Vorlesungen Mechatronik im Wintersemester

Energiforsk Project: DIAM for Pump Vibrations
Energiforsk Vibration Seminar 06.11.24 Helsinki

TECHNISCHE
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DIAM - A Matrix Tool for Pump Vibrations in Nuclear Power Plants

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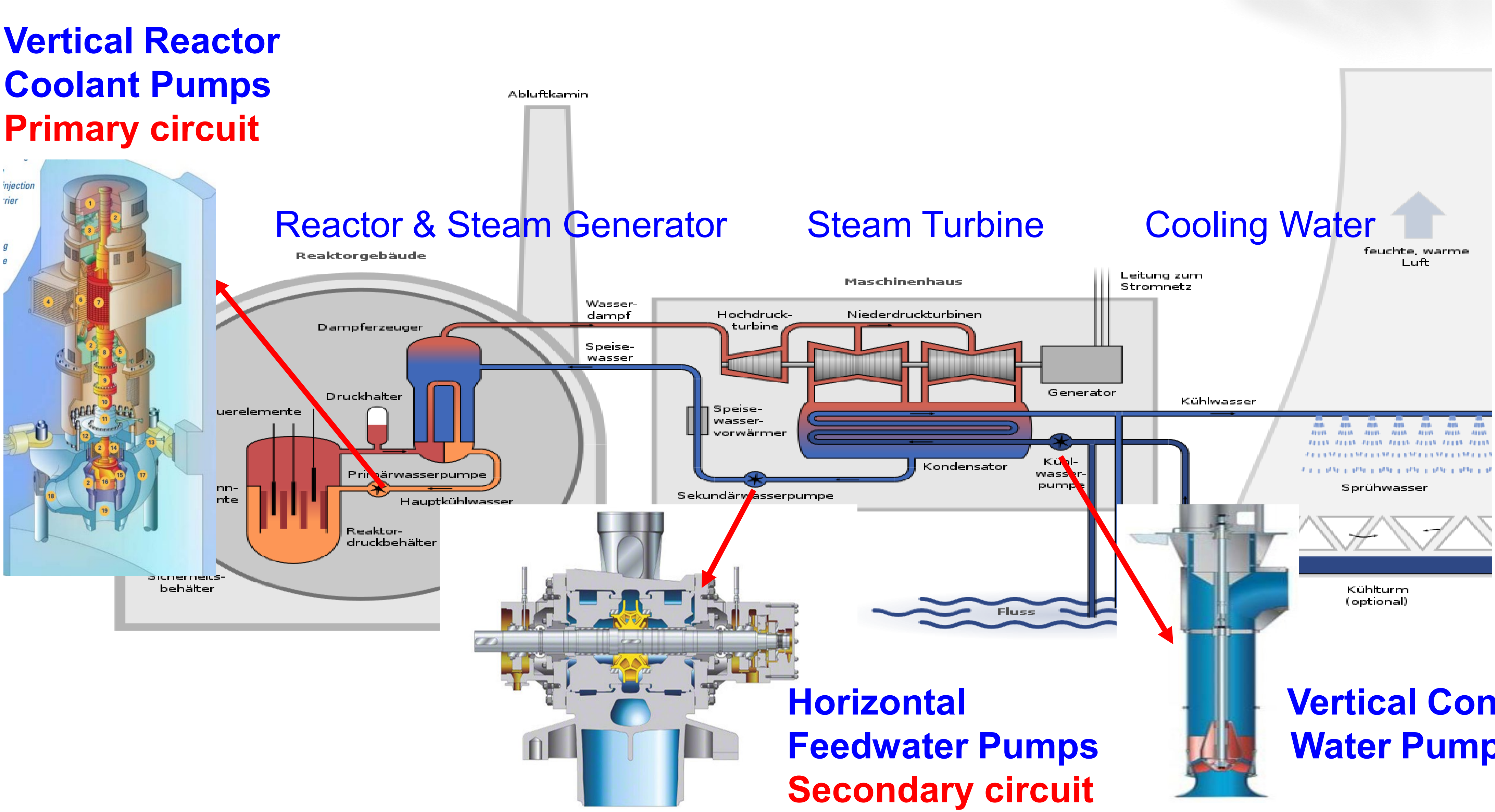
DIAM - A Matrix Tool for Pump Vibrations in Nuclear Power Plants

- The Different Pump Types in Nuclear Power Plants
- Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants
- Detection of Pump Vibrations at the Bearings and the Shaft
- DIAM – A Matrix Tool for the Solution of Vibration Problems
- Example: Identification and Mitigation of Subsynchronous Vibrations

The Different Pump Types in Nuclear Power Plants

Example: Pressurized Water Reactor (PWR)



Vertical Reactor Coolant Pumps
Primary circuit

Reactor & Steam Generator

Steam Turbine

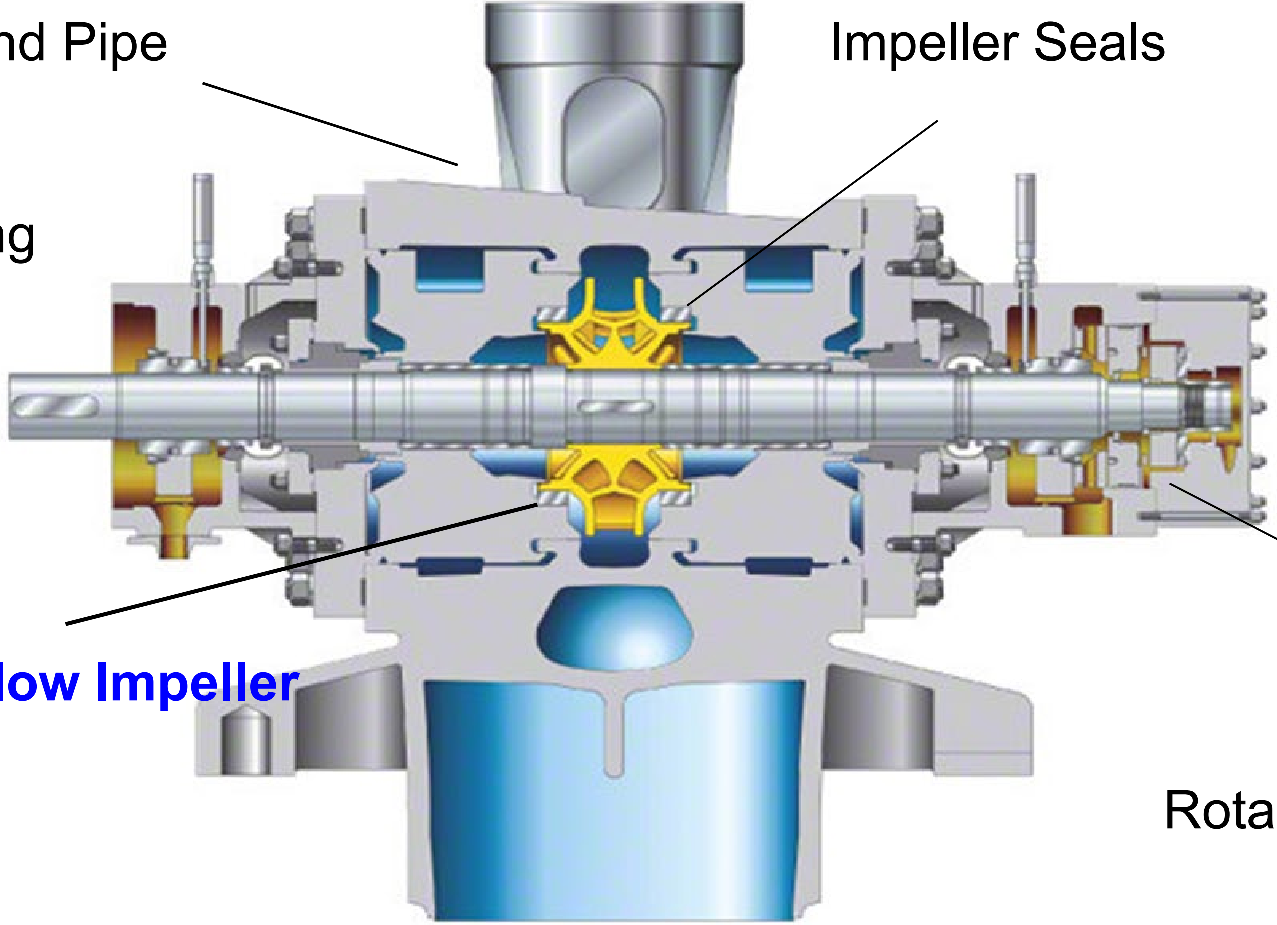
Cooling Water

Horizontal Feedwater Pumps
Secondary circuit

Vertical Condenser Water Pumps

The Different Pump Types in Nuclear Power Plants

Cross Section with Main Components and Data of a Horizontal Feed Water Pump



Pump Casing and Pipe

Impeller Seals

DE-Bearing Housing
with Radial 4-Lobe
Oil Film Bearings

NDE-Bearing Housing
with Radial 4-Lobe
Oil Film Bearing

Pump Shaft with
Bearing Double Flow Impeller

Axial Oil Film

Rotational Speed **5589 rpm**

Power **8000 KW,** Capacity **4000 m3 /h,** Pressure **124 bar,** Temperature **176 °C,**

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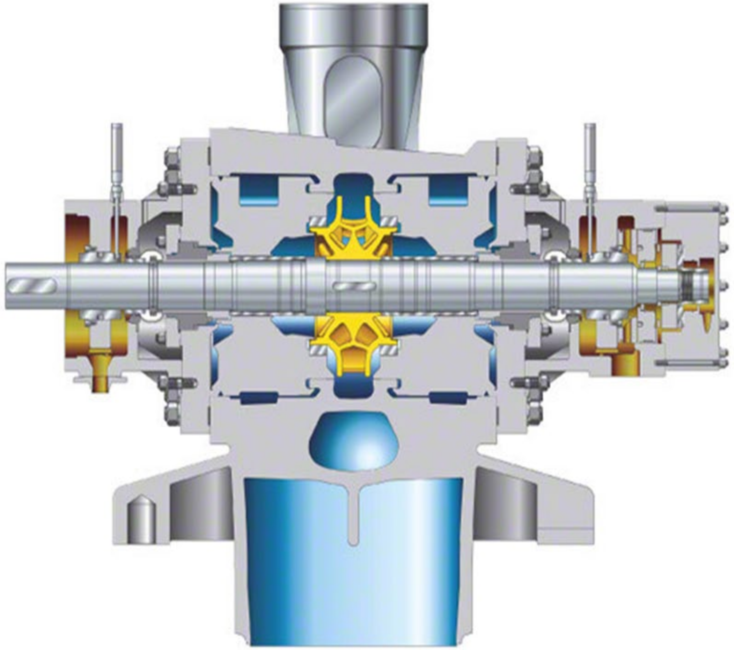
Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

Lateral Vibrations, Dynamic Characteristics, Excitations



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

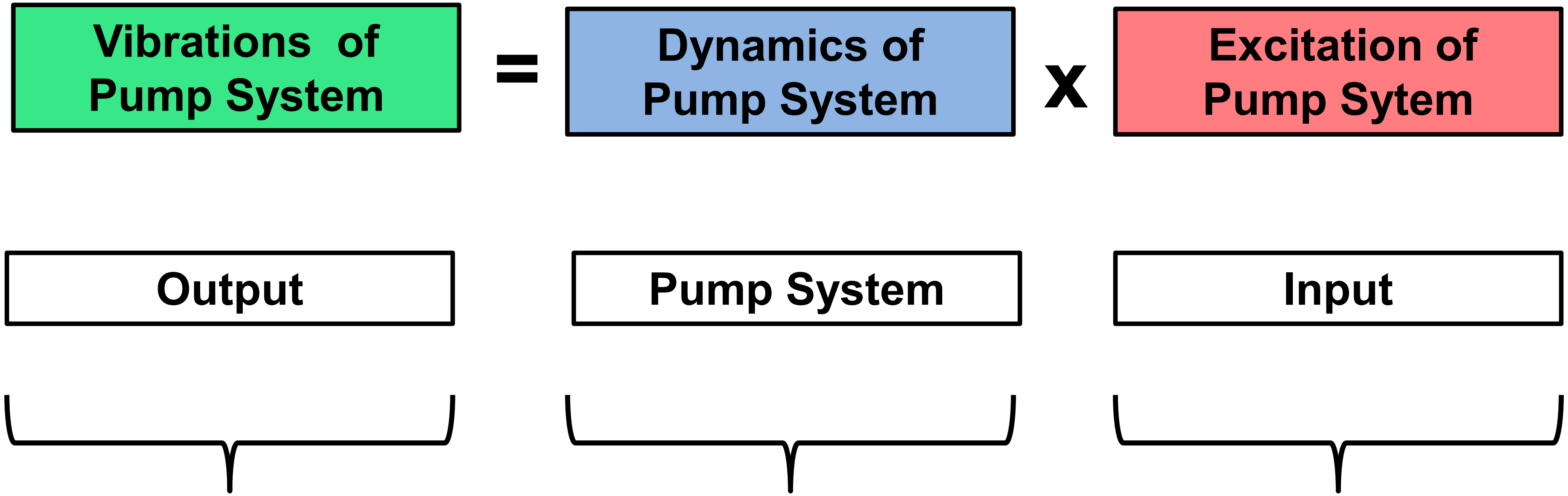
Dynamic Characteristics: Lateral natural frequencies, critical speeds, resonances, natural bending modes, damping, instability is possible

Excitations:

Mech. & Hydr. Unbalance, with rotational frequency Ω,
Fluid forces at impeller with **V**ane **P**assing **F**requency N x Ω
Self excited vibrations, Instability in bearings and seals

Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

Sources of Lateral Vibrations: Input–Output Relations



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

Output | **Pump System** | **Input**

Lateral Vibrations

- Natural frequencies
- Damping
- Mode shapes

- Mech.& Hydr. Unbalance
- Vane Pass Excitation (VPF)
- Self – Excitation, Instability

Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

Motivation for Investigations and Observations of Vibrations

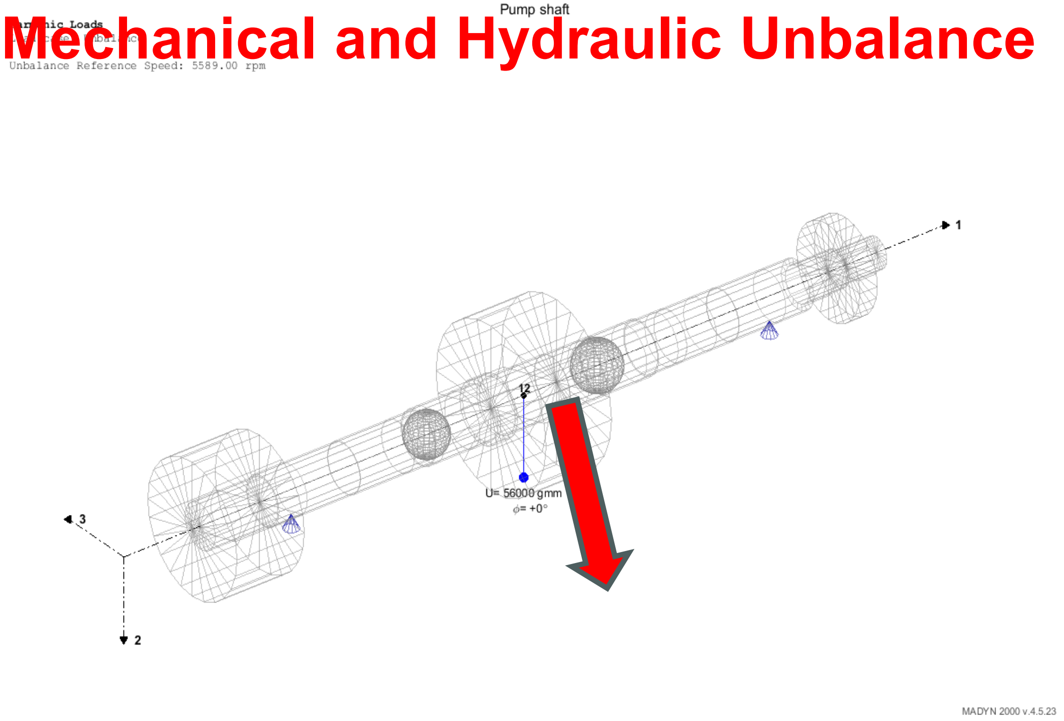
- How is the influence of **time dependent Forces** on the **dynamic behavior** of the Pump?
- Which **Motions of Vibration** and which **Internal Stresses** act on the rotating and on the non-rotating machine parts?
- Critical Conditions **(Resonances, Critical Speeds, Instabilities)**?
- **Can vibrations destroy machine parts?**
  Rubbing, Shaft and Impeller cracks, Bearing and Seal damages, large deformations,…
- Which **Interactions** have to be considered?
  Fluid Structure Interactions FSI (Impeller, bearings, seals),
  Rotor Structure Interaction RSI (Pump casing)

Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

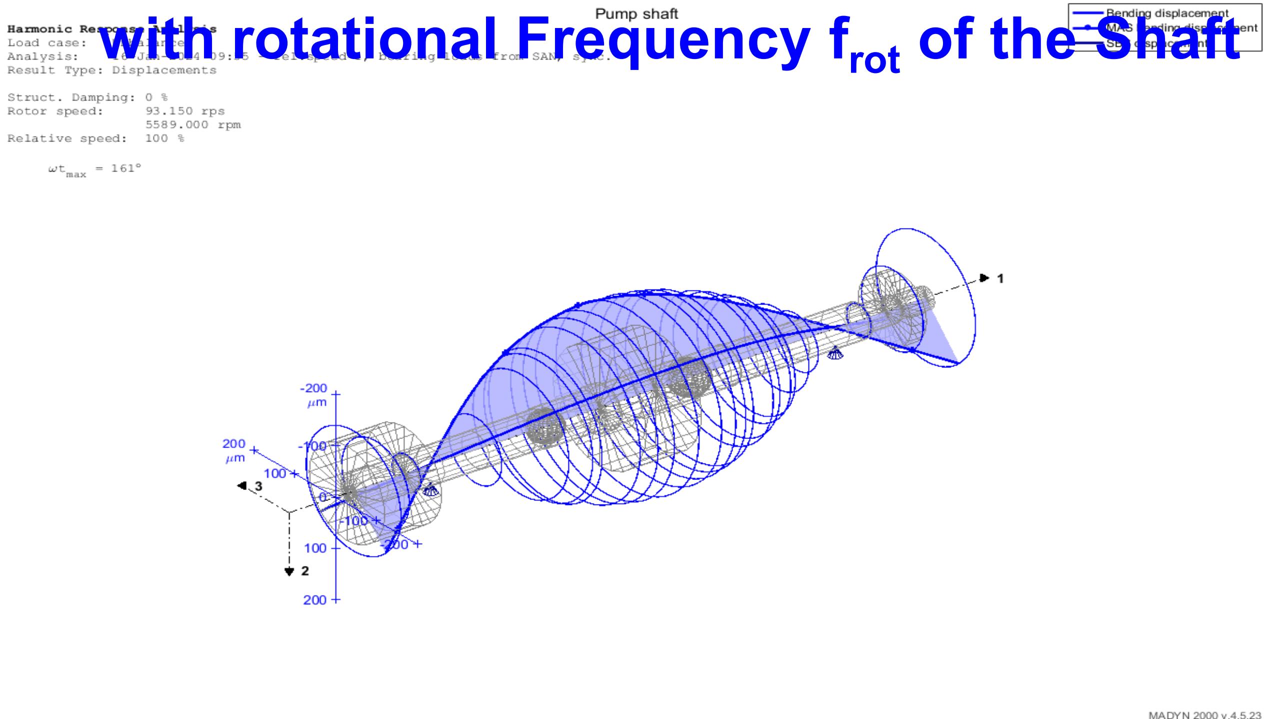
1. Vibrations of the Pump Shaft due to Mech. & Hydr. Unbalance Excitation

In this presentation only some of the most **important Vibration Phenomena** in Centrifugal Pumps are shown. For further information a total of 40 Phenomena (Component Resonances, Bearing damage, Coupling shift, Rotaing stall, Pressure Pulsations, Shaft cracks, Misalignment, etc.) are listed in the Project report.

Mechanical and Hydraulic Unbalance

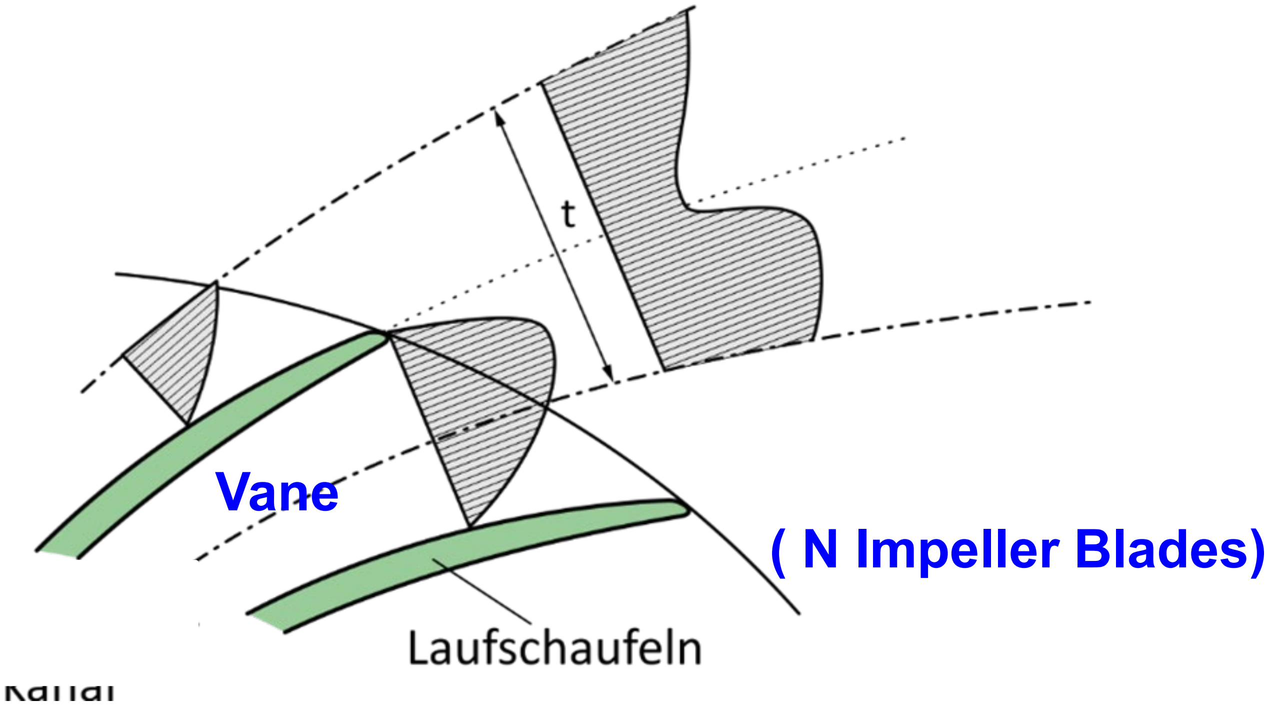


Vibrations due to Unbalance Excitation with rotational Frequency f_{rot} of the Shaft



Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

2. Vibrations with the Vane Pass Frequency (VPF = f_{rot} x N)



This **Fluid Structure Interaction** (FSI) creates **Fluid Forces** in the area between the **impeller** and **the volute** with the **Vane Pass Frequency VPF = f_{rot} x N** and higher **Harmonics** of it.

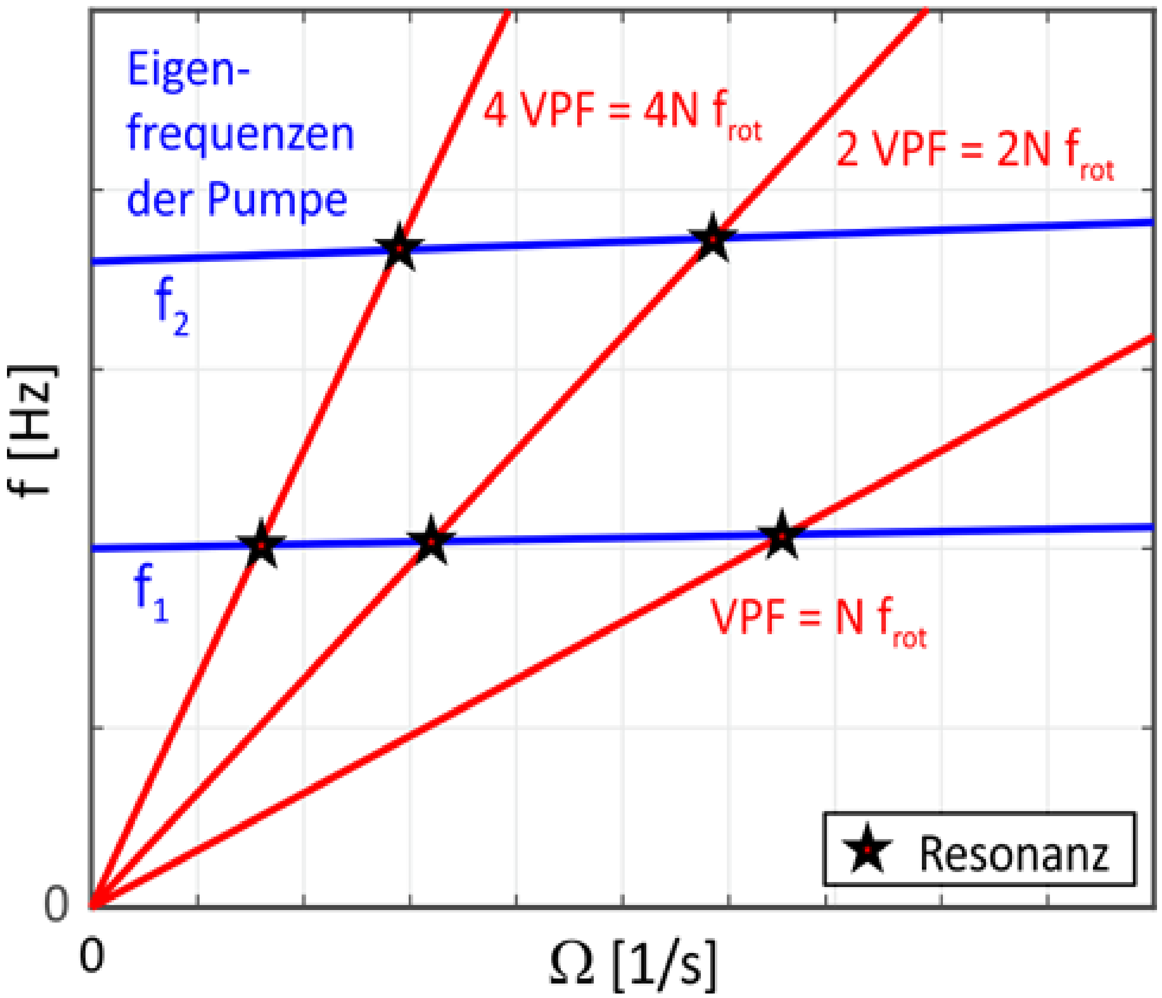
$f_{rot} = \Omega / 2\pi$ is the rotational frequency of the pump shaft in Hz and N is the number of impeller blades.

Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

Campbell Diagramm with VPF Excitation lines and Natural Frequencies

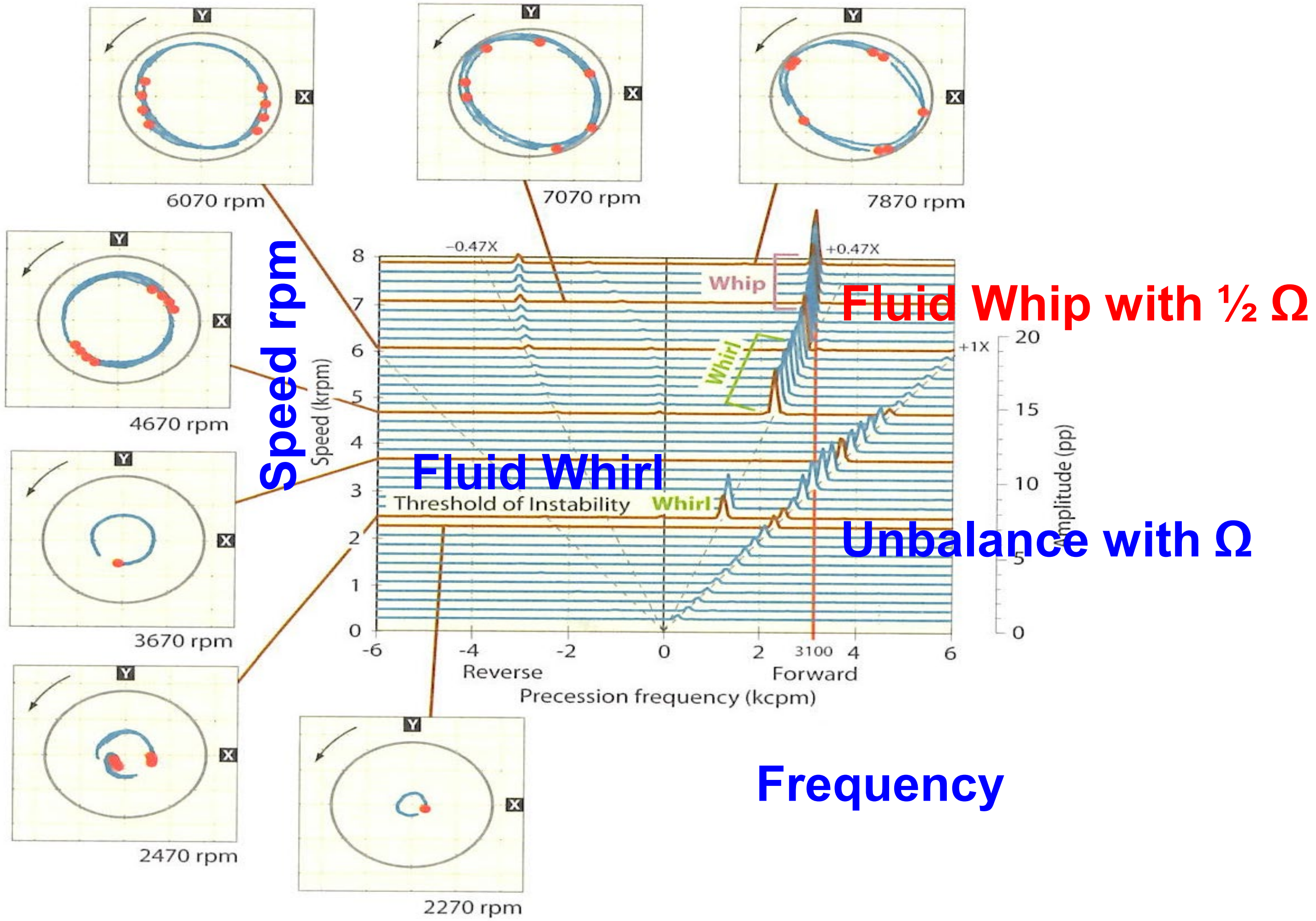
In a **Campbell Diagram** we can find possible **Resonances,** when the speed dependent **Excitation Frequencies VPF, 2 VPF**,..(red lines) cross the **lateral natural frequencies** (blue lines).

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



Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants

3. Fluid Film Instability (Fluid Whirl and Whip) with Half Rotational Frequency



Speed rpm

Fluid Whirl

Fluid Whip with ½ Ω

Unbalance with Ω

Frequency

DIAM - A Matrix Tool for Pump Vibrations in Nuclear Power Plants

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Detection of the Pump Vibrations at the Bearings and the Shaft

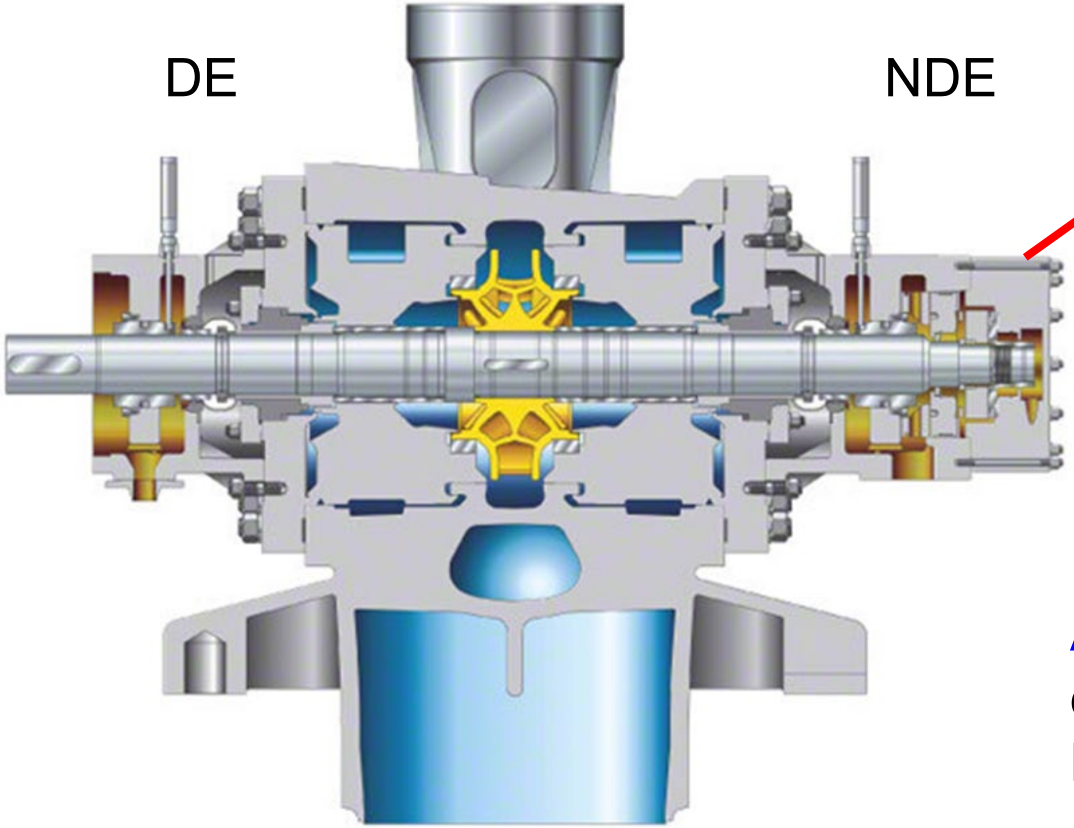
Monitoring by means of Absolute Velocity Measurements at Bearing Housings

The first step in the DIAM Procedure is the **Detection of Vibration** data in the time and in the frequency domain and also the Detection of other process data, like temperatures, pressures, flow rates, etc.

As example the following slides show the **Monitoring procedure** and the detected **absolute vibration velocities in mm/s** in three directions, detected at the **bearing housings** of the horizontal Feedwater pump

Detection of the Pump Vibrations at the Bearings and the Shaft

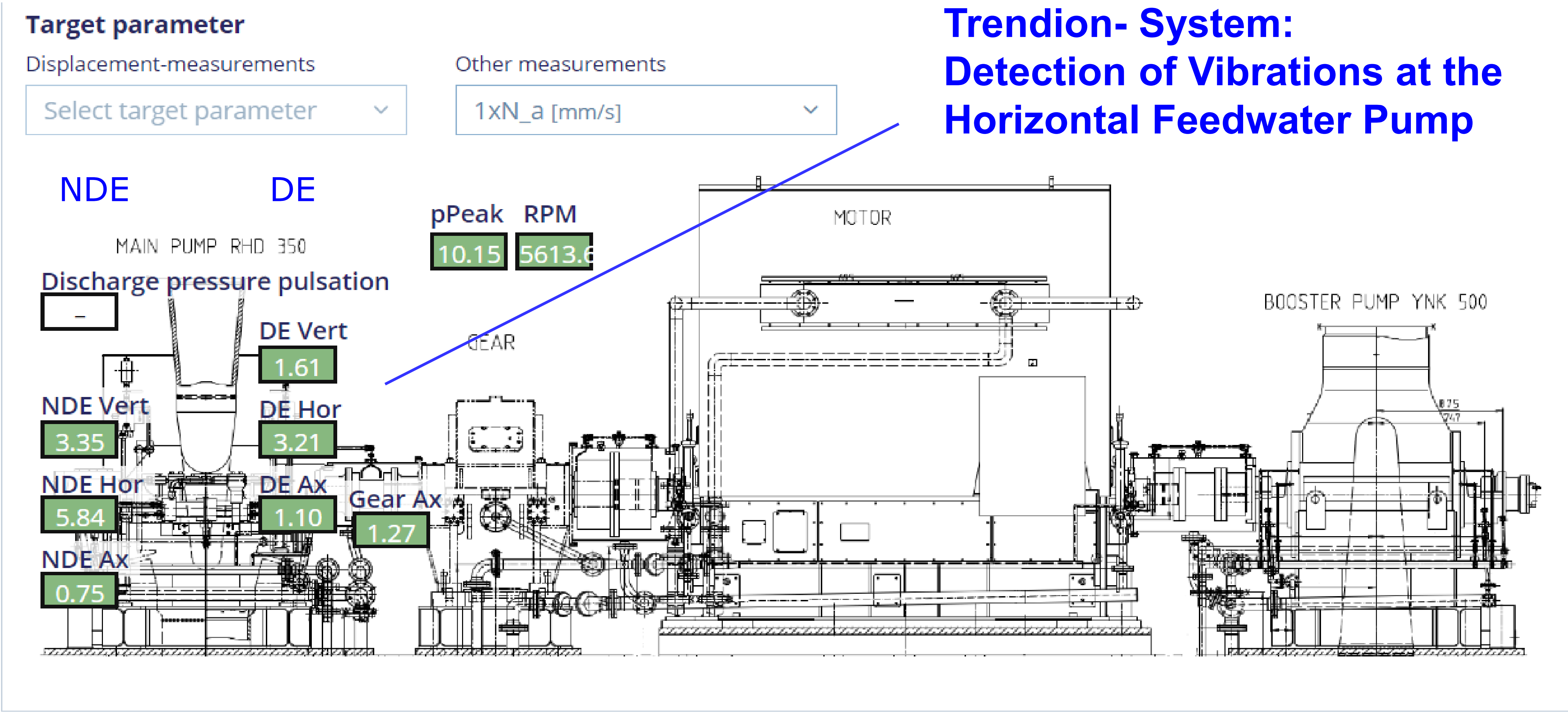
Monitoring by means of Vibration Velocity Measurements at Bearing Housings



Absolute RMS Vibration velocities $\dot{x}_{RMS}$ are determined at the two **Bearing Housings** (DE, NDE) in horizontal, vertical and axial directions

Detection of the Pump Vibrations at the Bearings and the Shaft

Monitoring of Absolute Vibration Velocities mm/s at Bearing Housings



Target parameter

Displacement-measurements: Select target parameter

Other measurements: 1xN_a [mm/s]

NDE

DE

pPeak: 10.15

RPM: 5613.

Discharge pressure pulsation: –

DE Vert: 1.61

NDE Vert: 3.35

DE Hor: 3.21

NDE Hor: 5.84

DE Ax: 1.10

Gear Ax: 1.27

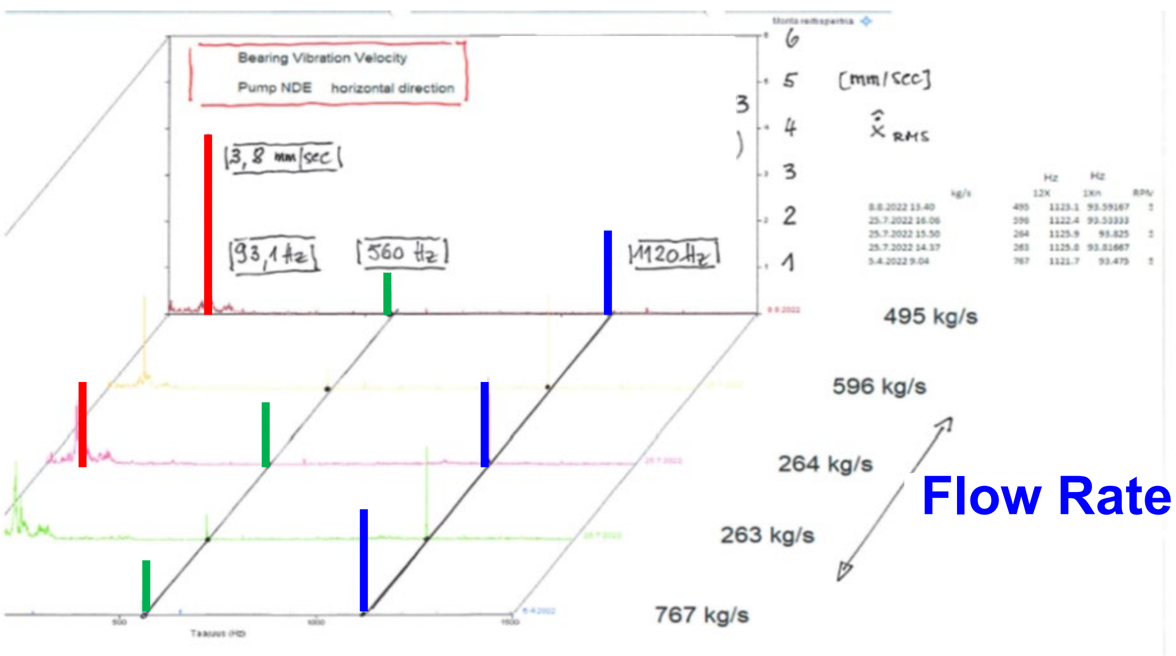
NDE Ax: 0.75

Trendion- System:
Detection of Vibrations at the Horizontal Feedwater Pump

Detection of Pump Virations at the Bearings and the Shaft

Monitoring of Absolute Vibration Velocities mm/s at NDE Bearing Housing

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



93 Hz 560 Hz 1120 Hz → Frequency Hz

How can the **vibrations** at **frequencies 93 Hz, 560 Hz** & **1120 Hz** be explained **?**

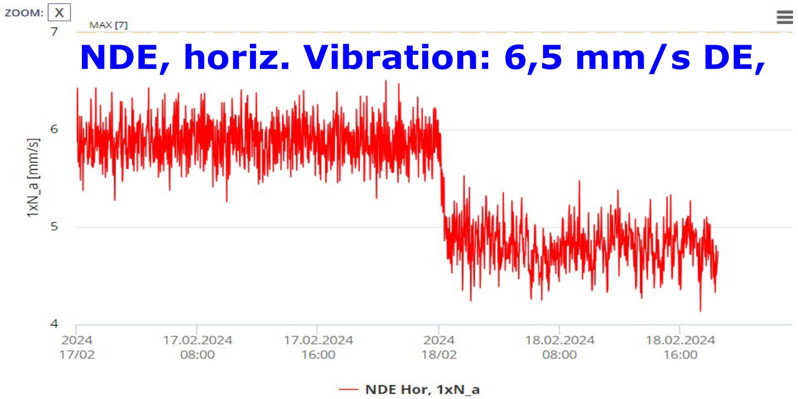
- **93 Hz :** Vibrations due to **Mech. & Hydr. Unbalance Excitation with** Rotational Frequency f_{rot}

- **560 Hz :** Vibrations due to **Vane Pass Frequency Excitation (1. order)** VPF = N x 93 Hz (N = 6 Blades)

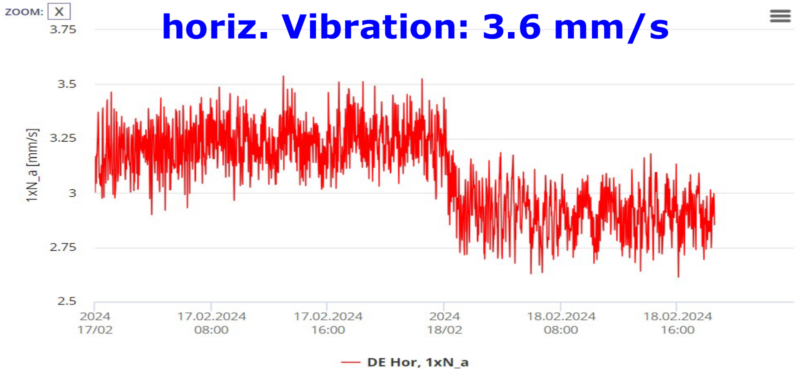
- **1120 Hz :** Vibrations due to **Vane Pass Frequency Excitation (2. order)** 2x VPF = 2N x 93 Hz

Detection of Pump Virations at the Bearings and the Shaft

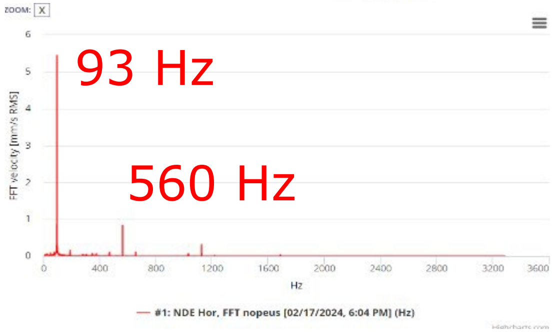
Horizontal Vibration Velocity at DE & NDE Bearing in Frequency and Time Domain



NDE, horiz. Vibration: 6,5 mm/s DE,



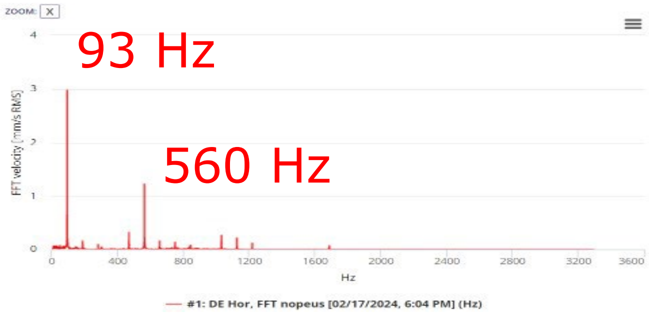
horiz. Vibration: 3.6 mm/s



93 Hz

560 Hz

Horizontal Vibrations at **NDE** and **DE** Bearing Housing both show a dominant **1xN Lateral Vibration** component in the **Frequency Domain**



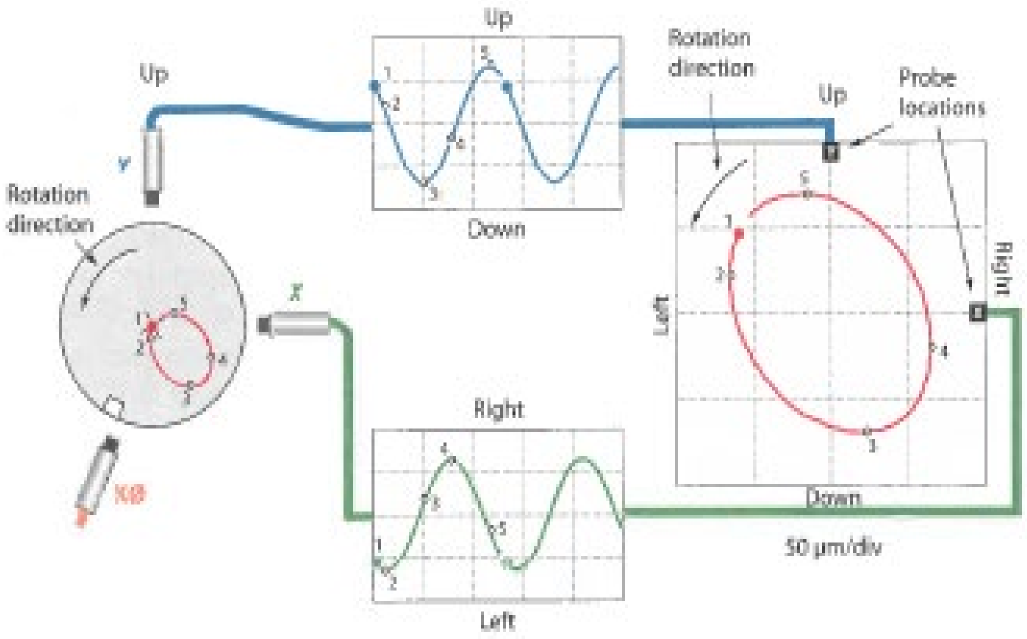
93 Hz

560 Hz

Detection of Pump Virations at the Bearings and the Shaft

Measurement of Relative Shaft Vibrations and Orbits

In some cases besides the measurements of absolute vibration velocities at the bearing housings also **relative shaft vibrations in µm** are measured with two sensors. In this way **vibration orbits** can be determined, which may help for a better **Identification** of the **Vibration Phenomena**.



Vibration Orbit,
measured with
two sensors

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DIAM – A Matrix Tool for the Solution of Vibration Problems

Matrices **M1** to **M4** & Flow Chart for the Vibration **Identification** and **Mitigation**

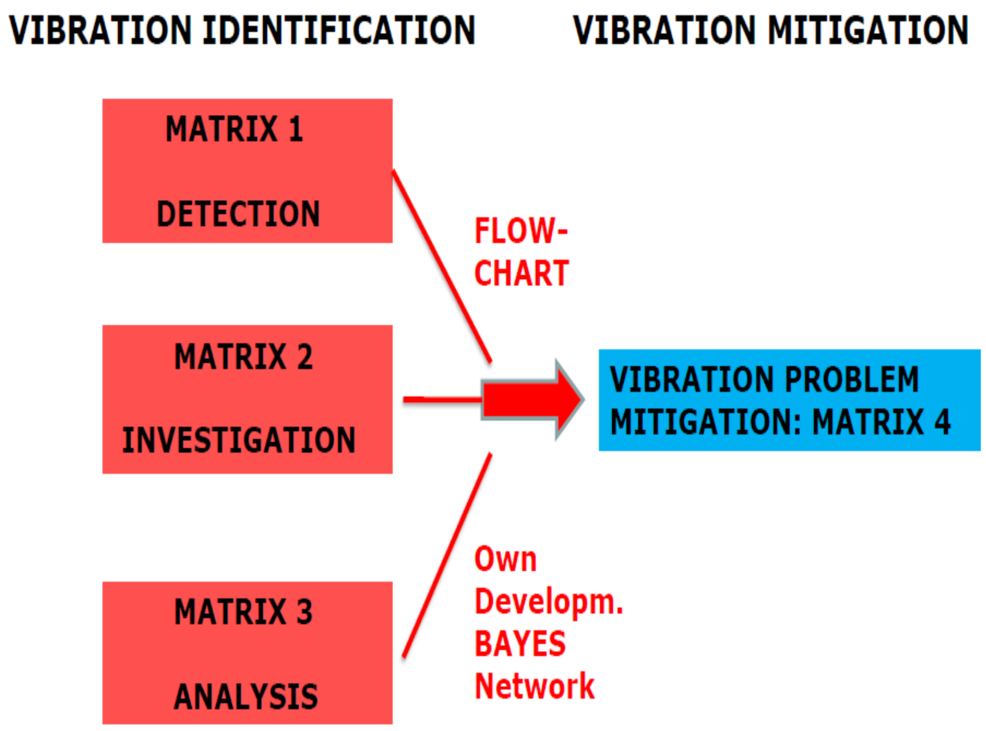
In case of a **pump vibration problem** a root cause analysis will start with a **Detection of Vibrations** (DoV) to find out by means of Matrix **M1** which of the possible **Vibration Phenomena** (CoV) may have caused the problem.

For the Identification of the **Cause of Vibrations** (CoV) additional methods for **Investigation of Vibrations** (IoV) in Matrix **M2** and more sophisticated methods for an **Analysis of Vibrations** (AoV) in Matrix **M3** can be applied in addition.

When the **Cause of Vibrations** has been identified with support of the 3 Matrices M_1 , M_2 , M_3 , possibilities for the **Mitigation of Vibrations** (MoV, Matrix **M4**) can be determined.

DIAM – A Matrix Tool for the Solution of Vibration Problems

Matrix Concept: Flow Chart for the Vibration **Identification** and **Mitigation**



VIBRATION IDENTIFICATION

VIBRATION MITIGATION

MATRIX 1
DETECTION

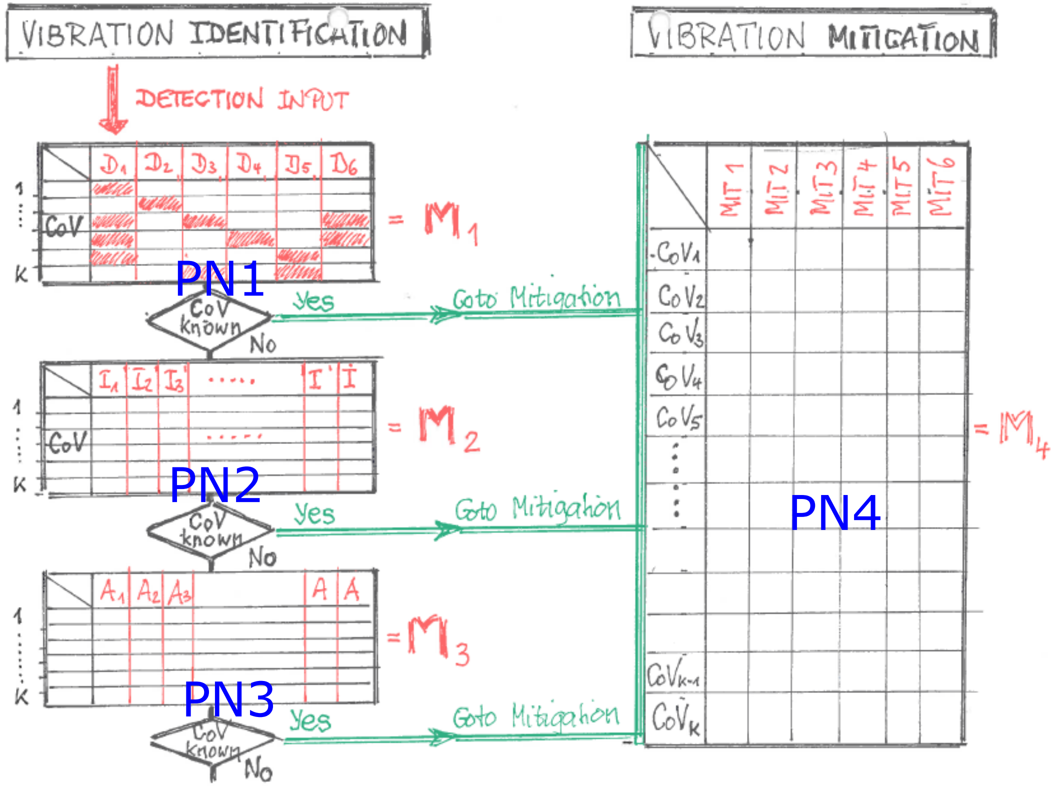
MATRIX 2
INVESTIGATION

MATRIX 3
ANALYSIS

FLOW-CHART

Own Developm. BAYES Network

VIBRATION PROBLEM MITIGATION: MATRIX 4



The described general procedure for solving vibration problems in centrifugal pumps with the steps **Detection, Investigation, Analysis and Mitigation** can be performed in the frame of the **DIAM-Matrix-Concept.**

DIAM – A Matrix Tool for the Solution of Vibration Problems

Matrix Concept: Flow Chart for the Vibration **Identification** and **Mitigation**

In the four Matrices **M1** to **M4** the relations between the **Cause of Vibrations** and the different **Detections, Investigations, Analysis-methods** and the **Mitigations** have been expressed by **Probability Numbers PN**.

In the **DIAM** project a first set of **Probability Numbers** has been selected for all four matrices, based on the experience from former problem cases. These numbers can be adjusted, when more improved knowledge is available for the **Vibration Phenomena.**

As example the next slide shows Matrix **M1,** in which 40 different **Vibration Phenomena** are related to 29 **Detections** by means of **Probability Numbers** in Matrix **M1.** The Matrices $\mathbf{M_2}$, $\mathbf{M_3}$ and $\mathbf{M_4}$ are built up in a similar way. They are not shown here.

DIAM – A Matrix Tool for the Solution of Vibration Problems

Development of Matrix **M1**: Detections(DoV) versus Vibration Phenomena (CoV)

Matrix M1

29 Detections (DoV)
Vibrations, Flow Rate, Temperatures, etc.

40 Vibration Phenomena (CoV)

Probability numbers

5 Highly probable
1 Not very probable
0 Not possible

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Vibration Phenomenon	section	Frequencies of Vibrations (fn = Shaft Freq. in Hz; VPF= Vane Pass Freq.)																					Flow Rate			Operating Data of Pump								
		Ramp change 1xfn Amplit.	Ramp Change 1xfn Phase	Step change 1xfn Amplit.	Step change of 1xfn Phase	Permanent high 1xfn Amplit.	Change of 2xfn Vibr.Amplit.	Change of 2xfn Vibr. Phase	Change of 3xfn Amplitude	Vibr. peaks at k x fn, k=1,2,3..	Vibr.peak at zlm x fn = VPF	Vibr.peak at = 2 x VPF	Vibr. peaks: Harmon. of VPF	Subsynchr. Vibr. 0,4-0,5xfn	Subsynchr. Vibr. 0,5 - 0,9 xfn	Subsynchr. Vibr. 0,1-0,3 xfn	Frequencies not related to fn	Vibr. spectrum above 500 Hz	Vibr. peaks betw. 1-20Hz	Axial Vibrations at Bearings	Vibr.peaks at motor speeds	Peaks at Grid freq. 50 Hz	Flow Rate between 0.8 to 1	Flow Rate between 0,5-0.8	Low Flow Rate up to 0,5	Change of Oil Temperature	Change of Fluid Temperature	Change of pressure in Pump	Imp/Diff Pressure field m=0	Imp/Diff Pressure field m= 2		Commonness	Severity	Sum of probabilities, if no blanks
Slow change of Unbalance (wear, cavitation,...)		4	4	0	0	0	1	1	1	3	1	1	1	1	1	1	0	1	1	1	0	0	1	2	1	1	1	1	1	1	0	4	2	0
Sudden increasing change of Unbalance		0	0	5	5	0	0	0	0	3	1	1	1	0	0	0	0	0	0	0	0	0	3	1	1	0	2	2	0	0	0	2	5	0
Hydraulic Unbalance due to Impeller tolerances		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0
Hydraulich Unbalance due to nonuniform flow		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0
Hydraulic Unbalance due to low quality sand cast		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0
Hydraulic Unbalance due to impeller cavitation		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0
Thermal or Mechanical Bow of Pump Shaft		0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	0	3	0	0	0	0	2	4	0
Operation in a Pump shaft critical speed		0	0	0	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	2	0	0	0	0	0	0	2	5	0
Resonance of pump components (Casing, pipes,.)		0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	3	2	1	0	0	0	0	0	0	2	4	0
Low damping (Fluid Film- or Roller Bearings)		0	0	0	0	4	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	3	2	1	0	0	0	0	0	0	2	4	0
Bearing damage, e.g. White metal damage		1	1	2	2	1	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	0	0	0	2	4	0
Mechanical and/or electrical Runout		2	2	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	0	0	0	2	2	0
Instability in Radial Fluid Bearings		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	3	1	0	0	0	0	3	5	0
Change of Static Bearing Load with Flow Rate		2	2	2	2	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	0	1	0	0	0	0	2	4	0
Change of viscosity in Fluid Bearings		2	2	1	1	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	3	1	0	0	0	0	2	3	0
Change of clearance in Fluid Bearings		2	2	1	1	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	0	1	0	0	0	0	2	3	0
Clearance increase in Seals due to Wear		2	2	1	1	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	0	0	0	3	5	0
Coupling shift (translational and or angular)		3	3	3	3	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	0	0	0	0	0	0	2	4	0
Change of support stiffness		4	4	2	2	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	0	0	0	0	0	0	3	4	0
Internal friction in Shrink fits		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	0	0	0	2	5	0
Rotating Stall		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	0	0	0	0	0	0	2	4	0
Impeller Inlet Recirculations		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	1	1	0	0	0	0	2	3	0
Rotating Stall at the guide vanes		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	0	0	0	0	0	0	2	3	0
Pressure pulsations cause casing & piping vibrations, also axial Impeller vibrations, m=0		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	5	0	0	2	4	0
Pressure pulsations lead to Dynamic Fluid Forces & cause Shaft & Bearing vibrations (zlm x fn)		0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0	0	0	0	0
Pressure pulsations may cause resonance vibr. of impeller with two nodal diam. mode, m=2		1	1	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	0	0	0	0	5	0	2	4	0
Blade Interference Forces at zlm x fn		1	1	1	1	2	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4	0	0	0	1	1	0	2	4	0
Acoustic Resonance with zlm x fn		0	0	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	0	0	0	0	0	0	2	3	0
Resonance at Bearing Housing natural frequency		0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	0	0	0	0	0	0	2	3	3	0	0	0	0	0	0	2	3	0
Peaks at k x fn due to geometr. deviations in Impeller vanes (geometr. Spacing, angle errors)		0	0	0	0	0	0	0	0	1	3	3	3	0	0	0	0	0	0	0	0	0	2	3	3	0	0	0	0	0	0	2	3	0
Bearing Misalignment		1	1	1	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	2	3	0
Misalignment due to Thermal Effects (Hot Fluid)		1	1	2	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	3	0	0	0	0	2	3	0
Misalignment due to Piping Forces		1	1	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	2	2	0
Nonlinearities: Loose parts (Bushes, Bearings)		0	0	2	2	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	2	2	0
Transverse Shaft Cracks in Pump shaft		3	3	0	0	2	5	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	1	0	0	0	0	0	2	5	0
Natural frequencies of structure, excited by broadband forces (e.g. recirculations, cavitation)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	2	4	0	0	0	0	0	0	2	3	0
Pressure pulsation and vibrat. due to Cavitation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	1	0	0	0	0	0	0	0	0	2	3	0
Broadband Excitation of low natural frequencies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	5	0	0	0	2	1	1	0	0	0	0	0	0	2	3	0
Electrical disturbances of instrumentation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Motor Vibrations transferred via foundation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

DIAM – A Matrix Tool for the Solution of Vibration Problems

Short Descrition of the Matrices M_1 to M_4 and the Flow Chart

- **MATRIX M1**

  relates the different **Vibration Phenomena** to different **Detection** Methods by means of **probability numbers**

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- **MATRIX M2**

  shows also **probability relations** between the different **Vibration Phenomena** and different ways for a further **Investigation**.

- **MATRIX M3**

  relates the different **Vibration Phenomena** to different more sophisticated analytical, numerical or experimental **Analysis Methods** by means of **probability numbers** as well.

DIAM – A Matrix Tool for the Solution of Vibration Problems

Short Descrition of the Matrices **M_1** to **M_4** and the Flow Chart

- **MATRIX M4**
  relates the different **Vibration Phenomena**
  with the **Mitigation** methods, again by probabilities.

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- A **Flow Chart**
  has been developed as a guideline how to use the **Matrices M1 to M3** for the **Identification** of an existing **Vibration Phenomena** and finally for a **Mitigation** method.

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DIAM - A Matrix Tool for Pump Vibrations in Nuclear Power Plants

- The Different Pump Types in Nuclear Power Plants
- Vibration Phenomena in Centrifugal Pumps of Nuclear Power Plants
- Detection of Pump Vibrations at the Bearings and the Shaft
- DIAM – A Matrix Tool for the Solution of Vibration Problems
- Example: Identification and Mitigation of Subsynchronous Vibrations

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix **M1**

Detection Input from Monitoring: (Yellow x)

- Ramp Change with 1xΩ
- Vibration frequency ½ x Ω
- Normal Flow Rate 0,8 to 1
- Change of Oil Temperature in Bearings

Data Processing in M1

For each row of M1 the **probabilitie numbers** are summed up for those columns with a yellow x. Relative probabilities are determined and a weighting of the **Matrix M1** determines three possible **Vibration Phenomena** (Green colour).

The corresponding **relative probabilities** are presented on the right side of M1. For this case they clearly indicate, that **Oil Film Instability in Bearings** is the most probable phenomenon with **35 %,** followed by Slow change of Unbalance and change of viscosity, each with **32 %**

Example: Identification and Mitigation of Subsynchronous Vibrations

Test Case: Instability in Fluid Film Bearings

29 Detections Vibrations, Flow Rates, Temperatures,..

		Frequencies of Vibrations (fn = Shaft Freq. in Hz; VPF= Vane Pass Freq.)																					Flow Rate			Operating Data of Pump												
																																		<---- Mark here "x" if not used in the				
		x	x											x									x			x								<---- Mark here "x" if detected				
Vibration Phenomenon	Report section	Ramp change 1xfn Amplit.	Ramp Change 1xfn Phase	Step change 1xfn Amplit.	Step change of 1xfn Phase	Permanent high 1xfn Amplit.	Change of 2xfn Vibr.Amplit.	Change of 2xfn Vibr. Phase	Change of 3xfn Amplitude	Vibr. peaks at k x fn, k=1,2,3..	Vibr.peak at zlm x fn = VPF	Vibr.peak at = 2 x VPF	Vibr. peaks: Harmon. of VPF	Subsynchr. Vibr. 0,4-0,5xfn	Subsynchr. Vibr. 0,5 - 0,9 xfn	Subsynchr. Vibr. 0,1- 0,3 xfn	Frequencies not related to fn	Vibr. spectrum above 500 Hz	Vibr. peaks betw. 1-20 Hz	Axial Vibrations at Bearings	Vibr.peaks at motor speeds	Peaks at Grid freq. 50 Hz	Flow Rate between 0,8 to 1	Flow Rate between 0,5-0,8	Low Flow Rate up to 0,5	Change of Oil Temperature	Change of Fluid Temperature	Change of pressure in Pump	Imp/Diff Pressure field m=0	Imp/Diff Pressure field m=2		Commonness	Severity	Sum of probabilities, if no blanks	Relative probabilities	Commonness	Severity	Commonness & Severity weighted probability
Slow change of Unbalance (wear, cavitation,...)		4	4	0	0	0	1	1	1	3	1	1	1	1	1	1	0	1	1	1	0	0	1	2	1	1	1	1	1	1	0	4	2	11	32%	43%	19%	26%
Sudden increasing change of Unbalance		0	0	5	5	0	0	0	0	3	1	1	1	0	0	0	0	0	0	0	0	0	3	1	1	0	2	2	0	0	0	2	5	0				
Hydraulic Unbalance due to Impeller tolerances		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0				
Hydraulich Unbalance due to nonuniform flow		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0				
Hydraulic Unbalance due to low quality sand cast		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0				
Hydraulic Unbalance due to impeller cavitation		1	1	0	0	4	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	3	4	0				
Thermal or Mechanical Bow of Pump Shaft		0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	0	3	0	0	0	0	2	4	0				
Operation in a Pump shaft critical speed		0	0	0	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	2	0	0	0	0	0	0	2	5	0				
Resonance of pump components (Casing, pipes,.)		0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	3	2	1	0	0	0	0	0	0	2	4	0				
Low damping (Fluid Film- or Roller Bearings)		0	0	0	0	4	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	3	2	1	0	0	0	0	0	0	2	4	0				
Bearing damage, e.g. White metal damage		1	1	2	2	1	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	2	4	0				
Mechanical and/or electrical Runout		2	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	2	2	0	0	0	0	0	0	2	2	0				
Instability in Radial Fluid Bearings		1	1	0	0	0	0	0	0	0	0	0	0	5	0	0	2	0	0	0	0	0	2	2	2	3	1	0	0	0	0	3	5	12	35%	35%	52%	54%
Change of Static Bearing Load with Flow Rate		2	2	2	2	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	2	2	4	0	1	0	0	0	0	2	4	0				
Change of viscosity in Fluid Bearings		2	2	1	1	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	1	1	1	3	1	0	0	0	0	2	3	11	32%	22%	29%	20%
Change of clearance in Fluid Bearings		2	2	1	1	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	2	2	1	0	1	0	0	0	0	2	3	0				
Clearance increase in Seals due to Wear		2	2	1	1	0	0	0	0	0	0	0	0	4	0	0	2	0	0	0	0	0	2	2	2	0	0	0	0	0	0	3	5	0				
Coupling shift (translational and or angular)		3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	2	4	0				
Change of support stiffness		4	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	3	4	0				
Internal friction in Shrink fits		1	1	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	2	5	0				
Rotating Stall		1	1	0	0																											2	4	0				
Impeller Inlet Recirculations		1	1	0	0																											2	3	0				
Rotating Stall at the guide vanes		1	1	0	0																											2	3	0				
Pressure pulsations cause casing & piping vibrations, also axial Impeller vibrations, m=0		1	1	0	0																											2	4	0				
Pressure pulsations lead to Dynamic Fluid Forces & cause Shaft & Bearing vibrations (zlm x fn)		0	0	0	0																											0	0	0				
Pressure pulsations may cause resonance vibr. of impeller with two nodal diam. mode, m=2		1	1	0	0																											2	4	0				
Blade Interference Forces at zlm x fn		1	1	1	1																											2	4	0				
Acoustic Resonance with zlm x fn		0	0	0	0																											2	3	0				
Resonance at Bearing Housing natural frequency		0	0	0	0																											2	3	0				
Peaks at k x fn due to geometr. deviations in Impeller vanes (geometr. Spacing, angle errors)		0	0	0	0																											2	3	0				
Bearing Misalignment		1	1	1	1																											2	3	0				
Misalignment due to Thermal Effects (Hot Fluid)		1	1	2	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	3	0	0	0	0	2	3	0				
Misalignment due to Piping Forces		1	1	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	2	2	0				
Nonlinearities: Loose parts (Bushes, Bearings)		0	0	2	2	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	2	2	0				
Transverse Shaft Cracks in Pump shaft		3	3	0	0	2	5	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	1	0	0	0	0	0	2	5	0				
Natural frequencies of structure, excited by broadband forces (e.g. recirculations, cavitation)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	2	4	0	0	0	0	0	0	2	3	0				
Pressure pulsation and vibrat. due to Cavitation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	1	0	0	0	0	0	0	0	0	2	3	0				
Broadband Excitation of low natural frequencies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	5	0	0	0	2	1	1	0	0	0	0	0	0	2	3	0				
Electrical disturbances of instrumentation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Motor Vibrations transferred via foundation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
																																			100%	100%	100%	100%

Matrix M1

Slow Change of Unbalance 32%

Detection Fluid Film Instability 35%

Change of Viscosity 32%

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix **M2 – Part 1**

The Matrix **M2** has two parts. The first part receives the results from **Matrix M1**and calculates based on the **M2**-**probabilities** and the easiness values the best suited Investigation methods for the identified Vibration phenomena. The result is highlighted by the blue colour.

In this example the recommended additional **Investigations** to confirm the **three** already identified **Vibration Phenomena** are besides others:

- Investigate and confirm the **frequency spectra** and if available **orbits**
- Investigate and confirm the **Bearing conditions** (Metal & fluid temperature)
- Investigate the conditions of the **Impeller**

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix **M2 – Part 2**

In the second part of the **Data processing** in **M2** the user can now select the best suited **Investigation method** by setting a **cross (x) in the yellow line.**

If we follow the recommendations from **Part 1** of the data processing we set the yellow cross in all blue columns.

By this selection the probability calculation with the **M2** **probabilities** leads already to a result of 100 % for the **oil film instability**

Due to the fact, that the Vibration Phenomena could already be identified by **Matrix M2**, we continue without the processing of **M3** (Analysis). **M3** can only be an additional help, but has no effect on the **Mitigation Matrix M4**

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix **M2**

27 Investigations (IoV)
Spectra& Orbits,Seals,
Bearings, Impeller,
Flow conditions, etc.

Vibration Phenomenon	IoV	Evidence of wear, cavit., corr.	Evidence of rotating part losses	Impeller tolerances out of range	Unsymmetric Fluid flow at inlet	Impeller sand cast quality low	Is pump sensitive for cavitation	Relat. shaft displ. at low speed	Large Ampl.-change with speed	Resonanceof comp. in Run ups	Sharp peaks in Run up curves	Bearing metal temperature	Signific. 1/2x fn freqency in	Strong change of Flow Rate	Change of Fluid Film Temp. In	Change : Operat. Clearance in	Wear in Impeller Seals	Pressure in Shrink Fits to low	Confirm Imp./Diff comb. m = 0	Confirm VPF in Freq. Spectrum	Confirm Imp./Diff. Comb. m= 2	Orbit circular or elliptical	Orbit & spectr.: subsynchr. freq.	Orbit& spectr. with regular	Orbit & spectrum : 1xfn,	Pump:Vert. Reactor Coolant	Pump: Horizontal Boilerfeed	Pump:Vert. Conden. Cooling	0	0	0	Sum of probabilities, if no blanks	Additional requirements	Relative probabilities
		x				x	x		x			x	x		x								x				x							
Major objectives		🟦				🟦	🟦		🟦			🟦	🟦		🟦								🟦			🟦	🟦	🟦						
Slow change of Unbalance (wear, cavitation,...)		3	0	1	1	2	3	0	0	0	0	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0		
Sudden increasing change of Unbalance		0	4	0	0	0	0	0	1	1	2	2	1	3	1	0	0	0	0	0	0	3	0	0	2	1	1	1	0	0	0	0		
Hydraulic Unbalance due to Impeller tolerances		0	0	5	1	1	1	0	1	0	1	0	0	2	0	0	0	0	0	0	0	3	0	0	2	1	1	1	0	0	0	0		
Hydraulich Unbalance due to nonuniform flow		0	0	1	5	1	1	0	1	0	1	0	0	2	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Hydraulic Unbalance due to low quality sand cast		1	0	1	1	5	1	0	1	0	1	0	0	2	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Hydraulic Unbalance due to impeller cavitation		1	0	1	1	1	5	0	1	0	1	0	0	2	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Thermal or Mechanical Bow of Pump Shaft		0	0	1	1	1	1	4	1	0	2	2	0	0	1	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Operation in a Pump shaft critical speed		0	1	1	1	1	1	0	2	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Resonance of pump components (Casing, pipes,.)		0	0	0	0	0	0	0	3	4	3	0	0	1	0	0	0	0	0	0	0	3	0	0	0	1	1	1	0	0	0	0		
Low damping (Fluid Film- or Roller Bearings)		0	0	0	0	0	0	0	2	0	5	0	3	0	2	0	0	4	0	0	0	1	1	0	0	1	1	1	0	0	0	0		
Bearing damage, e.g. White metal damage		1	1	0	0	1	1	0	1	0	0	4	1	0	2	0	0	0	0	0	0	1	0	0	3	1	1	1	0	0	0	0		
Mechanical and/or electrical Runout		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Instability in Radial Fluid Bearings		1	0	0	0	1	1	0	2	0	0	1	5	0	1	0	0	0	0	0	0	0	4	0	0	1	1	1	0	0	0	17		100%
Change of Static Bearing Load with Flow Rate		0	0	0	0	0	0	0	1	0	0	0	2	4	1	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0		
Change of viscosity in Fluid Bearings		0	0	0	0	1	1	0	1	0	0	2	2	0	5	0	0	0	0	0	0	0	2	0	0	1	1	1	0	0	0	0		
Change of clearance in Fluid Bearings		0	0	0	0	0	0	0	1	0	0	2	3	0	1	1	0	0	0	0	0	0	2	0	0	1	1	1	0	0	0	0		
Clearance increase in Seals due to Wear		1	0	0	0	0	0	0	2	0	0	0	3	0	0	4	4	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0		
Coupling shift (translational and or angular)		0	0	0	0																								0	0	0	0		
Change of support stiffness		0	0	0	0																								0	0	0	0		
Internal friction in Shrink fits		1	0	1	1																								0	0	0	0		
Rotating Stall		1	0	1	1																								0	0	0	0		
Impeller Inlet Recirculations		1	0	1	1																								0	0	0	0		
Rotating Stall at the guide vanes		1	0	1	1																								0	0	0	0		
Pressure pulsations cause casing & piping		1	0	0	0																								0	0	0	0		
Pressure pulsations lead to Dynamic Fluid Forces		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Pressure pulsations may cause resonance vibr. of		1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	0	1	1	1	0	0	0	0		
Blade Interference Forces at zlm x fn		1	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	1	4	1	1	0	0	0	1	1	1	0	0	0	0		
Acoustic Resonance with zlm x fn		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	1	1	1	0	0	0	0		
Resonance at Bearing Housing natural frequency		0	0	0	0	0	0	0	3	3	3	1	0	0	0	0	0	0	0	0	0	2	0	0	0	1	1	1	0	0	0	0		
Peaks at k x fn due to geometr. deviations in		0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Bearing Misalignment		1	1	0	0	0	1	1	0	0	0	2	0	0	1	1	1	1	0	0	0	1	0	3	0	1	1	1	0	0	0	0		
Misalignment due to Thermal Effects (Hot Fluid)		1	1	0	0	1	1	1	0	0	0	2	0	3	1	1	1	0	0	0	0	1	0	3	0	1	1	1	0	0	0	0		
Misalignment due to Piping Forces		1	1	0	0	0	1	1	0	0	0	2	0	0	1	1	1	0	0	0	0	1	0	3	0	1	1	1	0	0	0	0		
Nonlinearities: Loose parts (Bushes, Bearings)		0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0		
Transverse Shaft Cracks in Pump shaft		1	0	0	0	1	1	0	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0		
Natural frequencies of structure, excited by		0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Pressure pulsation and vibrat. due to Cavitation		2	0	0	0	1	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Broadband Excitation of low natural frequencies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Electrical disturbances of instrumentation		0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0		
Motor Vibrations transferred via foundation		0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	1	0	0	0	0		

Matrix M2

Detection Fluid Film Instability 100 %

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix **M4 (Mitigation)**

With the result from **Matrix M2**: **100 % Instability in Radial Fluid Bearing**, we set a yellow cross at this **Vibration Phenomena.**

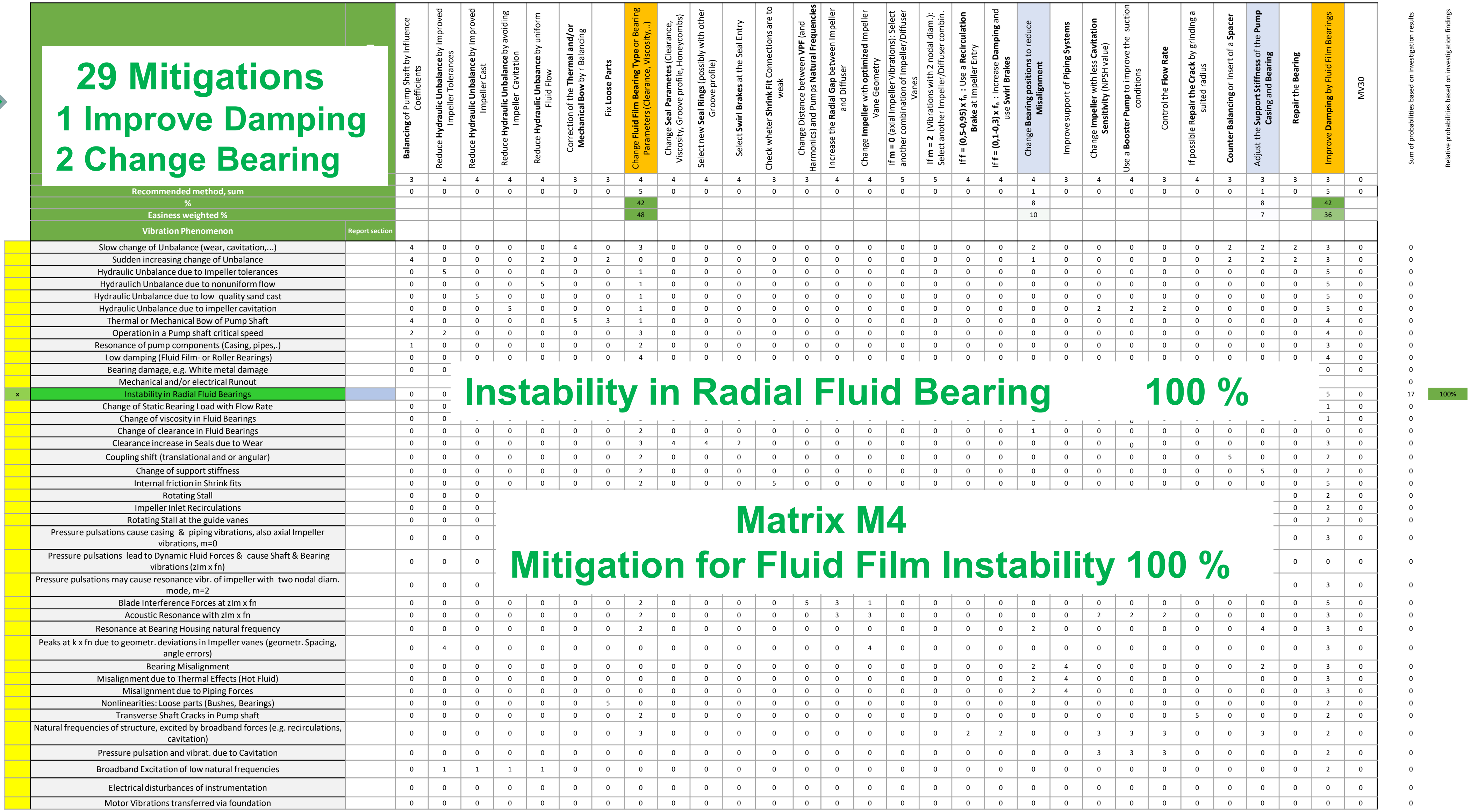
By means of **the probability numbers** in the row of **Instability in Radial Fluid Bearing** in **Matrix M4** (Mitigation) we obtain two results for the Mitigation of the Instability problem

- **Improve the Damping in the Fluid Film Bearing**
- **Change the Fluid Film Bearing type or the Bearing Prameters (Clearance, Viscosity,..)**

Example: Identification and Mitigation of Subsynchronous Vibrations

Data Processing in Matrix M4 – Mitigation

29 Mitigations
1 Improve Damping
2 Change Bearing



			Balancing of Pump Shaft by Influence Coefficients	Reduce **Hydraulic Unbalance** by Improved Impeller Tolerances	Reduce **Hydraulic Unbalance** by Improved Impeller Cast	Reduce **Hydraulic Unbalance** by avoiding Impeller Cavitation	Reduce **Hydraulic Unbaance** by uniform Fluid Flow	Correction of the **Thermal and/or Mechanical Bow** by r Balancing	Fix **Loose Parts**	Change **Fluid Film Bearing Type** or Bearing Parameters (Clearance, Viscosity,..)	Change **Seal Parametes** (Clearance, Viscosity, Groove profile, Honeycombs)	Select new **Seal Rings** (possibly with other Groove profile)	Select **Swirl Brakes** at the Seal Entry	Check wheter **Shrink Fit** Connections are to weak	Change Distance between **VPF** (and Harmonics) and Pumps **Natural Frequencies**	Increase the **Radial Gap** between Impeller and Diffuser	Change **Impeller** with **optimized** Impeller Vane Geometry	If **m = 0** (axial Impeller Vibrations): Select another combination of Impeller/Diffuser Vanes	If **m = 2** (Vibrations with 2 nodal diam.): Select another Impeller/Diffuser combin.	If **f = (0,5-0,95) x f_n** : Use a **Recirculation Brake** at Impeller Entry	If **f = (0,1-0,3) x f_n** : Increase **Damping** and use **Swirl Brakes**	Change **Bearing positions** to reduce **Misalignment**	Improve support of **Piping Systems**	Change **Impeller** with less **Cavitation Sensitivity** (NPSH value)	Use a **Booster Pump** to improve the suction conditions	Control the **Flow Rate**	If possible **Repair the Crack** by grinding a suited radius	**Counter Balancing** or Insert of a **Spacer**	Adjust the **Support Stiffness** of the **Pump Casing** and **Bearing**	**Repair** the **Bearing**	Improve **Damping** by Fluid Film Bearings	MV30	Sum of probabilities based on investigation results	Relative probabilities based on investigation findings
			3	4	4	4	4	3	3	4	4	4	4	3	3	4	4	5	5	4	4	4	3	4	4	3	4	3	3	3	3	0		
	Recommended method, sum		0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	5	0		
	%									42												8							8		42			
	Easiness weighted %									48												10							7		36			
	Vibration Phenomenon	Report section																																
	Slow change of Unbalance (wear, cavitation,...)		4	0	0	0	0	4	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	2	2	3	0	0	
	Sudden increasing change of Unbalance		4	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	2	2	3	0	0	
	Hydraulic Unbalance due to Impeller tolerances		0	5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	
	Hydraulich Unbalance due to nonuniform flow		0	0	0	0	5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	
	Hydraulic Unbalance due to low quality sand cast		0	0	5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	
	Hydraulic Unbalance due to impeller cavitation		0	0	0	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	5	0	0	
	Thermal or Mechanical Bow of Pump Shaft		4	0	0	0	0	5	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	
	Operation in a Pump shaft critical speed		2	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	
	Resonance of pump components (Casing, pipes,.)		1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	
	Low damping (Fluid Film- or Roller Bearings)		0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	
	Bearing damage, e.g. White metal damage		0	0																											0	0	0	
	Mechanical and/or electrical Runout																																0	
x	Instability in Radial Fluid Bearings		0	0																											5	0	17	100%
	Change of Static Bearing Load with Flow Rate		0	0																											1	0	0	
	Change of viscosity in Fluid Bearings		0	0																											1	0	0	
	Change of clearance in Fluid Bearings		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	
	Clearance increase in Seals due to Wear		0	0	0	0	0	0	0	3	4	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	
	Coupling shift (translational and or angular)		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	2	0	0	
	Change of support stiffness		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	2	0	0	
	Internal friction in Shrink fits		0	0	0	0	0	0	0	2	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	
	Rotating Stall		0	0	0																									0	2	0	0	
	Impeller Inlet Recirculations		0	0	0																									0	2	0	0	
	Rotating Stall at the guide vanes		0	0	0																									0	2	0	0	
	Pressure pulsations cause casing & piping vibrations, also axial Impeller vibrations, m=0		0	0	0																									0	3	0	0	
	Pressure pulsations lead to Dynamic Fluid Forces & cause Shaft & Bearing vibrations (zIm x fn)		0	0	0																									0	0	0	0	
	Pressure pulsations may cause resonance vibr. of impeller with two nodal diam. mode, m=2		0	0	0																									0	3	0	0	
	Blade Interference Forces at zIm x fn		0	0	0	0	0	0	0	2	0	0	0	0	5	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	
	Acoustic Resonance with zIm x fn		0	0	0	0	0	0	0	2	0	0	0	0	0	3	3	0	0	0	0	0	0	2	2	2	0	0	0	0	3	0	0	
	Resonance at Bearing Housing natural frequency		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	4	0	3	0	0	
	Peaks at k x fn due to geometr. deviations in Impeller vanes (geometr. Spacing, angle errors)		0	4	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	
	Bearing Misalignment		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	2	0	3	0	0	
	Misalignment due to Thermal Effects (Hot Fluid)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0		0	0	3	0	0	
	Misalignment due to Piping Forces		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	0	0	0	0	0	0	0	3	0	0	
	Nonlinearities: Loose parts (Bushes, Bearings)		0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	
	Transverse Shaft Cracks in Pump shaft		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	2	0	0	
	Natural frequencies of structure, excited by broadband forces (e.g. recirculations, cavitation)		0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	2	0	0	3	3	3	0	0	3	0	2	0	0	
	Pressure pulsation and vibrat. due to Cavitation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	0	2	0	0	
	Broadband Excitation of low natural frequencies		0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	
	Electrical disturbances of instrumentation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Motor Vibrations transferred via foundation		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Instability in Radial Fluid Bearing 100 %

Matrix M4
Mitigation for Fluid Film Instability 100 %

Vorlesungen Mechatronik im Wintersemester

Energiforsk Project: DIAM for Pump Vibrations
Energiforsk Vibration Seminar 06.11.24 Helsinki

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DIAM - A Matrix Tool for Pump Vibrations in Nuclear Power Plants

Rainer Nordmann, TU Darmstadt