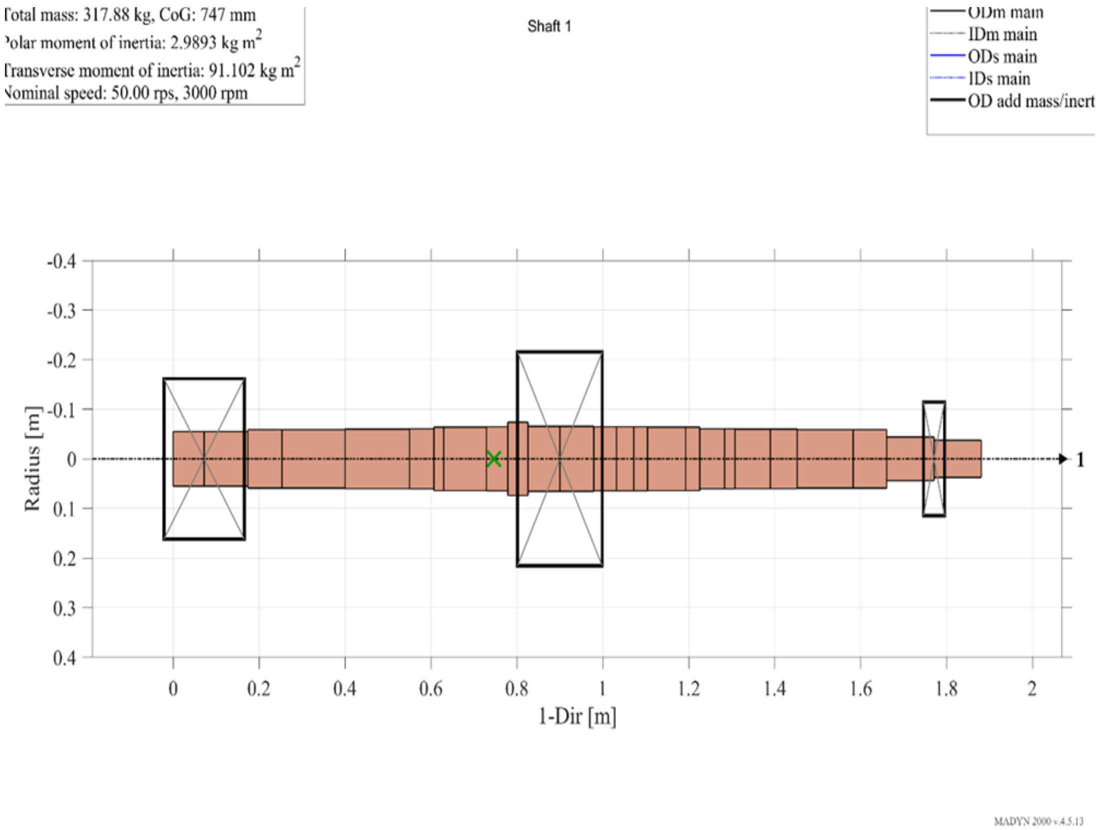
- **Test Set Up for Exp. Modal Analysis**
  - **Pump shaft with Masses and Moments of Inertia of impeller, coupling and axial bearing in free free condition**
  - **No bearings, no seals**
  - **No rotation of shaft**



Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Determination of the Lateral Natural Frequencies by a FE - Model

- **The FE Model consists of**
  - **Pump shaft (stiffness and mass of shaft)**
  - **Masses and Moments of Inertia of impeller, coupling and axial bearing**
  - **No bearings, no seals**
  - **No rotation of shaft**



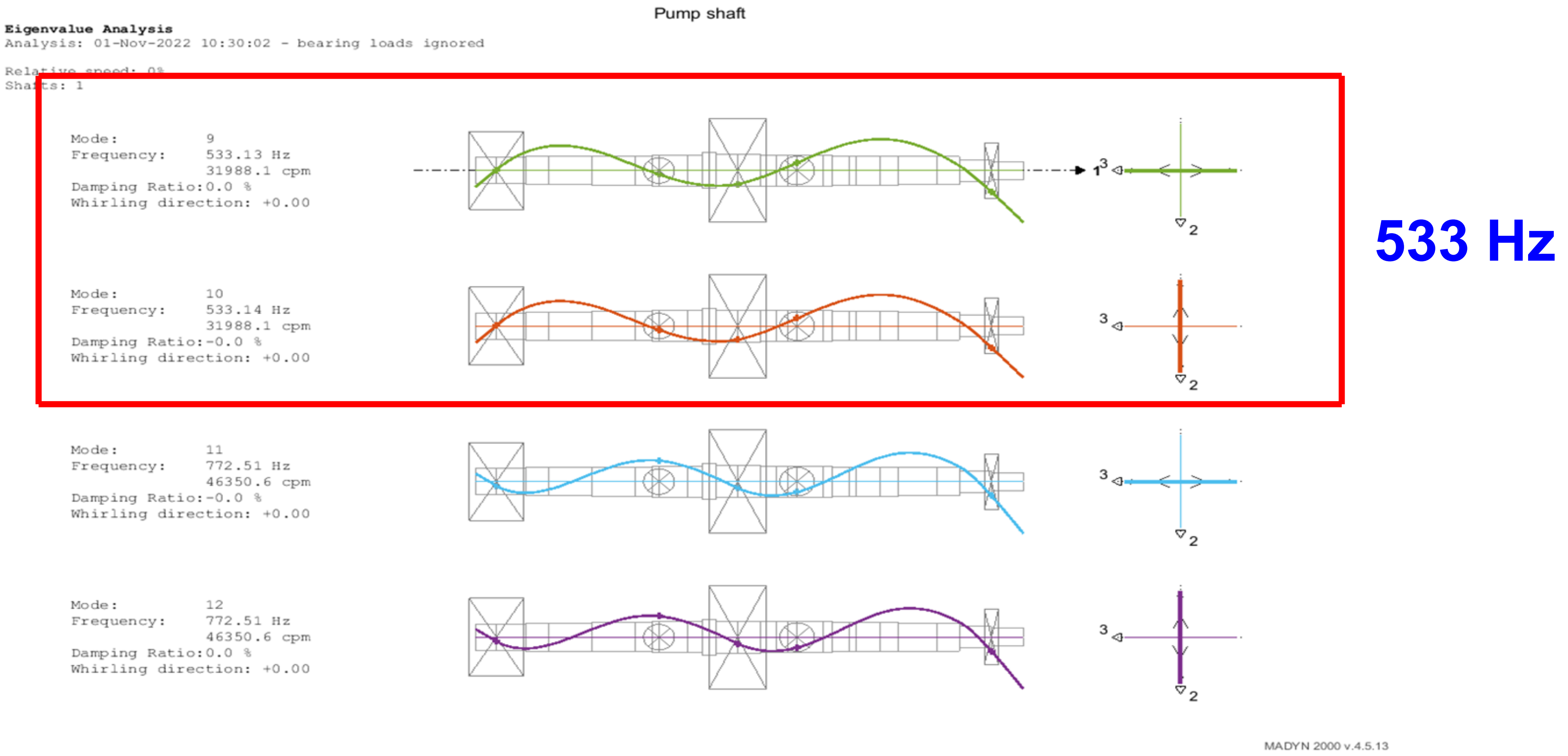
Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Calculated and measured Lateral Natural Frequencies of free-free pump shaft

	MADYN-Result	Modal Analysis Measurement (TVO)	Deviation
1. Natural frequency	0,0 Hz	0 Hz	
2. Natural frequency	0,0 Hz	0 Hz	
3. Natural frequency	108,6 Hz	104,7 Hz	+3,7 %
4. Natural frequency	309,5 Hz	304 Hz	+1,8 %
5. Natural frequency	533,1 Hz	541 Hz	-1,5 %
6. Natural frequency	772,5 Hz	791 Hz	-3,4 %
7. Natural frequency	1105,8 Hz	1126 Hz /1154 Hz	-1,8 % / -4,3 %
8. Natural frequency	1379,9 Hz	1300 Hz	+6,1 %

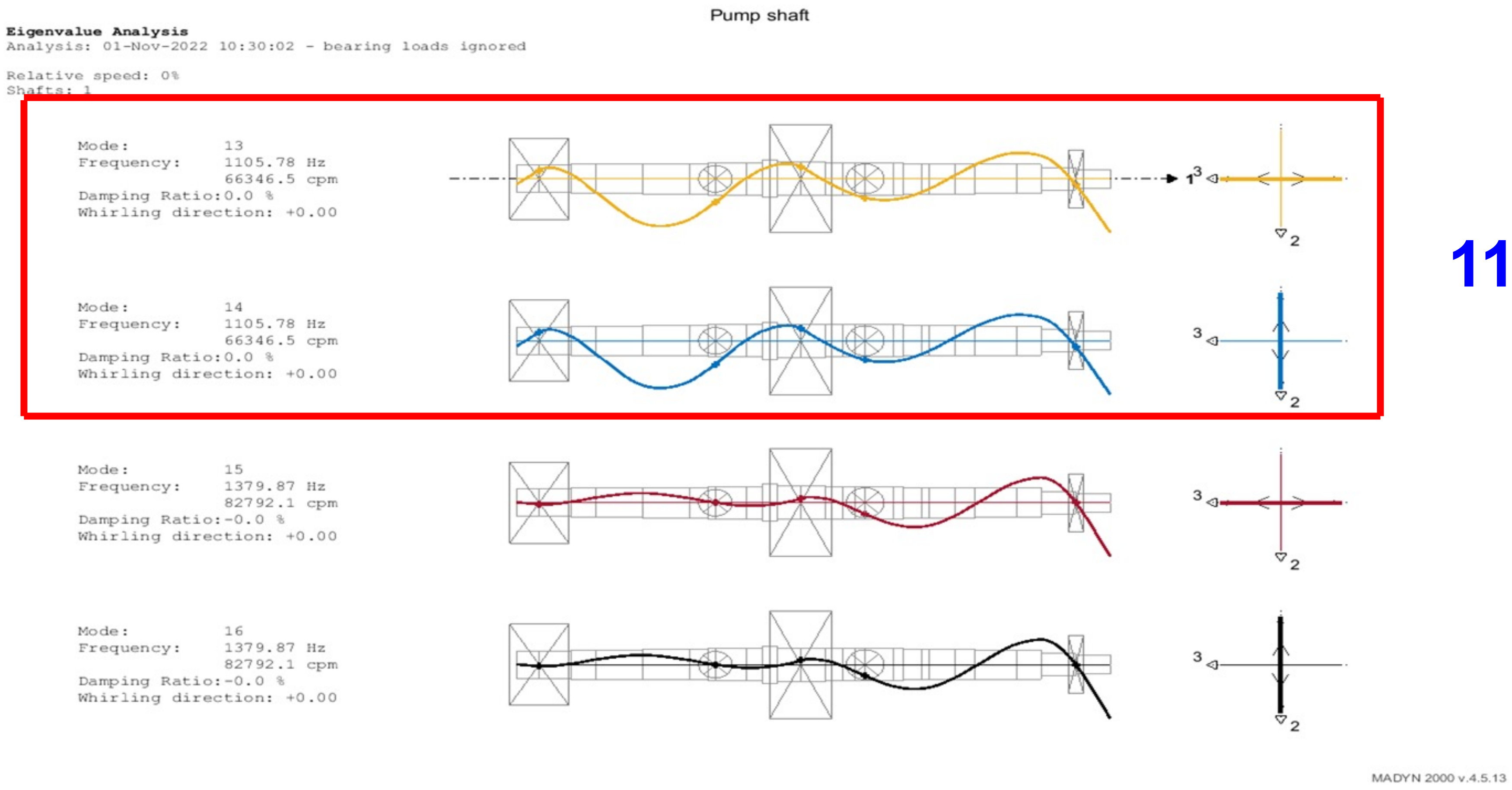
Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Lateral Natural Frequency and Mode Shape at 533 Hz



Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Lateral Natural Frequency and Mode Shape at 1105 Hz



1105 Hz

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Further Investigations of this Pump Vibrtion Problem

Further investigations of the **Dynamic behaviour of the Boiler Feed Pump** have shown:

- The **lateral natural frequencies** of the **free-free Pump shaft** did not change very much, when the full system with **Fluid Film Bearings, Seals and Shaft Rotation** has been considered

- The **Fluid Force Excitation** with the frequencies **VPF = 560 Hz and 2 VPF = 1120 Hz** leads to **Resonances of the Pump System,** mainly due to the Pump shaft dynamics. (see Campbell diagram). This may lead to **contacts** between **the rotating and** the **nonrotating components** (Bearings and Seal)

- It is difficult to determine the size of the **Fluid Force Amplitudes. Formulas** based on **Experimental Data** from the Literature can be used for an **Estimation of the Fluid Force.** The next slides show, how they can be used.

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Estimation of Fluid Forces

Estimation of Fluid Forces at the Impeller

It is customary to represent **hydraulic excitation forces** in term of a **normalized force coefficient,** defined as follows:

$$K_H = F_H \,/\, (\rho \cdot g \cdot H \cdot D_2 \cdot B_2)$$

where:

K_H = normalized hydraulic force
F_H = actual hydraulic force (lbf)
ρ = fluid density (lbf-sec^2/in^4)
g = gravitational acceleration (in/sec^2)
H = head generated by impeller stage (in)
D_2 = impeller outside diameter (in)
B_2 = impeller discharge width including shrouds (in)

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Estimation of Fluid Forces

Estimation of Fluid Forces at the Impeller

- The **formula** can be used to calculate different types of **Hydraulic Radial Forces**, acting at the impeller e.g. **Hydraulic Unbalance Forces**, Hydraulic Forces for **Vane Passing Frequenies**, etc.…).

- To determine the size of the **Hydraulic Forces F_H , the factor k_H** has to be known for the different types of Forces. These values can be found in a paper from Florjancic and Frei. They depend on the **frequency of the Hydraulic Force** and on the **Flow rate Q/Q_{opt}**

- In case of the **Boiler Feed Pump** the **Vane Pass Frequencies VP1 and VP2** are dominant. Values for this type of Hydraulic Force can be taken from the diagram.

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Estimation of Fluid Forces

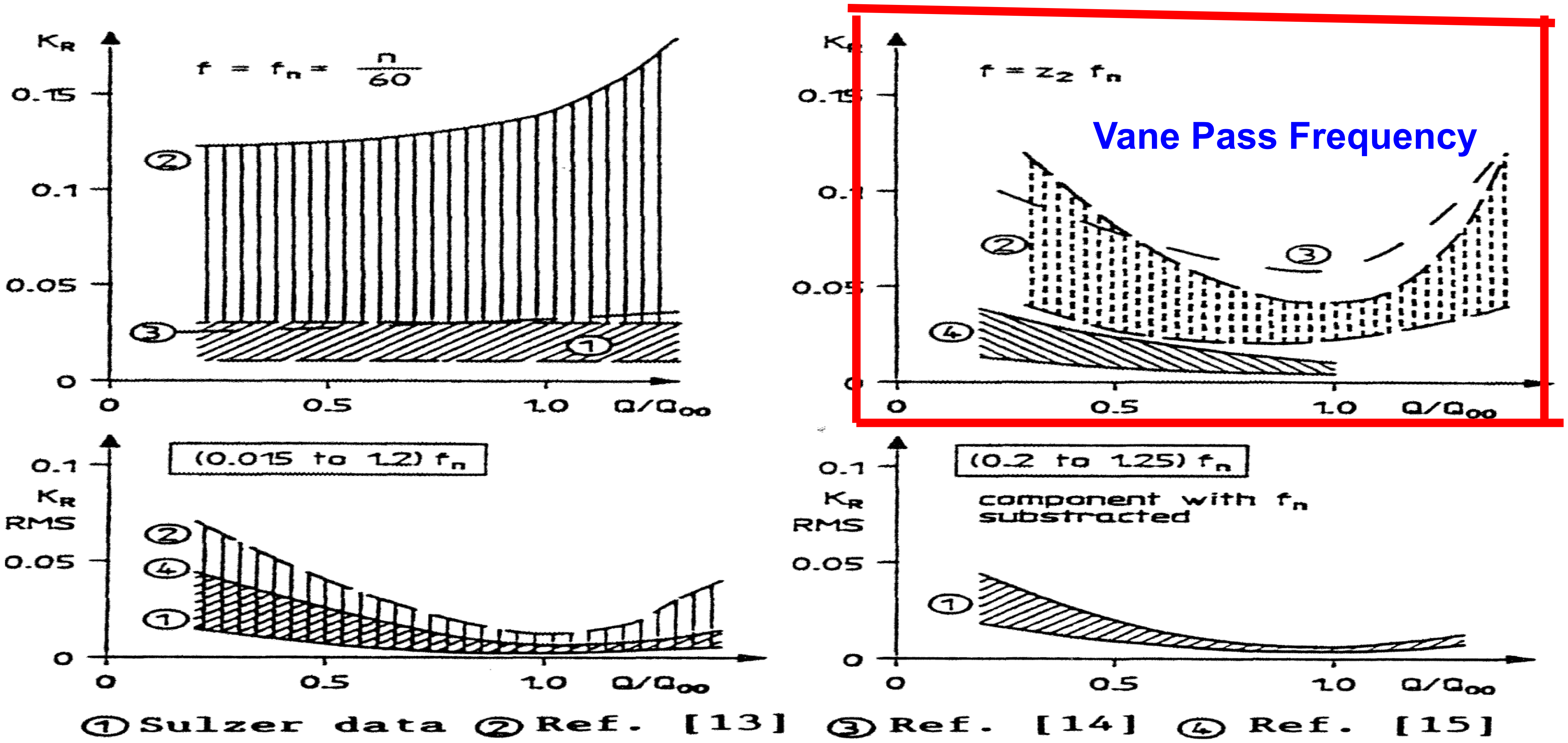
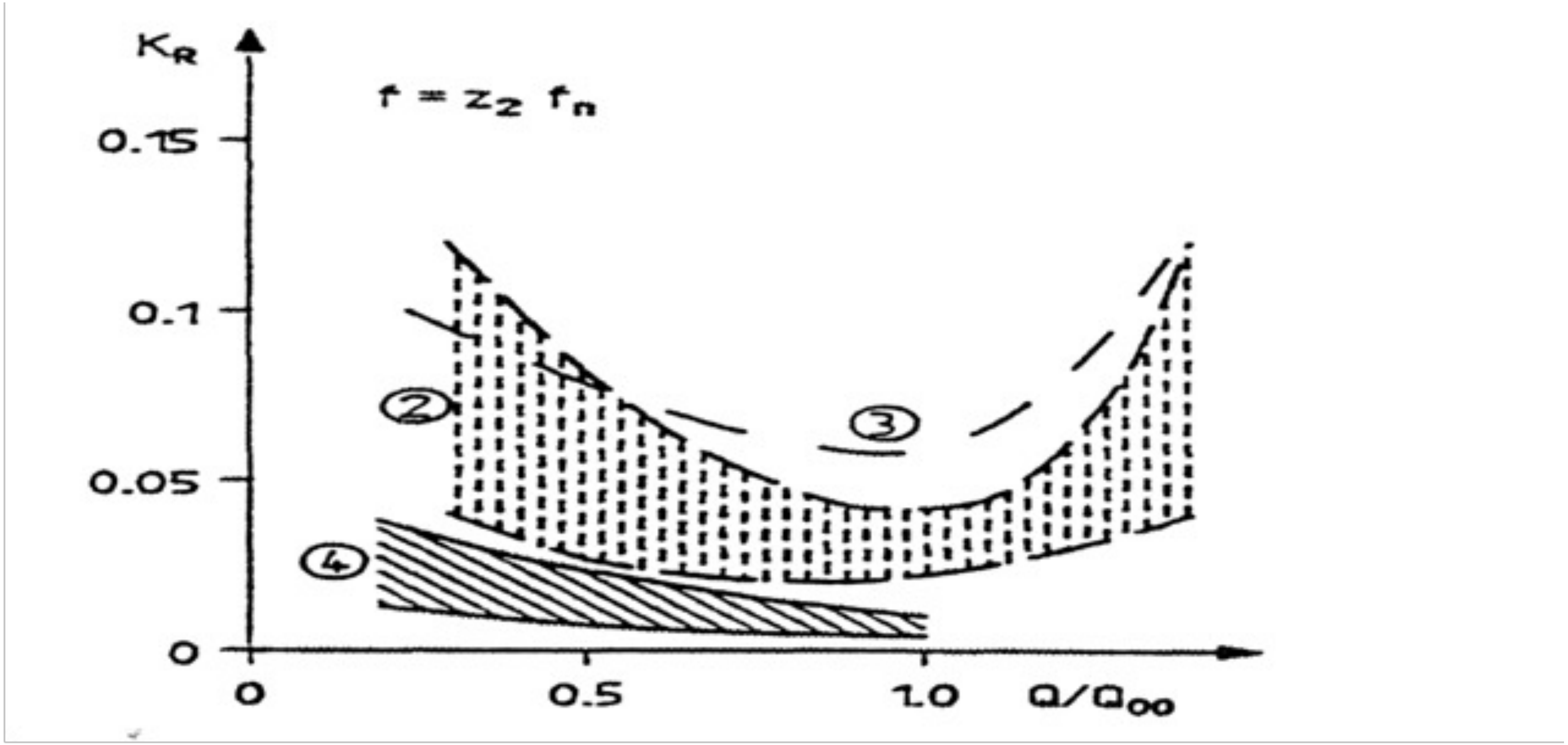


Figure 5. Hydraulic Lateral Excitation Forces.

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Estimation of Fluid Forces for the case of Vane Pass Frequency



Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Estimation of Fluid Forces for the case of Vane Pass frequency

Man findet für

den Optimalpunkt Q/Qopt = 1 : KH = 0,05
den Teillastbereich, z.B. Q/Qopt = 0,3 : KH = 0,10

Wenn man damit die Hydraulischen Kräfte FH für den Optimalpunkt und für den Teillastbereich berechnet, so erhält

den Optimalpunkt Q/Qopt = 1 : FH = 17,25 kN
den Teillastbereich, z.B. Q/Qopt = 0,3 : FH = 34,50 kN

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Conclusions

- Vibrations of the **Boiler Feed Pump** can strongly be excited by Fluid Forces with **Vane Pass Frequency VPF** and Harmonics (e.g. 2 VPF). **Resonances** may occur at this Frequencies (see Campbell diagram).

- Under special **flow conditions** Fluid Forces at the impeller are **synchronous** to the **rotating frequency** of the shaft.

- This **hydraulic forces** behave the same way as a **mechanical unbalance. Hydraulic Unbalance forces** are caused by deviations from **rotational symmetry** of the **fluid flow through the impeller** channels (different blades and vanes, geometrical unequality, material roughess, cavitation, unequal energy transfer).

Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces

Conclusions

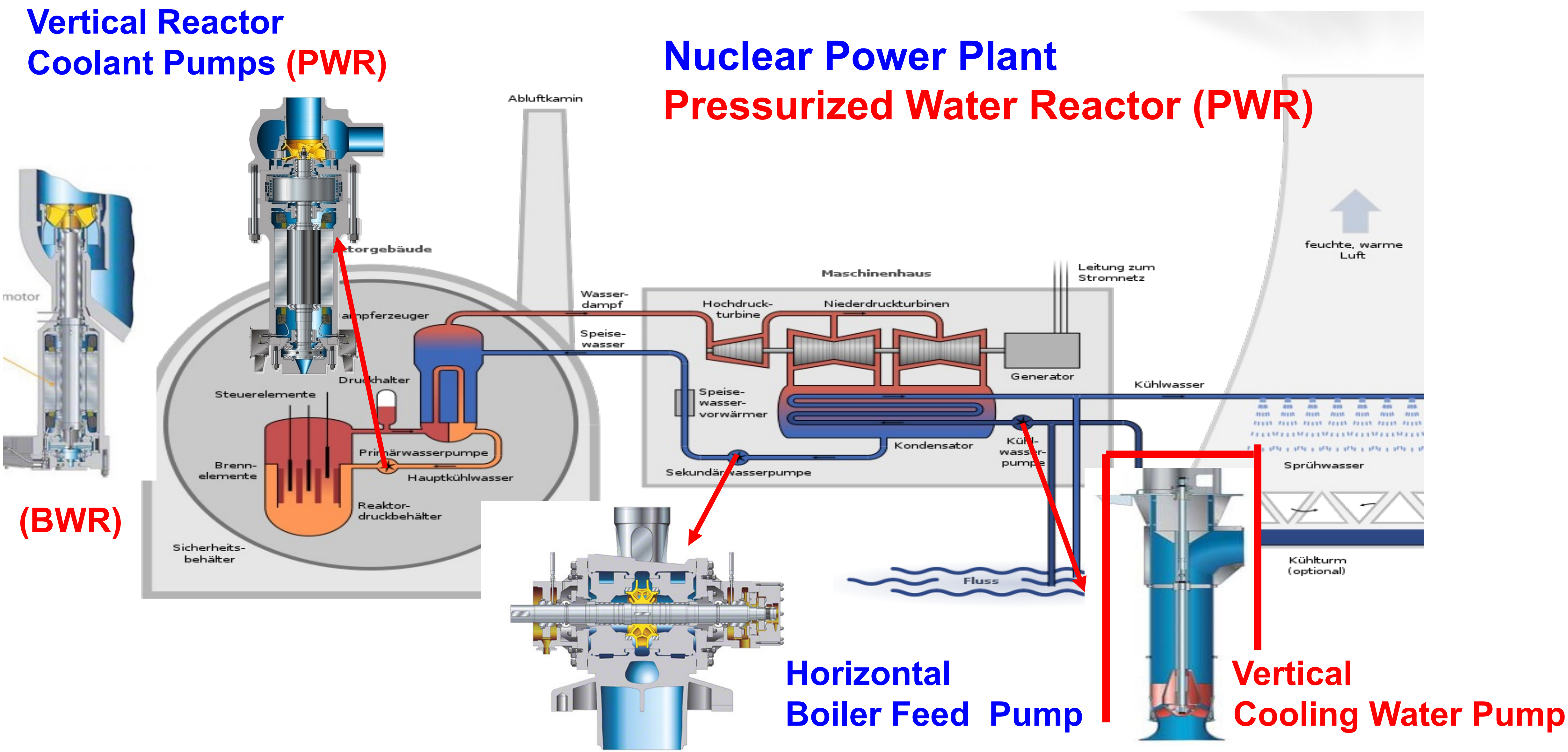
- **Verhoeven** (1988) states that the **unbalance forces** observed in practical pumps **almost always exceed** those that can be attributed to **mechanical unbalance**. The cause of this discrepancy is **hydraulic unbalance forces**, which he states are usually **much larger than those due to mechanical unbalance**.

Pump Vibrations in Power Plants

- Different Vertical and Horizontal Pumps in Power Plants
- A typical Vertical Pump System for a Nuclear Power Plant
- Vibration Phenomena in Pump Systems
- Modeling of Pump Systems to predict Vibration Phenomena
- Monitoring of Pump Systems for Vibration Control
- Evaluation of Fluid Forces in Pump Systems
- Vibrations of a Horizontal Boiler Feed Pump due to Fluid Forces
- Vibrations of Vertical Pumps due to Unbalance and Instability

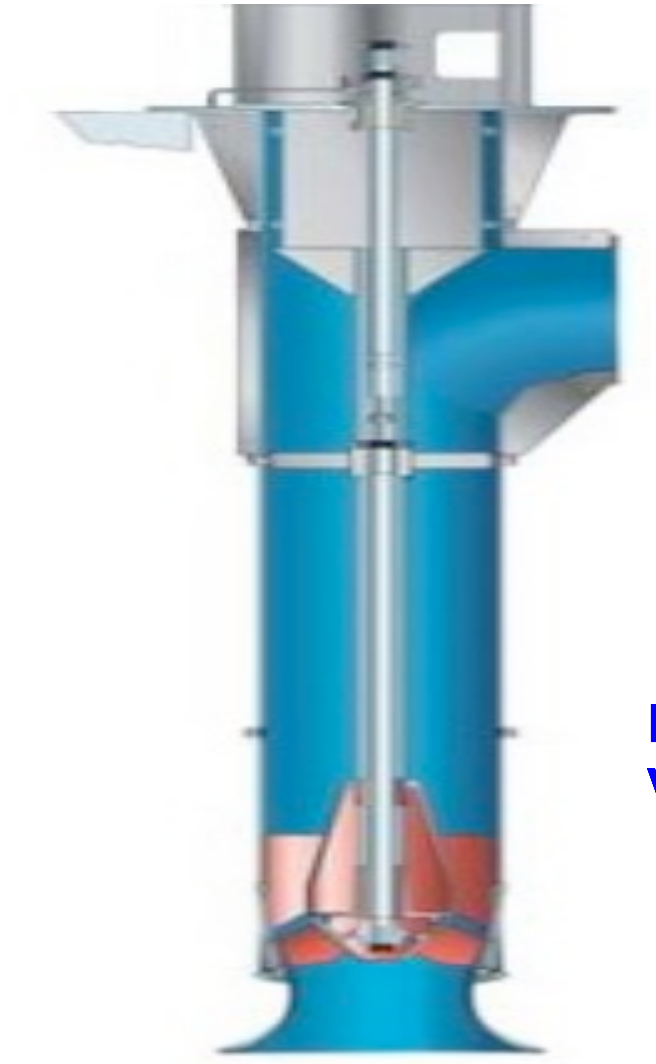
Vibrations of Vertical Pumps due to Unbalance and Instability

Vertical Cooling Water Pump

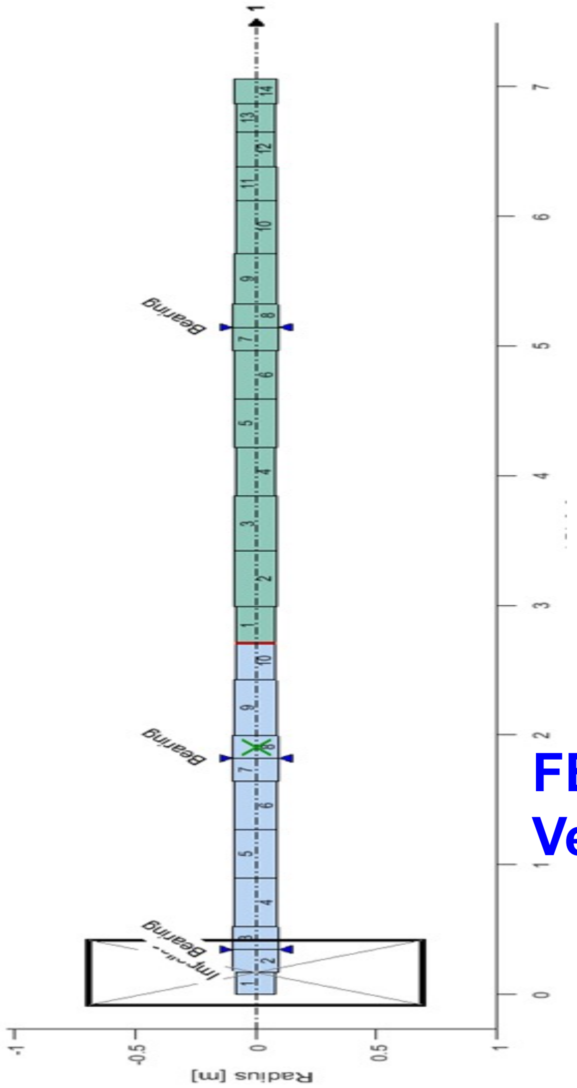


Vibrations of Vertical Pumps due to Unbalance and Instability

Vertical Cooling Water Pump



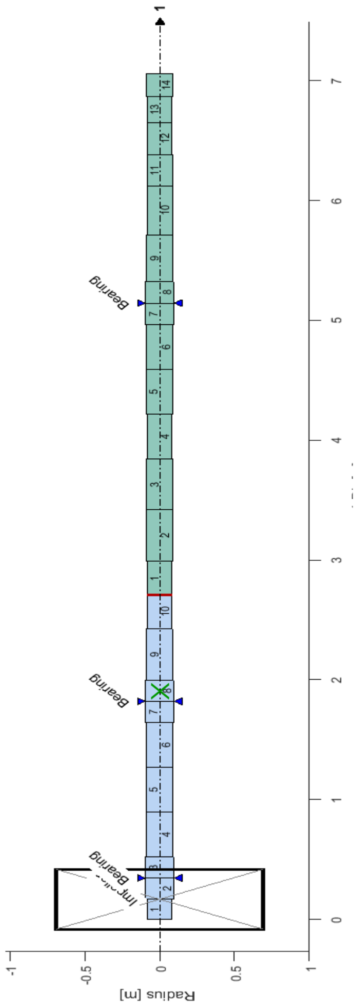
Real System of Vertical Pump

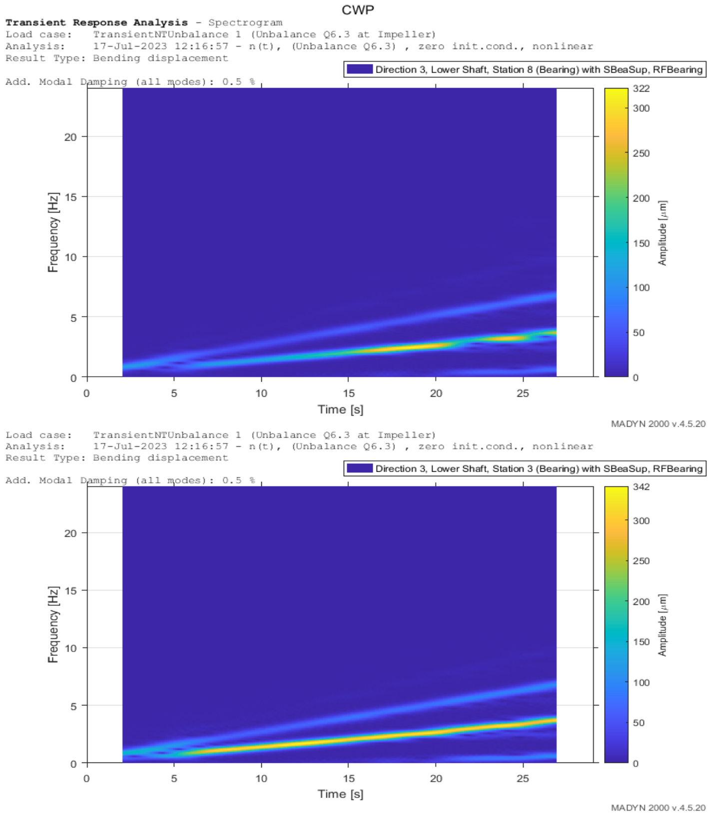


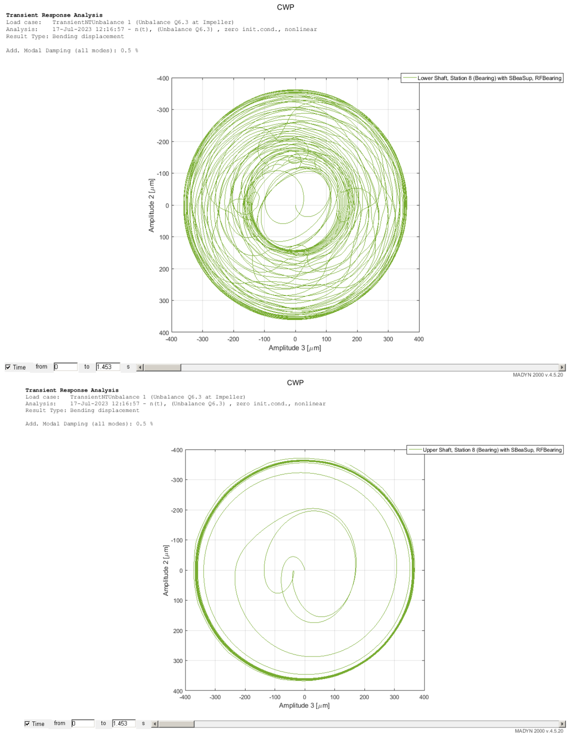
FE-Model of Vertical Pump

Nonlinear calculations for unbalance vibrations

Nonlinear fluid bearings, Low Unbalance,with dominant Half Frequency (Instability)







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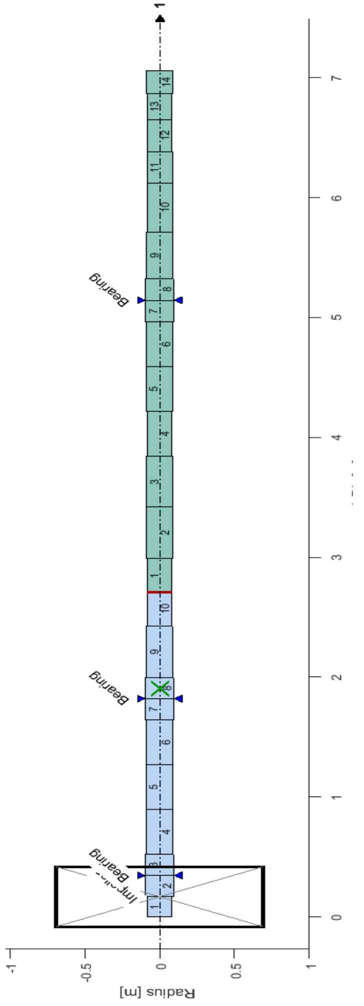
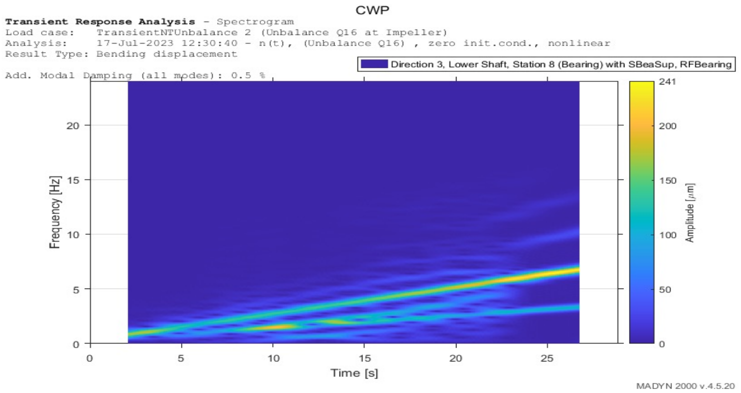
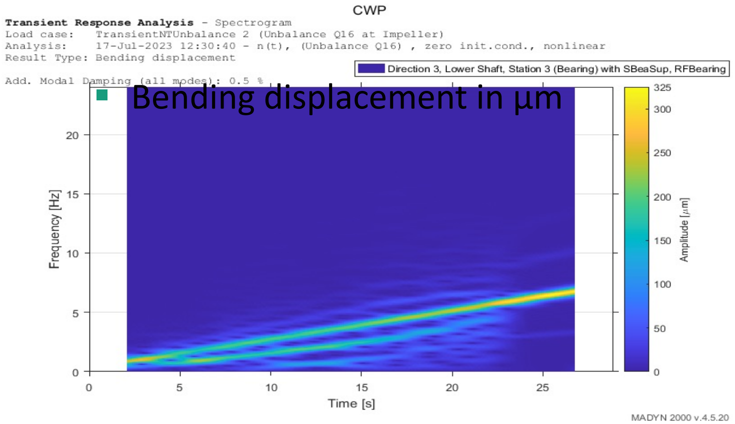
Nonlinear calculations for unbalance vibrations

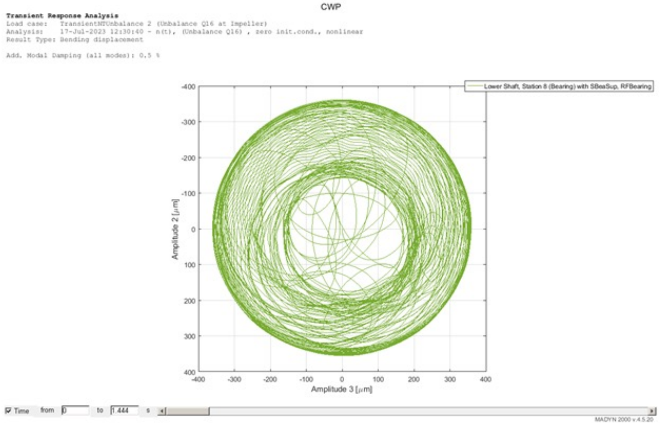
Nonlinear fluid bearings , High Unbalance with dominant rotational frequency

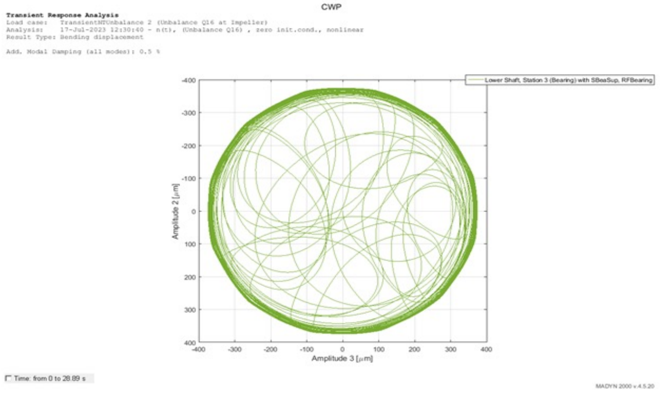






- Bending displacement in µm





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Pump Vibration Problems in Power Plants

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