Vorlesungen Mechatronik im Wintersemester

# Research Program Vibrations
# ENERGIFORSK Vibration Group

TECHNISCHE UNIVERSITÄT DARMSTADT

## DIAM – A Matrix Tool for Turbine and Generator Vibrations

**D**etection, **I**nvestigation, **A**nalysis, **M**itigation

**Prof. Dr.-Ing. Rainer Nordmann**

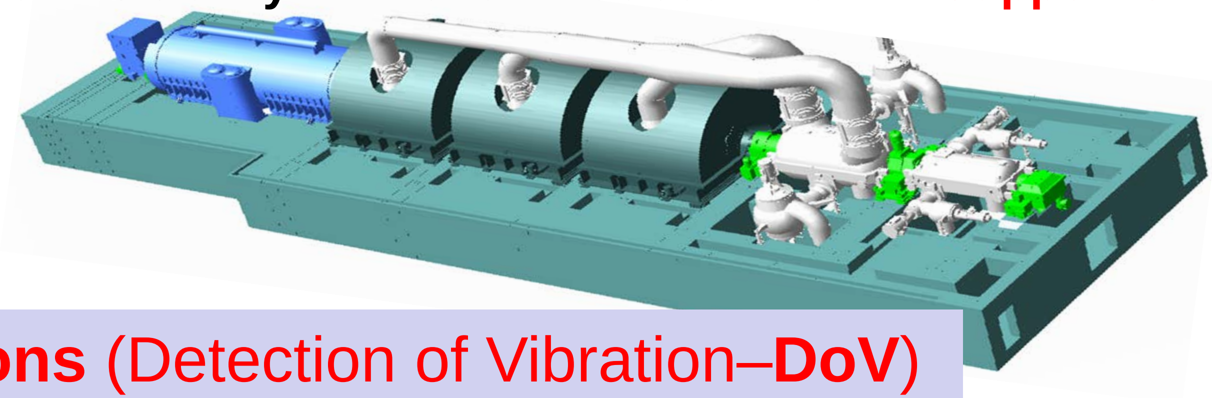
# Vibration Phenomena and Detections

## Vibration Phenomena (Cause of Vibration-CoV)

Cyclic Vibrations Unbalance Change Misalignment

Change of Seawater-Temp. Transverse Shaft Cracks Coupling Errors

Oil Film&Seal Instability Friction Induced Vibr. Support Stiffness Change



## Detections (Detection of Vibration–DoV)

Change of Vibration Amplitudes and Phase: 1/2xN, 1xN, 2xN, 3xN, …

1xN Vector Rotation, Change of Natural Frequencies

Change of Oil Film Temperature, Change: Cooling Water Temp. (Geno)

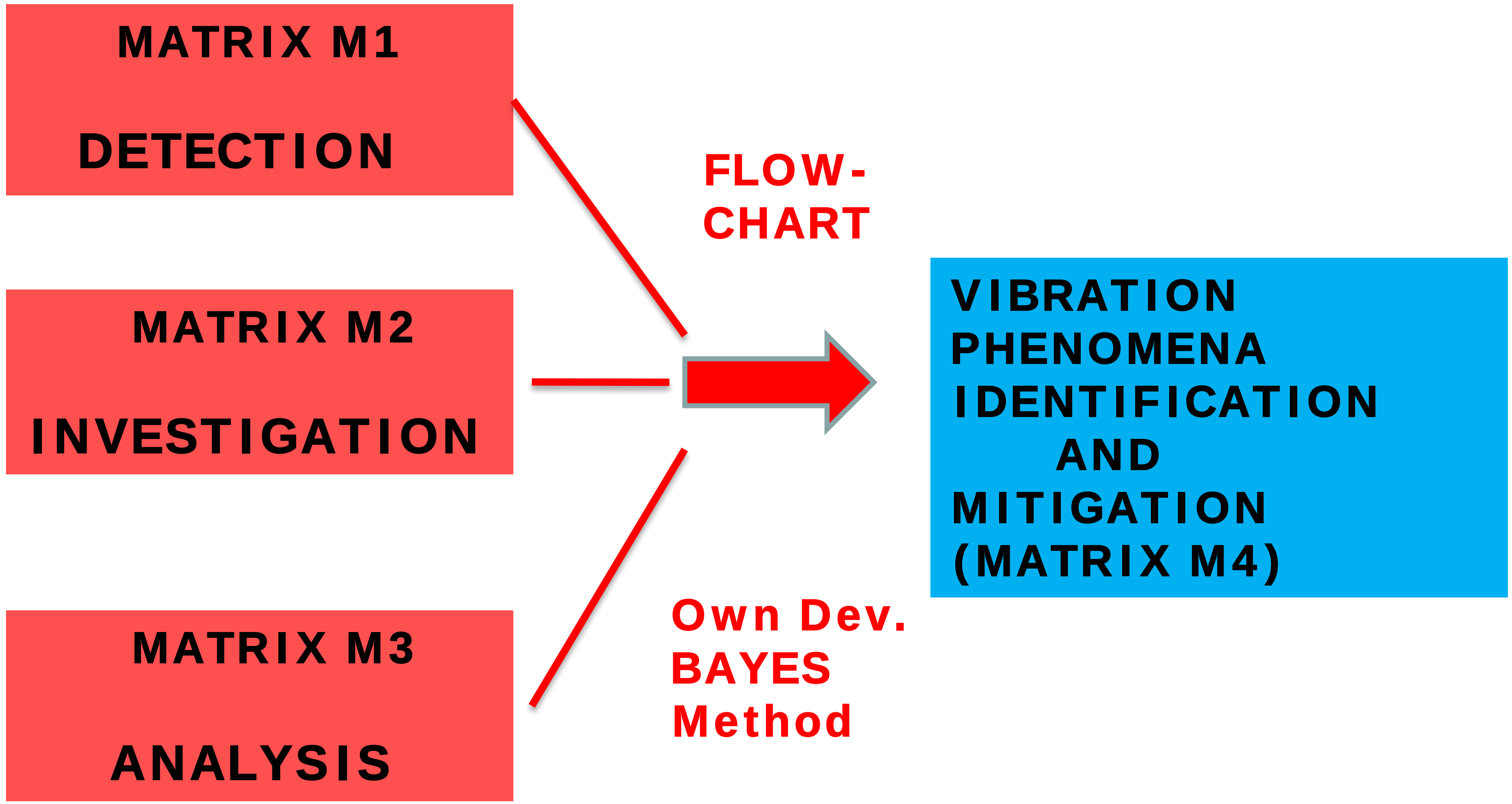
# Project Description

## Objective of the project DIAM

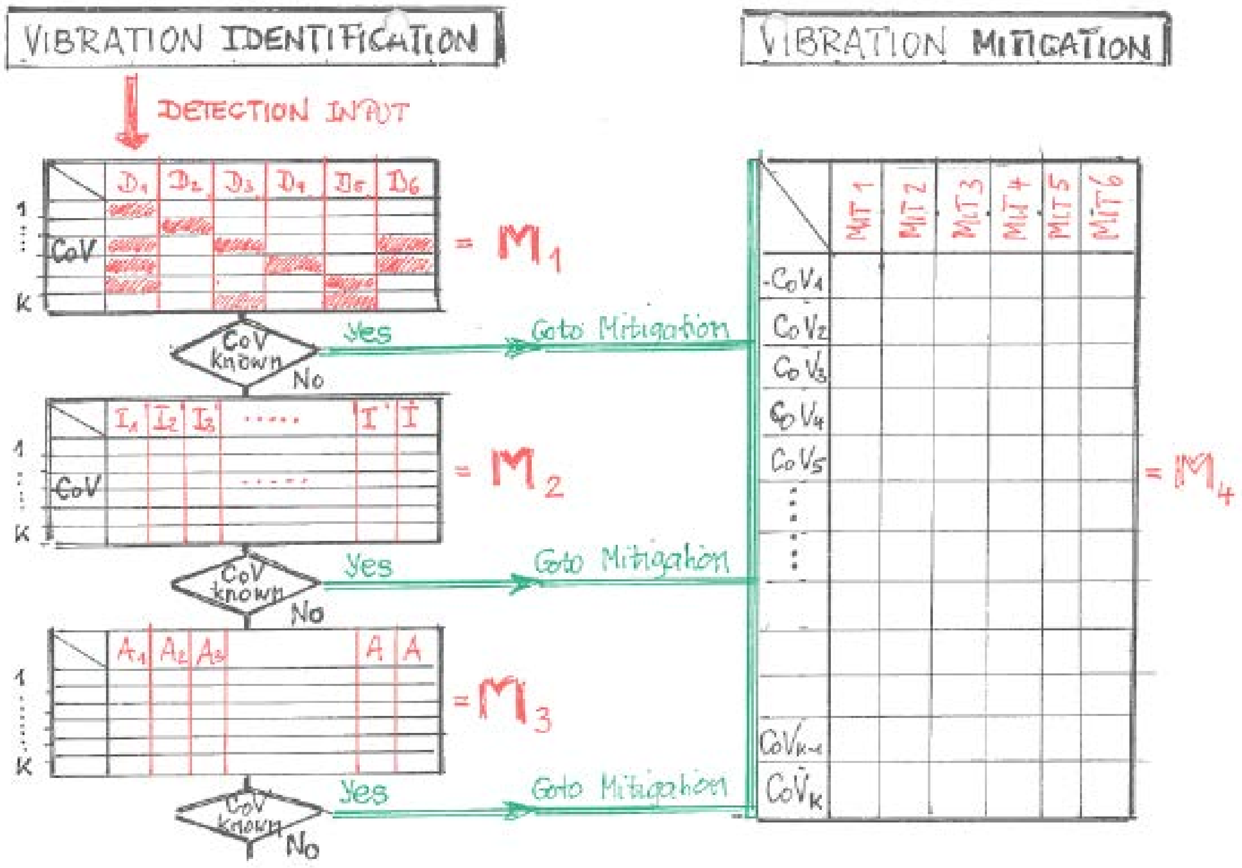
## A) Development of the Matrix Tool DIAM

In 3 Matrix presentations different **Vibration phenomena** will be related to different **D**etection, **I**nvestigation and **A**nalysis (**DIA**) methodologies. A flow chart based on a selected method (Own development, Bayes Network) has been worked out as a guideline, how to use these Matrices for the Identification of the **Vibration Phenomena** and finally how a **Mitigation** of the Vibration problem can be achieved.

# Project Description



# Project Description



# Project Description

- **MATRIX M1**

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

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- **MATRIX M2**

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

- **MATRIX M3**

  relates the different Vibration Phenomena to different well suited analytical, numerical or experimental **Analysis** methods by means of probabilities as well.

# Project Description

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

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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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# Project Description

## Objective of the project DIAM

### B) Collection of further Vibration phenomena.

Besides Vibrations, that occurred in Scandinavian NPP (1. project), this new Project includes now also additional Vibration problems, detected in NPPs in other countries and in other kind of plants.

Grouping of all Vibration problems into the area of **Lateral Vibrations** only.

Assembly of all Lateral **Vibration Phenomena** in a list of 18 cases

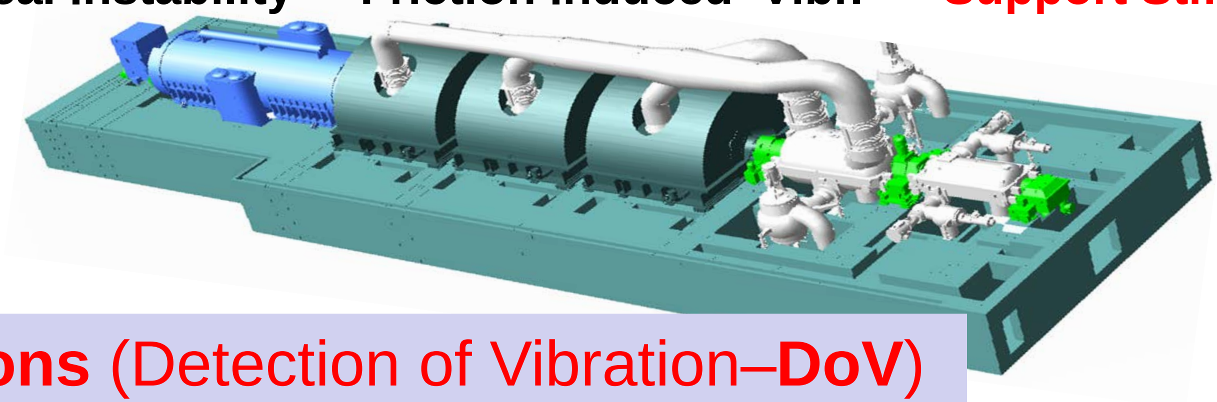
# Vibration Phenomena and Detections

## Vibration Phenomena (Cause of Vibration-CoV)

Cyclic Vibrations | Unbalance Change | Misalignment

Change of Seawater-Temp. | Transverse Shaft Cracks | Coupling Errors

Oil Film&Seal Instability | Friction Induced Vibr. | Support Stiffness Change



## Detections (Detection of Vibration–DoV)

Change of Vibration Amplitudes and Phase: 1/2xN, 1xN, 2xN, 3xN, …

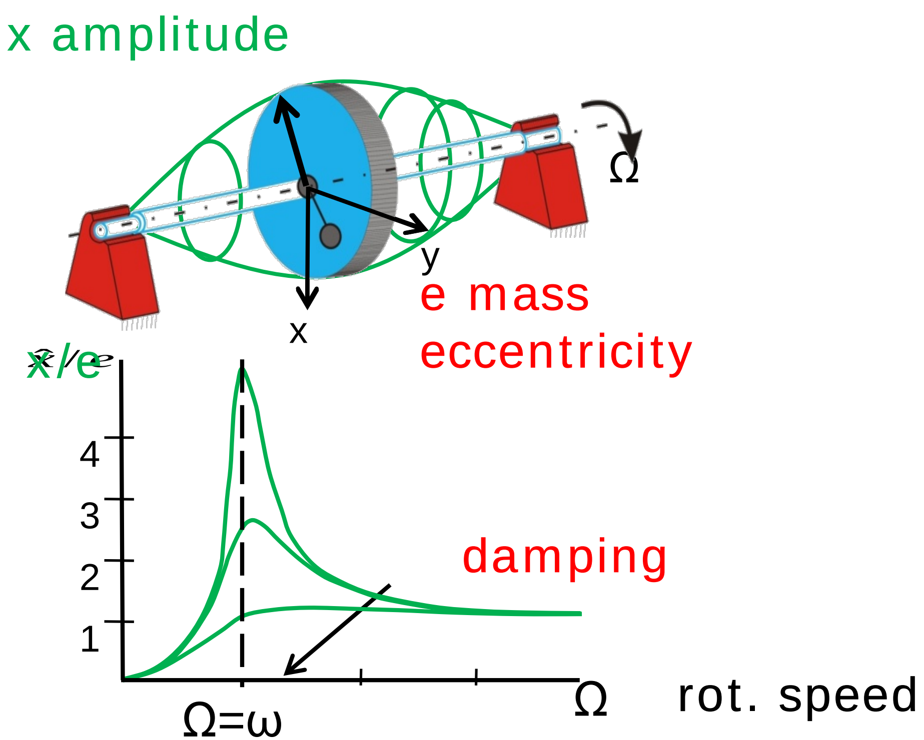
1xN Vector Rotation, Change of Natural Frequencies

Change of Oil Film Temperature, Change: Cooling Water Temp. (Geno)

# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

**Change of Unbalance:** Change of Unbalance can be slow (thermal effect) or suddenly (Blade Loss).




## Detections (DoV)

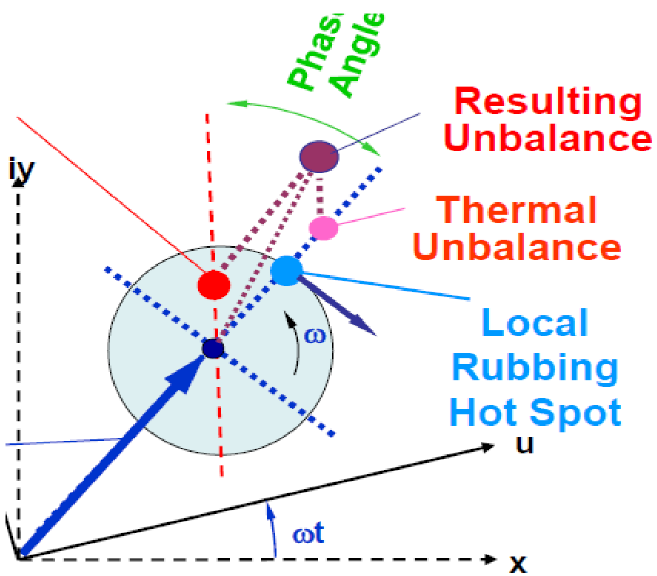
Slow or sudden change of Amplitude and Phase of the 1xN Lateral Vibrations.

Change of Amplitude and Phase can also be effected due to a change in the system dynamic behavior.

# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

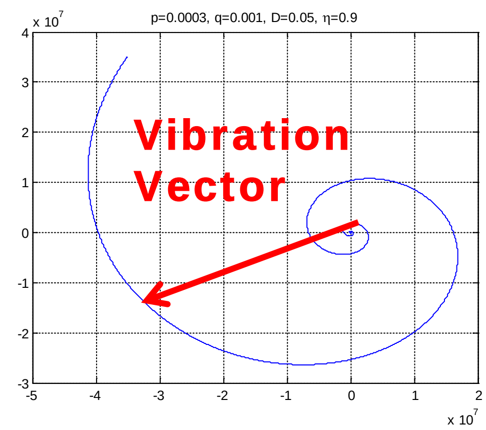
**Cyclic Vibration:** Superposition of an Original Mechanical Unbalance with a Rotating Thermal Unbalance.Local Heat input, Thermal Deflection & Bow




## Detections (DoV)

Change of Amplitude and Phase of the 1xN Lateral Vibration.

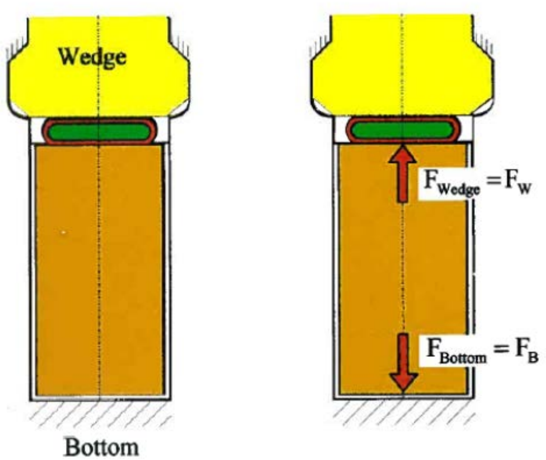
Vibration Vector in the Polar Diagram rotates continously with a period between 1 to 15 hours (can be stable or unstable).



# Vibration Phenomena and Detections

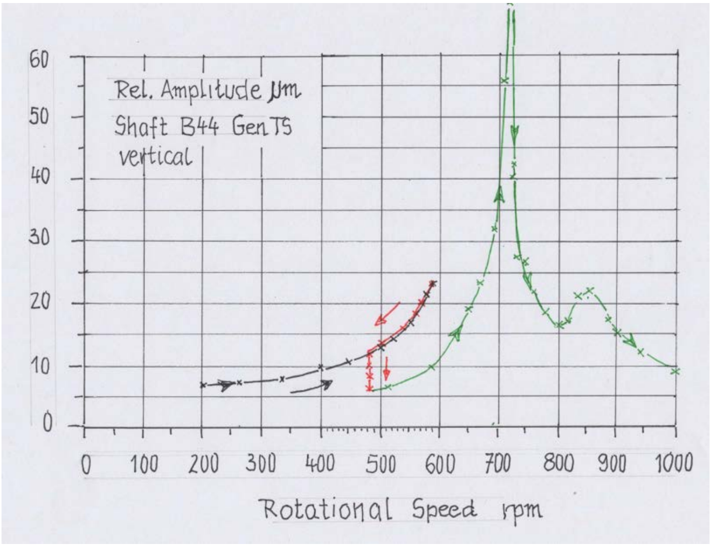
## Vibration Phenomena (CoV)

**Friction induced Mechanical Bow in Turbogenerators:**
Unbalance due to the friction induced bow depends on temperature, rotational speed and the mounting pressure.




## Detections (DoV)

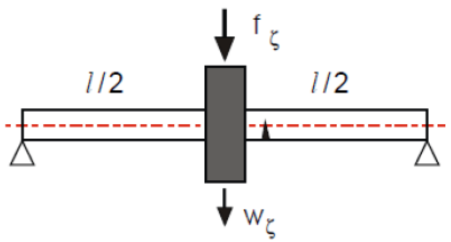
Change of Amplitude and Phase of the 1xN Lateral Vibration due to friction induced bow.

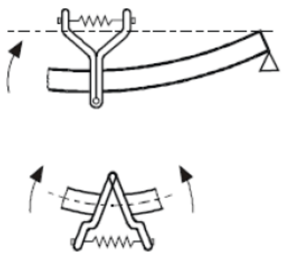


# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

### Transverse Shaft Cracks in Turbine Trains:



Modelling of a flexible Laval shaft with mass in the center and a crack close to the mass. Crack modelled as a hinge joint.

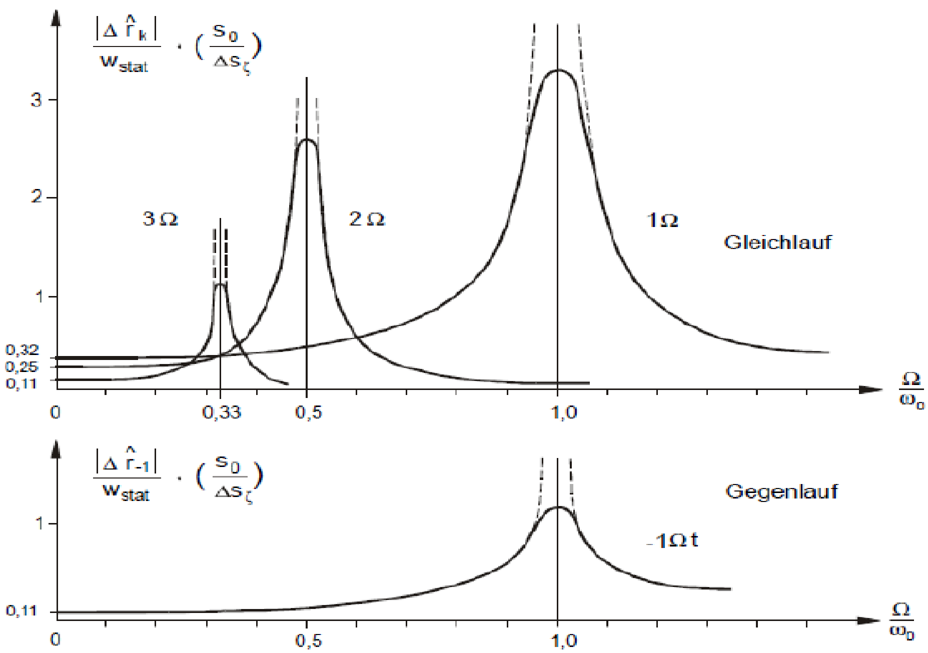
For this model the crack dependent forward and backward excitation participation factors are as follows:

| | | | | | |
|---|---|---|---|---|---|
| Forward Excitation: | +1Ω | + 0,318 | Backward Excitation: | - 1Ω | 0,106 |
| | +2Ω | + 0,250 | | - 2Ω | 0,00 |
| | +3Ω | + 1.106 | | - 3Ω | -0.02 |

# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

### Transverse Shaft Cracks in Turbine Trains:

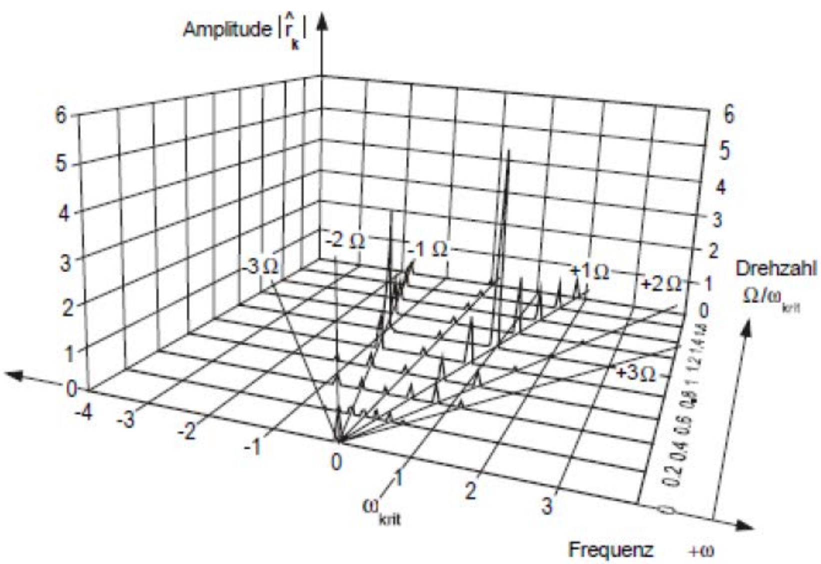



The crack dependent vibration response of the Laval shaft with the described crack has forward Harmonics with 1xN, 2xN and 3xN and a backward Harmonic with -1xN.

# Vibration Phenomena and Detections

## Detections (DoV)

**Transverse shaft cracks in turbine trains:** Shaft cracks cause changes in 1xN and 2xN Vibrations and also in higher Harmonics, e.g. 3xN, depending on the nonlinearity of the crack behavior.

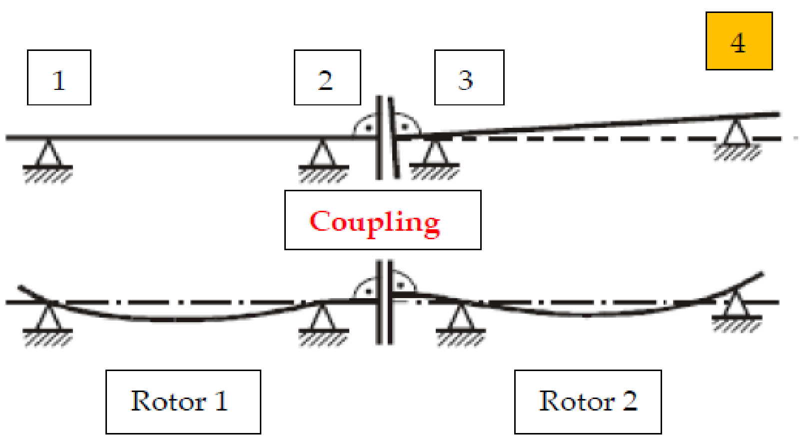



The double sided frequency spectrum with forward and backward frequencies can be a very helpful tool for the Crack Identification.

# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

**Misalignment in Shaft Trains:** Misalignment occurs, when the bearings of a shaft train are not in the right vertical position for a moment free coupling of the rigid flanges of two rotors (see figure).




We consider the case of angular misalignment, when the two shafts, shown in the figure, have a relative angular displacement. The vertical location of Bearing 4 is too high in the uncoupled case. Therefore a relative angular displacement occurs. When the two shafts are now rigidly connected together, a static moment in the coupling is needed and this leads to static bending line in the shafts and will also change the static Bearing Forces

# Vibration Phenomena and Detections

## Vibration Phenomena (CoV)

**Misalignment in Shaft Trains:**
Misalignment is a static phenomenon and cannot directly be considered as a vibration problem. However, Misalignment changes the static Bearing Forces and this will finally lead to a change in the dynamic characteristic of the dynamic rotor system due to the dynamic oil film forces, which depend on the static equilibrium.

## Detections (DoV)

Depending on the static Oil Film Bearing Forces the dynamic behavior of the rotor system may lead to the following changes:

- Low Bearing loads may lead to an oil film instability with 1/2xN vibrations
- High Bearing loads can cause Bearing nonlinearities with 2xN vibrations
- Changes of Bearing loads may also change the 1xN vibration component

# Detections in Power Plants

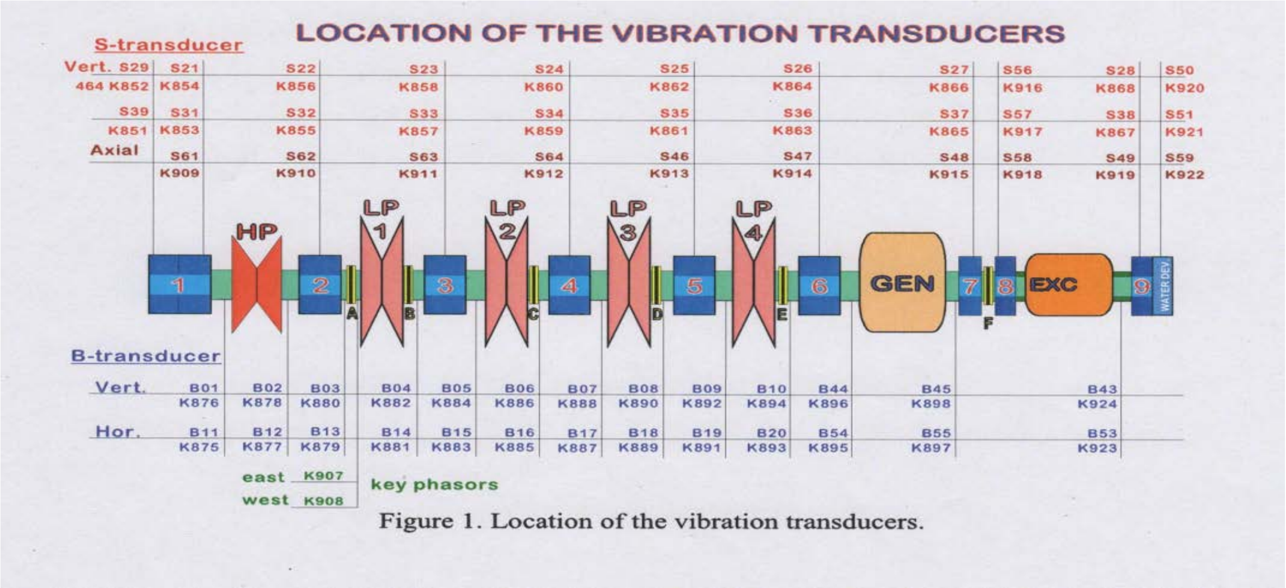
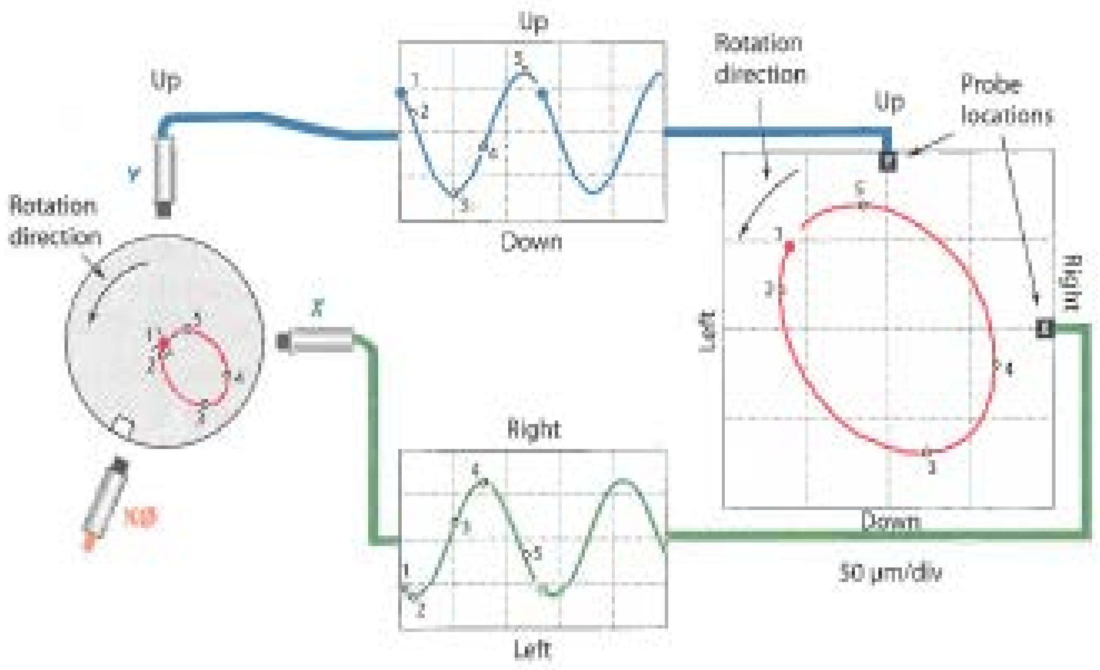


Figure 1. Location of the vibration transducers.

The base for the Identification of Vibration Phenomena in Power Plants is to measure absolute velocity vibrations in mm/sec at the bearings and relative shaft vibrations in um (displacements) close to the bearings or on shaft ends.

# Detections in Power Plants

Example: **Detection of Relative Lateral Shaft Vibrations** in horizontal and vertical direction. The superposition of the two signals shows the **Orbit** at this shaft position.



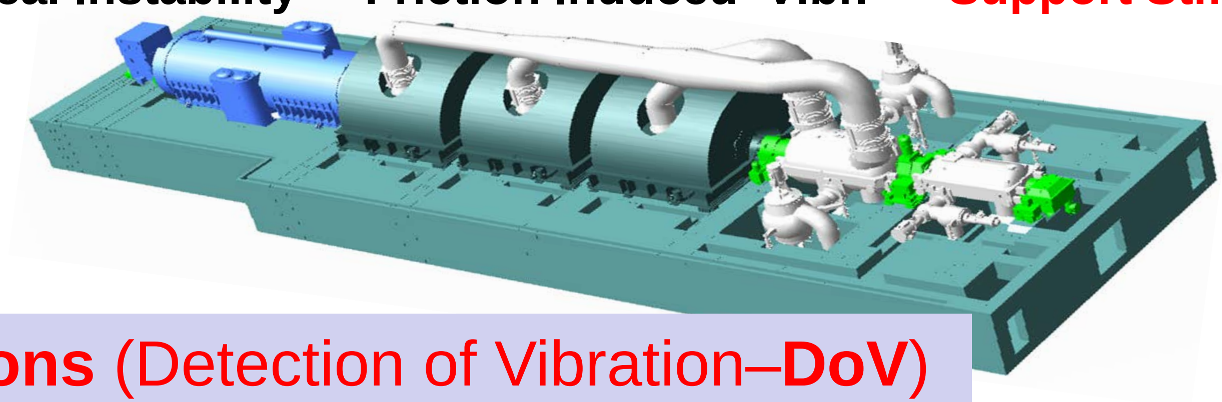
# Vibration Phenomena and Detections

## Vibration Phenomena (Cause of Vibration-CoV)

**Cyclic Vibrations** **Unbalance Change** **Misalignment**

**Change of Seawater-Temp.** **Transverse Shaft Cracks** **Coupling Errors**

**Oil Film&Seal Instability** **Friction Induced Vibr.** **Support Stiffness Change**



## Detections (Detection of Vibration–DoV)

**Change of Vibration Amplitudes and Phase: 1/2xN, 1xN, 2xN, 3xN, …**

**1xN Vector Rotation, Change of Natural Frequencies**

**Change of Oil Film Temperature, Change: Cooling Water Temp. (Geno)**

# Vibration Phenomena and Detections

| | |
|---|---|
| **PHENOMENON 1:**<br>**CoV 1** | **Slow Change of Unbalance,** e.g. due to a Thermal effects with a thermal bow or due to slowly increasing Mechanical Unbalance (Report A, 5.1) |
| **PHENOMENON 2:**<br>**CoV 2** | **Sudden Change of a Mechanical Unbalance,** e.g. due to a Blade loss or due a fast moving part in the rotating system (Report A, 5.1) |
| **PHENOMENON 3:**<br>**CoV 3** | **Cyclic or Spiral Vibrations.** Superposition of an Original Mechanical Unbalance with a rotating Thermal Unbalance (Report A, 5.2) |
| **PHENOMENON 4:**<br>**CoV 4** | **Change of Oil Film Bearing Coefficients,** e.g. due to oil film temperature, Static Bearing loads or due to clearance changes (Report A, 5.6) |
| **PHENOMENON 5:**<br>**CoV 5** | **Friction induced mechanical bow in Turbogenerators,** depends on temperature, rotational speed and mounting pressure (Report A, 5.3) |
| **PHENOMENON 6:**<br>**CoV 6** | **Change of Sea water temperature with Condenser deformation and change of Static Bearing location.** (Report A, 5.4) |

# Vibration Phenomena and Detections

| | |
|---|---|
| DETECTION 1:<br>DoV 1 | **Slow change of the amplitude of the 1xN Lateral vibrations.** Can be caused by a change of Excitation or by a change of the system dynamic behavior. |
| DETECTION 2:<br>DoV 2 | **Slow change of the phase of the 1xN Lateral vibration.** Can be caused by a change of Excitation or by a change of the system dynamic behavior. |
| DETECTION 3:<br>DoV 3 | **Sudden change (increase) of the amplitude of the 1xN Lateral vibration.** Can be caused by a sudden change of Unbalance (e.g. by a Blade loss). |
| DETECTION 4:<br>by DoV 4 | **Sudden change of the phase of the 1xN Lateral vibration.** Can be caused a sudden change or by a change of Unbalance (e.g. by a Blade loss). |
| DETECTION 5:<br>DoV 5 | **Change of amplitude and phase of the 1xN Lateral vibration. Vibration Vector in polar diagram rotates continuously** (period 1 to 10 hours). |
| DETECTION 6:<br>DoV 6 | **Change (increase) of the amplitude of the ½ xN Lateral vibration.** Can be caused by a sub-synchronous instability in Oil Film Bearings or in Seals |

# Phenomena versus Detections: Matrix M1

## Matrix M1

**15 Detections**

**Vibrations,Temperat.**

**18 Vibration Phenomena**

| Vibration Phenomenon | | Sensor detection | | | | | | | | | | | | Temperature | | | Condition | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 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**

# Data Processing in Matrix M1 Excel Table

## Data Processing in Matrix M1:

For each row of M1 the probabilities are summed up for those columns with a yellow x from detection. This leads to the sum of probabilities. Relative probabilities are determined and a weighting of the probabilities is considered with commonness and severity.

An application is shown for the case of 1/2xN fequency detection, which leads to five 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 36 %.

# Data Processing in Matrix M1 Excel Table

| Vibration Phenomenon | Anomaly description | 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 | Sum of probabilities, if no blanks | Relative probabilities | Commonness | Severity | Commonness & Severity weighted probability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sensor detection | | | | | | | | | | | | Temperature | | | Condition | | | | | | | | | |
| | | | | | | | x | x | | | | | | x | | | | | | | | | | | | |
| Slow Change of Unbalance | | 5 | 5 | | | 2 | | | | | | | | | 2 | 3 | 3 | 3 | 3 | 4 | 2 | 0 | | | | |
| Sudden Change of Mechanical Unbalance | | | | 5 | 5 | | | | | | | | | | | | 3 | 1 | 1 | 2 | 5 | 0 | | | | |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | 3 | 3 | | | 5 | | | | | | | | | | | 3 | 2 | 2 | 2 | 2 | 0 | | | | |
| Change of Oil Film Bearing Coefficients | | 4 | 4 | | | 1 | 2 | 2 | 2 | 2 | | | | 5 | | 2 | 3 | 1 | 3 | 2 | 2 | 9 | 20% | 18% | 11% | 10% |
| Friction induced Mechanical Bow | | 2 | 2 | 3 | 3 | | | | | | | | | 1 | 5 | | 1 | 3 | 3 | 2 | 4 | 0 | | | | |
| Change of Sea Water Temp.& Cond. Deform. | | 3 | 3 | | | | 2 | 2 | 2 | 2 | 1 | 1 | | 2 | | 5 | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 6 | 13% | 18% | 4% | 5% |
| Change of Seawater Temp./ Thermal bow | | 4 | 4 | | | | | | 1 | 1 | | | | 1 | | 5 | [illegible] | [illegible] | [illegible] | [illegible] | 2 | 0 | | | | |
| Oil Film Instability in Bearings | | | | | | | 5 | 5 | | | | | | 3 | | 1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13 | 29% | 26% | 38% | 36% |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | | | | | 2 | 2 | 5 | 5 | | | | 1 | | | 2 | 2 | 3 | 2 | 5 | 5 | 11% | 10% | 15% | 14% |
| Instability in Steam Turb. Clearance Excitation | | | | | | | 2 | 2 | 4 | 4 | | | | | | | 2 | 2 | 3 | 2 | 5 | 0 | | | | |
| Misalignment in Shaft trains I - Instability | | | | | | | 3 | 3 | | | | | | 2 | | | 1 | 2 | 3 | 2 | 5 | 8 | 18% | 16% | 24% | 22% |

**36 %**

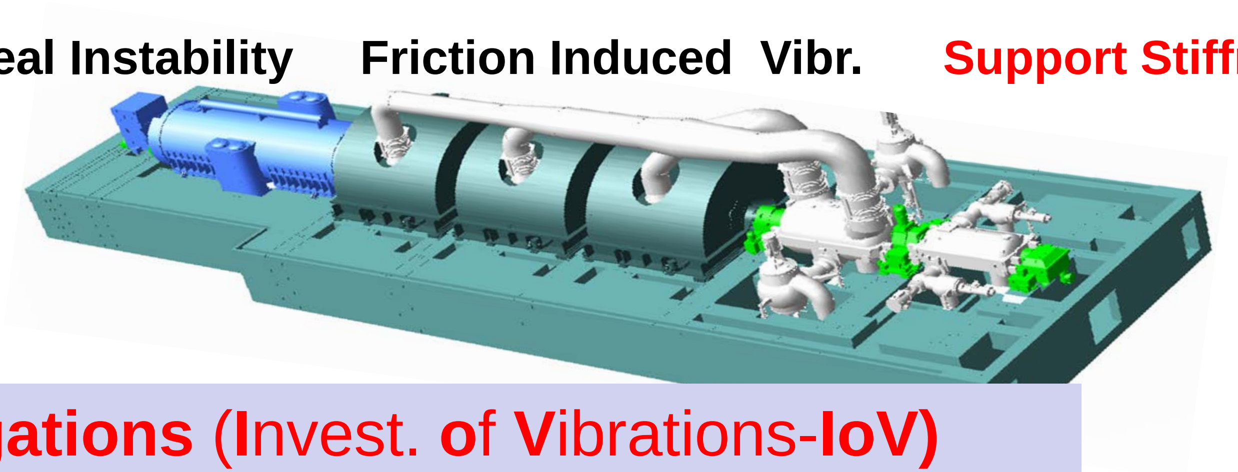
# Vibration Phenomena and Investigations

## Vibration Phenomena (Cause of Vibration-CoV)

Cyclic Vibrations
Unbalance Change
Misalignment

Change of Seawater-Temp.
Transverse Shaft Cracks
Coupling Errors

Oil Film&Seal Instability
Friction Induced Vibr.
Support Stiffness Change



## Investigations (Invest. of Vibrations-IoV)

Contribution of frequency components (1/2xN,1xN…..) in Spectra & Orbits,

Change of static shaft location in Bearings and Seals, Condenser pressure,

Decrease or Increase of Oil Film Temperature, Observations Control room?

# Vibration Phenomena and Investigations

INVESTIGATION 13: **Does the orbit at Bearing locations look like a orbit** with
IoV 13 the main frequency 1xN and higher Harmonics? Example: Cracked Shaft

INVESTIGATION 14: **Did the oil film temperature in the bearings increase?** Increase means
IoV 14 lower viscosity and higher Sommerfeld number. Higher eccentricity

INVESTIGATION 15: **Did the oil film temperature in the bearings decrease?** Decrease means
IoV 15 higher viscosity and lower Sommerfeld number. Lower eccentricity.

INVESTIGATION 16: **Did only one Bearing show not normal Vibration behavior, Alarm?**
IoV 16 There is probably an anomaly at this Bearing only (clearance, bolts?)

INVESTIGATION 17: **Has the static location of the shaft in Seal elements change?**
IoV 17 Danger of rubbing and cyclic vibrations!

INVESTIGATION 18: **Did condenser pressure and temperature change,** when the sea water
IoV 18 temperature has changed?

# Phenomena versus Investigations: Matrix M2

**18 Investigation**

**18 Vibration Phenomena**

| | IoV1 Remarkable Events before | IoV2 Observations from Control Room | IoV3 Have Spectra mainly 1X components? | IoV4 Have Spectra 1X and 2X components | IoV5 Have Spectra 1X and 1/2 X components | IoV6 Have Spectra 1X & nat. freq.? | IoV7 Have Spectra 1X & Higher Harmonics | IoV8 Static Brg. Loc.:higher ecc. | IoV9 Static Brg. Loc.: Lower ecc. | IoV10 Bearing Orbit with 1X | IoV11 Bearing Orbit with 1X &2X | IoV12 Bearing Orbit with 1X & 1/2X | IoV13 Bearing Orbit with 1X &Higher Harmonics | IoV14 Increase of oil temperature? | IoV15 Decrease of oil temperature? | IoV16 Only one Bearing not normal? | IoV17 Static shaft loc. of Seals change? | IoV18 Did condenser pressure change? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easiness | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 |
| Objectives, sum | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Objectives, % | | | | | | | | | | | | | | | | | | |
| Easiness weighted % | | | | | | | | | | | | | | | | | | |
| Vibration Phenomenon | | | | | | | | | | | | | | | | | | |
| Slow Change of Unbalance | | | 4 | | | | | 2 | 2 | 4 | | | | | | | 2 | 2 |
| Sudden Change of Mechanical Unbalance | | | 4 | | | | | | | 5 | | | | | | | 1 | 1 |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | | 5 | | | | | | | 5 | | | | | | | 3 | 1 |
| Change of Oil Film | | | 2 | 2 | | | | 3 | 3 | 2 | 2 | | | 4 | 4 | 1 | | |
| Friction induced Mechanical Bow | | | 4 | | | | | | | | | | | | | | | |
| Change of Sea Water Temp.& Cond. Deform. | | | 3 | | | | | | | | | | | 2 | 2 | | | |
| Change of Seawater Temp./ Thermal bow | | | 3 | | | | | | | | | | | | | | | 5 |
| Oil Film Instability in Bearings | | | | | | | | | | | | | | | | 2 | | |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | | | | | | | | | | | | | 1 | | 4 | |
| Instability in Steam Turb. Clearance Excitation | | | | | | | | | | | | | | | | | | |
| Misalignment in Shaft trains I - Instability | | | | | | | | | | | | | | 1 | 1 | | | |
| Misalignment in Shaft trains II - Change 1X vibr. | | | 4 | | | | | | | | | | | 1 | 1 | | | |
| Misalignment in Shaft trains III - Banana Orbit | | | | 4 | | | 3 | 3 | | | 4 | | 3 | 2 | | | | |
| Generator Rotor with Uneq. Moments of Inert. | | | | 4 | | | | | | | 4 | | | | | | | |
| Transverse Shaft cracks in Turbine trains | | | | 4 | | | 4 | | | | 4 | | 4 | | | | | |
| Radial or Angular Coupling Errors | | | 4 | | | | | | | 4 | | | | | | | | |
| Support Stiffness changes in Turbine trains | | | 1 | 1 | | | 3 | 2 | 2 | 1 | 1 | | 3 | 1 | 1 | 5 | | |

**Probability numbers**

**5 Highly probable**

**1 Not very probable**

**0 Not possible**

# Data Processing in Matrix M2 Excel Table (1)

## Data Processing in Matrix M2:

The Matrix M2 has two parts. The first part receives the results from Matrix M1and 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 Investigation methods to confirm the oil film Instability are:

- Investigate the frequency spectra
- Investigate the orbits
- Investigate the static bearing location

# Data Processing in Matrix M2 Excel Table (1)

| | Investigation objective | IoV1 Remarkable Events before | IoV2 Observations from Control Room | IoV3 Have Spectra mainly 1X components? | IoV4 Have Spectra 1X and 2X components | IoV5 Have Spectra 1X and 1/2 X components | IoV6 Have Spectra 1X & nat. freq.? | IoV7 Have Spectra 1X & Higher Harmonics | IoV8 Static Brg. Loc.:higher ecc. | IoV9 Static Brg. Loc.: Lower ecc. | IoV10 Bearing Orbit with 1X | IoV11 Bearing Orbit with 1X &2X | IoV12 Bearing Orbit with 1X & 1/2X | IoV13 Bearing Orbit with 1X &Higher Harmonics | IoV14 Increase of oil temperature? | IoV15 Decrease of oil temperature? | IoV16 Only one Bearing not normal? | IoV17 Static shaft loc. of Seals change? | IoV18 Did condenser pressure change? | Sum of probabilities in detection | Relative probabilities in detection | Commonness in detection | Severity in detection | Commonness & Severity weighted probability in detection |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easiness | | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | | | | | |
| Objectives, sum | | 0 | 0 | 4 | 2 | 10 | 3 | 1 | 7 | 13 | 0 | 2 | 10 | 1 | 6 | 7 | 6 | 2 | 0 | | | | | |
| Objectives, % | | | | 5 | 3 | 13 | 4 | 2 | 10 | 18 | | 3 | 13 | 2 | 8 | 9 | 7 | 3 | | | | | | |
| Easiness weighted % | | | | 6 | 3 | 14 | 5 | 2 | 10 | 19 | | 2 | 10 | 1 | 8 | 9 | 8 | 3 | | | | | | |
| **Vibration Phenomenon** | | | | | | | | | | | | | | | | | | | | | | | | |
| Slow Change of Unbalance | | | | 4 | | | | | 2 | 2 | 4 | | | | | | | 2 | 2 | 0 | | | | |
| Sudden Change of Mechanical Unbalance | | | | 4 | | | | | | | 5 | | | | | | | 1 | 1 | 0 | | | | |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | | | 5 | | | | | | | 5 | | | | | | | 3 | 1 | 0 | | | | |
| Change of Oil Film | | | | 2 | 2 | | | | 3 | 3 | 2 | 2 | | | 4 | 4 | 1 | | | 9 | 20% | 18% | 11% | 10% |
| Friction induced Mechanical Bow | | | | 4 | | | | | | | 4 | | | | | | | | | 0 | | | | |
| Change of Sea Water Temp.& Cond. Deform. | | | | 3 | | | | | 3 | 3 | 3 | | | | 2 | 2 | | | | 6 | 13% | 18% | 4% | 5% |
| Change of Seawater Temp./ Thermal bow | | | | 3 | | | | | | | 3 | | | | | | | | 5 | 0 | | | | |
| Oil Film Instability in Bearings | | | | | | 5 | | | 1 | 4 | | | 5 | | | | 2 | | | 13 | 29% | 26% | 38% | 36% |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | | | | | 5 | | | 1 | | | | | | 1 | | 4 | | 5 | 11% | 10% | 15% | 14% |
| Instability in Steam Turb. Clearance Excitation | | | | | | | 5 | | | | | | | | | | | | | 0 | | | | |
| Misalignment in Shaft trains I - Instability | | | | | | 4 | 1 | | 1 | 3 | | | 4 | | 1 | 1 | | | | 8 | 18% | 16% | 24% | 22% |
| Misalignment in Shaft trains II - Change 1X vibr. | | | | 4 | | | | 1 | 2 | 2 | 4 | | | 1 | 1 | 1 | | | | 0 | | | | |
| Misalignment in Shaft trains III - Banana Orbit | | | | | 4 | | | 3 | 3 | | | 4 | | 3 | 2 | | | | | 0 | | | | |
| Generator Rotor with Uneq. Moments of Inert. | | | | | 4 | | | | | | | 4 | | | | | | | | 0 | | | | |
| Transverse Shaft cracks in Turbine trains | | | | | 4 | | | 4 | | | | 4 | | 4 | | | | | | 0 | | | | |
| Radial or Angular Coupling Errors | | | | 4 | | | | | | | 4 | | | | | | | | | 0 | | | | |
| Support Stiffness changes in Turbine trains | | | | 1 | 1 | | | 3 | 2 | 2 | 1 | 1 | | 3 | 1 | 1 | 5 | | | 4 | 9% | 12% | 9% | 13% |
| Turbine train is running in a Resonance condition | | | | 4 | 1 | | 1 | 1 | | 1 | 4 | 1 | | 1 | 1 | 1 | 1 | | | 0 | | | | |

# Data Processing in Matrix M2 Excel Table (2)

## Data Processing in Matrix M2:

In the second part of the Data processing the user can now select the best suited Investigation method by setting a cross (x) in the yellow line. With the recommended Spectra and Orbit investigations the probability calculation with the M2 probabilities leads to a

relative probability of 56 % for the oil film instability

relative probability of 44 % for a Misalignment with unloaded Bearing and corresponding Instability

# Data Processing in Matrix M2 Excel Table (2)

| | Investigation findings | IoV1 Remarkable Events before | IoV2 Observations from Control Room | IoV3 Have Spectra mainly 1X components? | IoV4 Have Spectra 1X and 2X components | IoV5 Have Spectra 1X and 1/2 X components | IoV6 Have Spectra 1X & nat. freq.? | IoV7 Have Spectra 1X & Higher Harmonics | IoV8 Static Brg. Loc.:higher ecc. | IoV9 Static Brg. Loc.: Lower ecc. | IoV10 Bearing Orbit with 1X | IoV11 Bearing Orbit with 1X &2X | IoV12 Bearing Orbit with 1X & 1/2X | IoV13 Bearing Orbit with 1X &Higher Harmonics | IoV14 Increase of oil temperature? | IoV15 Decrease of oil temperature? | IoV16 Only one Bearing not normal? | IoV17 Static shaft loc. of Seals change? | IoV18 Did condenser pressure change? | 0 | Sum of probabilities, if no blanks | Additional requirements | Relative probabilities |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | x | | | | | | | x | | | | | | | | | | |
| Objectives | | | | | | | | | | | | | | | | | | | | | | | |
| Major objectives | | | | | | | | | | | | | | | | | | | | | | | |
| **Vibration Phenomenon** | 0 | | | | | | | | | | | | | | | | | | | | | | |
| Slow Change of Unbalance | | | | 4 | | | | | 2 | 2 | 4 | | | | | | | 2 | 2 | | 0 | 1 | |
| Sudden Change of Mechanical Unbalance | | | | 4 | | | | | | | 5 | | | | | | | 1 | 1 | | 0 | | |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | | | 5 | | | | | | | 5 | | | | | | | 3 | 1 | | 0 | | |
| Change of Oil Film Bearing Coefficients | | | | 2 | 2 | | | | 3 | 3 | 2 | 2 | | | 4 | 4 | 1 | | | | 0 | | |
| Friction induced Mechanical Bow | | | | 4 | | | | | | | 4 | | | | | | | | | | 0 | | |
| Change of Sea Water Temp.& Cond. Deform. | | | | 3 | | | | | 3 | 3 | 3 | | | | 2 | 2 | | | | | 0 | | |
| Change of Seawater Temp./ Thermal bow | | | | 3 | | | | | | | 3 | | | | | | | | 5 | | 0 | 1 | |
| Oil Film Instability in Bearings | | | | | | 5 | | | 1 | 4 | | | 5 | | | | 2 | | | | 10 | | 56% |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | | | | | 5 | | | 1 | | | | | | 1 | | 4 | | | 0 | | |
| Instability in Steam Turb. Clearance Excitation | | | | | | | 5 | | | | | | | | | | | | | | 0 | | |
| Misalignment in Shaft trains I - Instability | | | | | | 4 | 1 | | 1 | 3 | | | 4 | | 1 | 1 | | | | | 8 | | 44% |
| Misalignment in Shaft trains II - Change 1X vibr. | | | | 4 | | | | 1 | 2 | 2 | 4 | | | 1 | 1 | 1 | | | | | 0 | | |
| Misalignment in Shaft trains III - Banana Orbit | | | | | 4 | | | 3 | 3 | | | 4 | | 3 | 2 | | | | | | 0 | | |
| Generator Rotor with Uneq. Moments of Inert. | | | | | 4 | | | | | | | 4 | | | | | | | | | 0 | | |
| Transverse Shaft cracks in Turbine trains | | | | | 4 | | | 4 | | | | 4 | | 4 | | | | | | | 0 | | |
| Radial or Angular Coupling Errors | | | | 4 | | | | | | | 4 | | | | | | | | | | 0 | | |
| Support Stiffness changes in Turbine trains | | | | 1 | 1 | | | 3 | 2 | 2 | 1 | 1 | | 3 | 1 | 1 | 5 | | | | 0 | | |

**56 %**

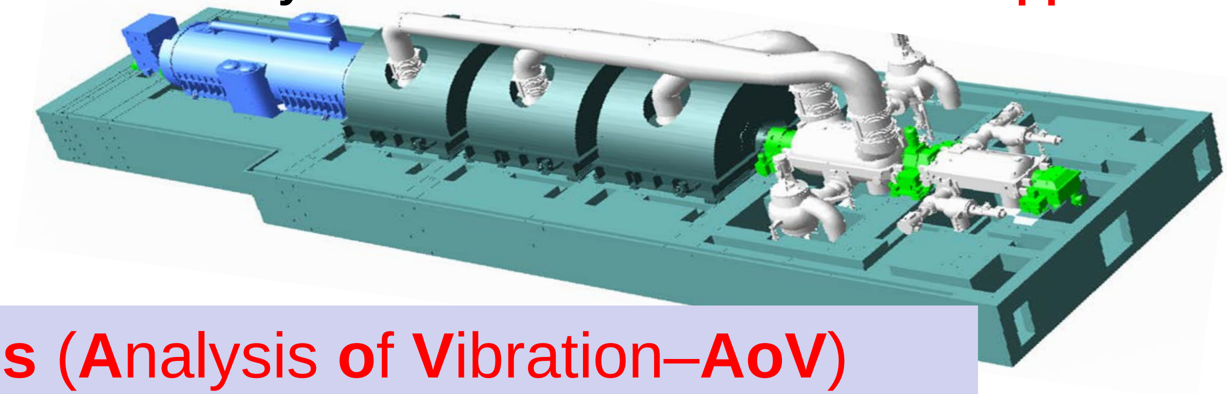
# Vibration Phenomena and Analysis

## Vibration Phenomena (Cause of Vibration-CoV)

Cyclic Vibrations     Unbalance Change     Misalignment

Change of Seawater-Temp.   Transverse Shaft Cracks   Coupling Errors

Oil Film&Seal Instability   Friction Induced Vibr.   Support Stiffness Change



## Analysis (Analysis of Vibration–AoV)

Finite Element Analysis (Eigenvalues, Unbalance Response, Cyclic Vibr.)

Stiffness and Damping Coeff, e.g. Seals & Bearings, Shaft Center line Anal.

Run up and down behavior, Influence of Power, Operation Modal Analysis

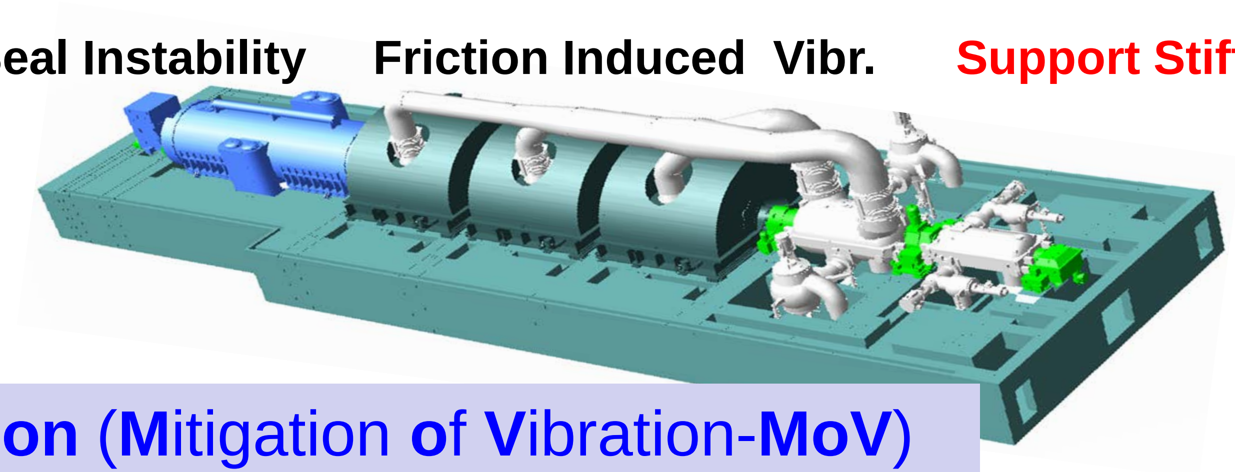
# Vibration Phenomena and Mitigation

## Vibration Phenomena (Cause of Vibration-CoV)

Cyclic Vibrations Unbalance Change **Misalignment**

Change of Seawater-Temp. **Transverse Shaft Cracks** **Coupling Errors**

Oil Film&Seal Instability Friction Induced Vibr. **Support Stiffness Change**



## Mitigation (Mitigation of Vibration-MoV)

**Balancing of Flexible Rotors, Counter balancing, Improve Damping**

**Avoid rubbing (Seals, Bearings), Change Seal and Bearing parameters,**

**Change vertical Brg. Location, Check support stiffness, Repair cracks**

# Vibration Phenomena and Mitigations

| | |
|---|---|
| MITIGATION 1:<br>MoV 1<br>.<br>. | **High 1xN-Lateral Vibrations due to Unbalance:** Balancing of Flexible Rotor by means of Influence Coefficients. Avoid Critical Speeds close to Operating speed. In case of Blade Loss: Shut down the machine. After repair work: Balancing. |
| MITIGATION 2:<br>MoV 2 | **High Lateral Vibrations due to Unbalance (1xN) or Instability** Improve Damping in Oil Film Bearings. Contact Manufacturer |
| MITIGATION 3:<br>MoV 3<br>.<br>. | **Cyclic or Spiral Vibrations:** Avoid rubbing in Seals, Bearings and Exciter Brushes. Adjust Rotor-Stator Distance. Reduce Friction Forces Improve Damping. Control pressure in Oil Seal Systems. Contact Manufacturer for Design Changes in critical elements. |
| MITIGATION 4:<br>MoV 4<br>. | **Friction induced Mechanical Bow:** Avoid un-symmetry in Circumference for friction, pressure and temperature. Control of winding temperature by Cooling water. |
| MITIGATION 5:<br>MoV 5 | **Change of Sea water temperature with thermal bow:** Protect rotor by means of a metal sheet against water. Reduce Active Power. |
| MITIGATION 6:<br>MoV 6 | **Oil Film Instability in Bearings:** Change Bearing Type or parameters (clearance, oil viscosity, width), Improve damping. (Manufacturer) |

# **Phenomena** versus **Mitigation: Matrix M4**

12 Mitigations

18 Vibration Phenomena

| Miti…thod | | MoV1: Balancing by Influence | MoV2: Improve Damping by Oil Film | MoV3: Avoid rubbing in seals, Exc. Brushes and Bearings | MoV4: Avoid Unsymmetry in Circumference for friction, pressure | MoV5: Protect Rotor against water | MoV6: Change Bearing Type or Bearing Parameters (Clearance, viscosity,..) | MoV7: Change Seal Parameters | MoV8: Change vertical Bearing positions to reduce Misalignment | MoV9: Slots in two pole generators | Mov10: If possible, repair the crack by | Mov11: Counter Balancing or insert of a | MoV12: Check clearances in Bearings | MoV13. No Mitigation needed | Relative probabilities based on investigat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 | 3 | 2 | 4 | 2 | 2 | 2 | 2 | 4 | 2 | 2 | 2 | 5 | |
| Recommended method, sum | | 0 | 5 | 0 | 0 | 0 | 5 | 0 | 2 | 0 | 0 | 0 | 3 | 0 | |
| % | | | 33 | | | | 33 | | 13 | | | | 20 | | |
| Easiness weighted % | | | 43 | | | | 29 | | 11 | | | | 17 | | |
| Vibration Phenomenon | 0 | | | | | | | | | | | | | | |
| Slow Change of Unbalance | | 5 | | | | 3 | | | | | | | | | |
| Sudden Change of Mechanical Unbalance | | 5 | 2 | | 3 | 3 | | | | | | | | | |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | | 3 | 5 | | | | | | | | | | | |
| Change of Oil Film Bearing Coefficients | | | | | | | 5 | | | | | | | | |
| Friction induced Mechanical Bow | | 2 | 3 | | 5 | | | | | | | | | | |
| …ange of Sea Water …np.& Cond. Deform. | | | | | | | | | | | | | | 5 | |
| …ange of Seawater Temp./ Thermal bow | | 3 | 3 | | | 5 | | | 2 | | | 3 | | | |
| Oil Film Instability in Bearings | | | 5 | | | | 5 | | 2 | | | | 3 | | 56% |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | 4 | 2 | | | | 5 | | | | | | | |
| Instability in Steam Turb. Clearance Excitation | | | 4 | 2 | | | 2 | 5 | | | | | | | |
| Misalignment in Shaft trains I - Instability | | | | | | | | | 5 | | | | | | 44% |
| Misalignment in Shaft… | | | | | | | | | | | | | | | |

x

**Probability numbers**

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

# Data Processing in Matrix M4 Excel Table

## Data Processing in Matrix M4:

In Matrix M4 the best suited Mitigation method is calculated on the base of the Matrix probabilities, the identified Vibration Phenomena (marked by a cross x) and the easiness for realization.

In case of the oil film instability it is recommended to improve the system damping and to change the bearing type or the bearing parameters.

# Research Program Vibrations
# ENERGIFORSK Vibration Group

TECHNISCHE UNIVERSITÄT DARMSTADT

## DIAM – A Matrix Tool for Turbine and Generator Vibrations

**D**etection, **I**nvestigation, **A**nalysis, **M**itigation

**Prof. Dr.-Ing. Rainer Nordmann**

MiM

# Data Processing in Matrix M1-Bayesian Method

**Comparison of formulas for probability of a Vibration Phenomena**

**Original Method** (used in project)

Sum of all Detections $Det_{i,j}$

$$\frac{Com_i \times (Det_{i,1} + Det_{i,2} + \ldots + Det_{i,j})}{\Sigma_i \{Com_i \times (Det_{i,1} + Det_{i,2} + \ldots + Det_{i,j})\}}$$

**Bayesian Method**

Product of all Detections $Det_{i,j}$

$$\frac{Com'_i \times (Det''_{i,1} \times Det''_{i,2} \times \ldots \times Det''_{i,j})}{\Sigma_i \{Com'_i \times (Det''_{i,1} \times Det''_{i,2} \times \ldots \times Det''_{i,j})\}}$$

# Data Processing in Matrix M1-Bayesian Method

**Original** | **Bayesian**

**Bayesian Updating**

| Vibration Phenomenon | Anomaly description | 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 | Sum of probabilities, if no blanks | Relative probabilities | Commonness | Severity | Commonness & Severity weighted probability | Product of Probabilities (1=20%, 2=40%, 3=60%, 4=80%, 5=100%) | rel. Probability Distribution of Failures (Commonness) | Cond. Prob |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sensor detection | | | | | | | | | | | | Temperature | | | Condition | | | | | | | | | | | | |
| | | | | | | | x | x | | | | | | x | | | | | | | | | | | | | | | |
| Slow Change of Unbalance | | 5 | 5 | | | 2 | | | | | | | | | 2 | 3 | 3 | 3 | 3 | 4 | 2 | 0 | | | | | 0 | 9,1% | 0,0% |
| Sudden Change of Mechanical Unbalance | | | | 5 | 5 | | | | | | | | | | | | 3 | 1 | 1 | 2 | 5 | 0 | | | | | 0 | 4,5% | 0,0% |
| Cyclic Vibrations. Mech. &Therm. Unbalance | | 3 | 3 | | | 5 | | | | | | | | | | | 3 | 2 | 2 | 2 | 2 | 0 | | | | | 0 | 4,5% | 0,0% |
| Change of Oil Film Bearing Coefficients | | 4 | 4 | | | 1 | 2 | 2 | 2 | 2 | | | | 5 | | 2 | 3 | 1 | 3 | 2 | 2 | 9 | 20% | 18% | 11% | 10% | 0,16 | 4,5% | 15,2% |
| Friction induced Mechanical Bow | | 2 | 2 | 3 | 3 | | | | | | | | | 1 | 5 | | 1 | 3 | 3 | 2 | 4 | 0 | | | | | 0 | 4,5% | 0,0% |
| Change of Sea Water Temp.& Cond. Deform. | | 3 | 3 | | | | 2 | 2 | 2 | 2 | 1 | 1 | | 2 | | 5 | 3 | 1 | 1 | 3 | 1 | 6 | 13% | 18% | 4% | 5% | 0,064 | 6,8% | 9,1% |
| Change of Seawater Temp./ Thermal bow | | 4 | 4 | | | | | | 1 | 1 | | | | 1 | | 5 | 3 | 1 | 1 | 2 | 2 | 0 | | | | | 0 | 4,5% | 0,0% |
| Oil Film Instability in Bearings | | | | | | | 5 | 5 | | | | | | 3 | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5 | 13 | 29% | 26% | 38% | 36% | 0,6 | 4,5% | 56,8% |
| Labyrinth Seal Instabiliy in HP or LP Turbines | | | | | | | 2 | 2 | 5 | 5 | | | | 1 | | | 2 | 2 | 3 | 2 | 5 | 5 | 11% | 10% | 15% | 14% | 0,032 | 4,5% | 3,0% |
| Instability in Steam Turb. Clearance Excitation | | | | | | | 2 | 2 | 4 | 4 | | | | | | | 2 | 2 | 3 | 2 | 5 | 0 | | | | | 0 | 4,5% | 0,0% |
| Misalignment in Shaft trains I - Instability | | | | | | | 3 | 3 | | | | | | 2 | | | 1 | 2 | 3 | 2 | 5 | 8 | 18% | 16% | 24% | 22% | 0,144 | 4,5% | 13,6% |

Vorlesungen Mechatronik im Wintersemester

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