RESEARCH PROGRAM VIBRATIONS
ENERGIFORSK VIBRATIONS GROUP

Vibrations caused by load-follow in Nuclear Power Plants

Impact on the dynamic behavior of significant systems, structures and components

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AGENDA

- Introduction: project description
- Vibration phenomena in NPP components and systems
- Impact of load-follow on process and operating parameters
- Vibrations in NPP components and systems due to load-follow
  - Main recirculation pumps
  - Piping system
- Experimental & numerical methods and evaluation criteria for vibration problems in NPPs due to load-follow
- Mitigation methods for vibration problems in NPPs
- Conclusion

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Introduction: project description

Objective of the project

- Nuclear Power Plants have been constructed as **base load plants** generating **electrical power** at **stable load**

- **Load-follow (part-load operation)** of **NPP** becomes essential due to significant increase of highly intermittent power sources, like solar, wind,…

- Risk of **vibrations** due to **load-follow** has to be minimized
  - **Understanding** of what type of **problem** may occur is essential

Introduction: project description

Scope of the project

- **Vibration** phenomena in NPP **components** and **systems**
- **Impact** of **load-follow** on **process** and **operating** parameters
- **Vibrations** in NPP components and systems at **part-load**
- Evaluation of **vibrations** in NPPs due to **load-follow**

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Vibration phenomena in NPP components and systems

Valves,

Heat Exchanger

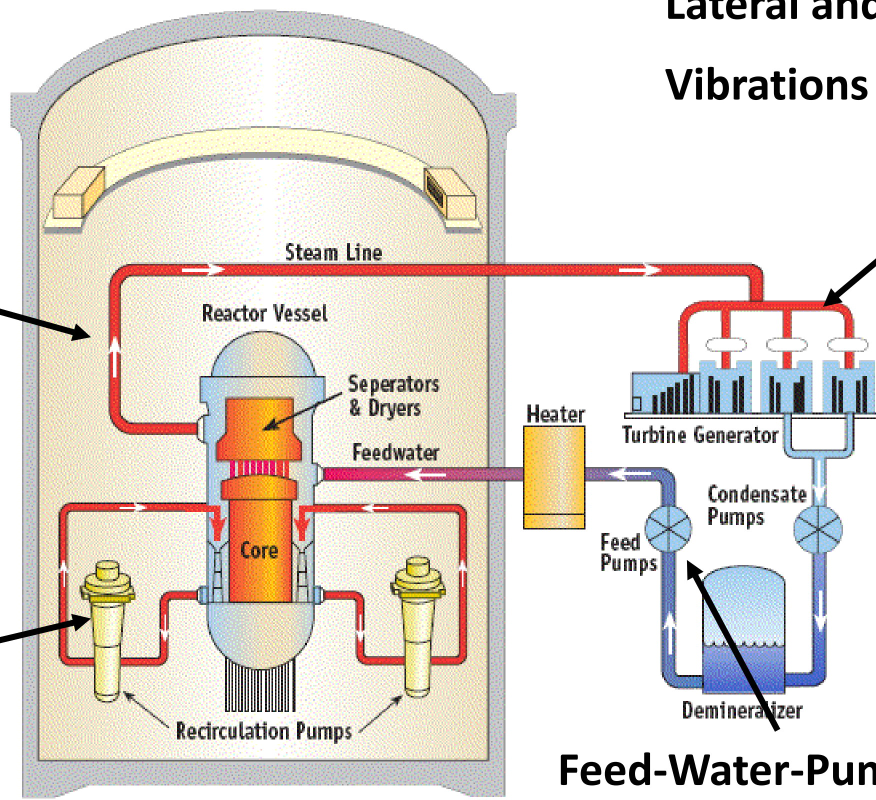
Piping System

Vibrations

Steam Turbine–Generator,

Lateral and Torsional

Vibrations of the Shaft



End-Winding

Vibrations

Main Recirculation

Pump Vibrations

Feed-Water-Pump

Vibrations

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Vibration phenomena in NPP components and systems

Vibrations depend on the Dynamics of the component and Excitation

Vibrations of the Power Plant Component = **Dynamics** of the Power Plant Component X **Excitation** of the Power Plant Component

Output	**Component Dynamics**	**Input**
Vibrations	▪ Natural frequencies ▪ Mode shapes ▪ Damping	▪ Fluid flow excitation ▪ Electrical excitation ▪ Mechanical excitation

Vibration phenomena in NPP components and systems

Impeller

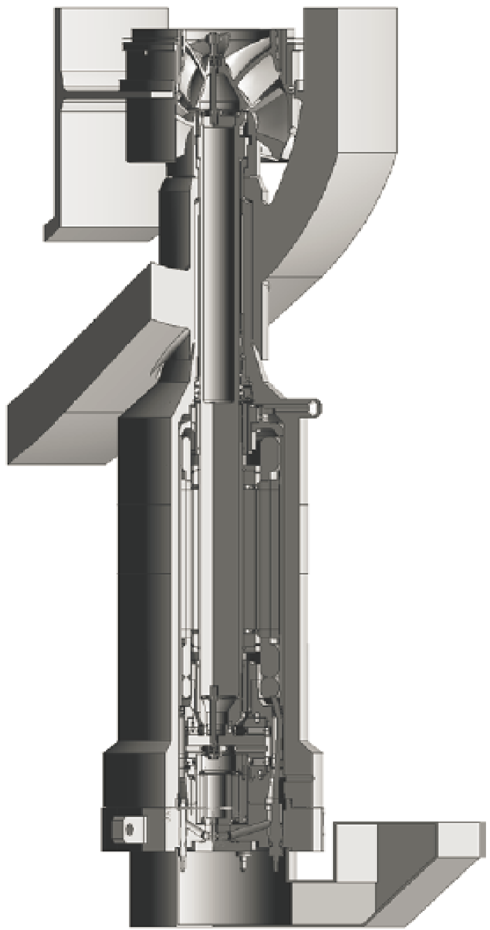
RPV

Pump shaft

with

fluid

bearings



Vibrations in the **main recirculation pumps** due to:

- **Unbalance**
- **Rotor-stator interaction**
- **Instability in the fluid bearings**
- **Misalignment**

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Vibration phenomena in NPP components and systems

Vibrations in the **piping system** due to:

- **Turbulent buffeting**
- **Flow pulsations**
- **Vortex shedding**
- **Acoustical resonance**
- **Fluid-elastic instability**

Connected pumps and fans

Heat exchanger

Dead ended side branches

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Impact of load-follow on process and operating parameters

Load-follow techniques

Thermal power of the reactor core can be changed by:

- A reduced **coolant flow** by main **recirculation** pumps
  - **Power** is **proportional** to the **coolant flow**
  - **Load-follow** between **60** and **100%** of rated power
- **Inserting** the **control rods**
  - Control rods influence the moderation ratio
  - Load-follow below 60% of rated power

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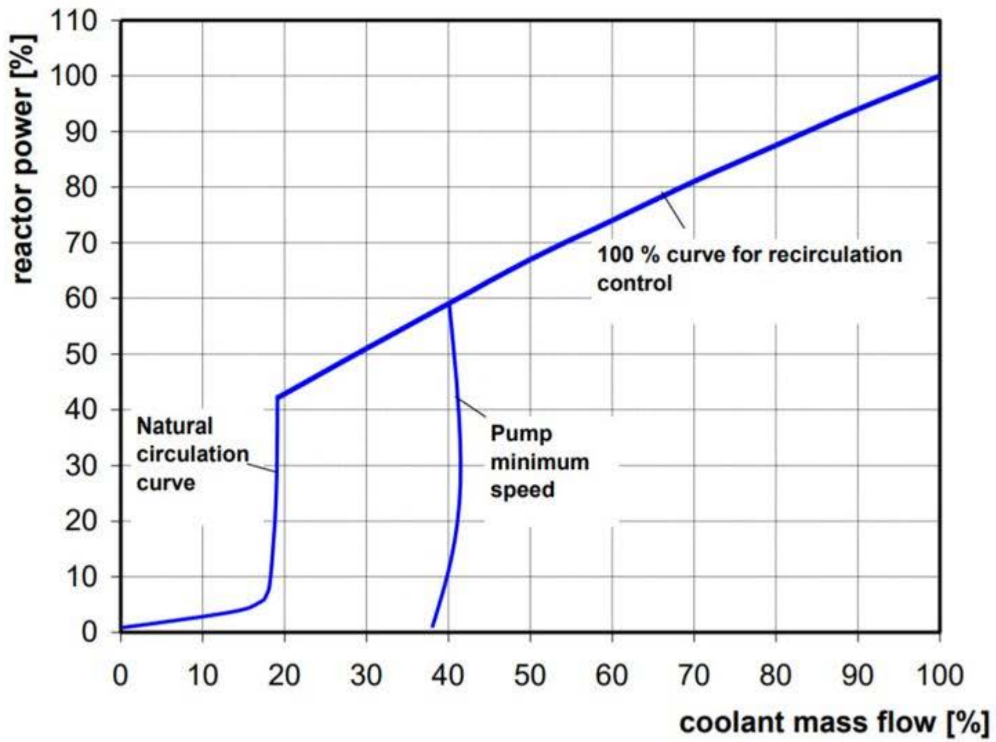
Impact of load-follow on process and operating parameters

Figure 3.14: Schematic characteristic curve for BWR power regulation with recirculation pumps



Source: Ludwig, *et al.*, 2010.

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Impact of load-follow on process and operating parameters

Due to **load-follow process** and **operating** parameters **change: Which** parameters **change**?

Power can be expressed by **potential** and **flow quantities**:

	Potential	Flow
Thermodynamics:	Enthalpy (Kj/kg)	Mass flow (kg/sec)
Mechanics:	Torque (Nm)	Angular velocity (1/sec)
Electrical domain:	Voltage (V)	Current (I)

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Impact of load-follow on process and operating parameters

- Due to the **synchronization** with the **power grid** the **angular velocity** and **voltage** of the **generator-turbine shaft** remain **constant** → for the **pumps** the angular **velocity** Ω **changes**
- **Mass flow** changes **proportional** to the **reduction** in **power** and the **enthalpy** remains **constant**

Other **parameters** may **change** as well, namely:

- **Pressure**
- **Temperature**
- **Moisture** content
- **Flow-rate** of pumps
- Parameters of the **generator** (i.e. **field current**)

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Vibration phenomena in NPP components and systems due to load-follow

Impeller

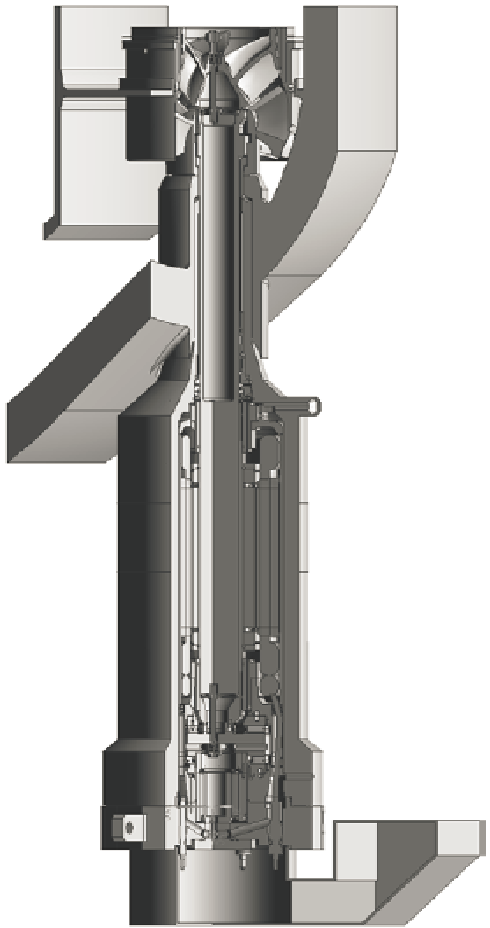
RPV

Pump shaft

with

fluid

bearings



At first **vibrations** in the main recirculation **pumps** at **nominal load** are **presented**, followed by **vibrations** in the main recirculation **pumps** at part-load (**load-follow**)

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Vibration phenomena in NPP components and systems due to load-follow

Vibrations due to load-follow in the main recirculation pumps

When the power of the reactor is controlled by means of the vertical main recirculation pumps the angular frequency Ω of the pumps will be changed. As a result of a varied Ω the mass flow $\dot{m}$ will be changed as well.

Besides this the pressure p and the static bearing forces are influenced.

- The excitation frequencies vary with the angular frequency Ω
- The natural frequencies and damping of the pump are influenced by the angular frequency
- Due to both effects the pump vibrations depend on load-follow

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Vibration phenomena in NPP components and systems due to load-follow

Vibrations depend on the Dynamics of the component and Excitation

Vibrations of the Power Plant Component at part-load = **Dynamics** of the Power Plant Component at part-load X **Excitation** of the Power Plant Component at part-load

Output	**Component Dynamics**	**Input**
Vibrations	▪ Natural frequencies ▪ Mode shapes ▪ Damping	▪ Fluid flow excitation ▪ Electrical excitation ▪ Mechanical excitation

Vibration phenomena in NPP components and systems due to load-follow

Vibrations in the main recirculation pumps at **nominal** load due **to unbalance excitation**:

Excitation (input): Unbalance **forces** ($\sim m \cdot e \cdot \Omega^2$), **unbalance** ($m \cdot e$), angular **frequency** $\boldsymbol{\Omega}$, mech. and hydr. unbalance

Component dynamics: Natural frequencies $\boldsymbol{\omega_j}$, damping values $\boldsymbol{\alpha_j}$ and mode shapes $\boldsymbol{\phi_j}$ depend on the system parameters $\boldsymbol{M}, \boldsymbol{K}, \boldsymbol{D}$ and $\boldsymbol{\Omega}$

Vibrations (output): The vibrations depend on the **excitation** and on the component dynamics. Critical operating states at: $\boldsymbol{\Omega} \sim \boldsymbol{\omega_j}$

Vibration phenomena in NPP components and systems due to load-follow

Change of Vibrations in the Recirculation pumps due to Unbalance Excitation in case of Load Follow	Angular Frequency of Pump Shaft Ω	Mass Flow of water m• through the pump	Pressure differences in the pump Δp	Static bearing forces in pumps F_{st}
Excitation Exc.Amplitude $\sim me\Omega^2$	Reduced due to Ω decrease	Possible change of e	No change	No change
Exc. Frequency Ω	Ω reduced	No change	No change	No change
Dynamic Behavior Matrices M, D, K	Change due to Ω change	Damping D may change	Change of Seals: D, K	Change of Brgs.: D, K
Natural Frequencies ω_j	Change due to Ω change	Possibly no change	Small influence	Change to Brgs. D, K
Damping α_j	Change due to Ω change	Influence on damping	Positive influence	Changedue to Brgs. D, K
Vibration Response Response Amplitude	Probably lower Ampl.	Influence on Amplitude	Small influence	Possible influence
Response Frequency	Ω reduced at part load	No influence	No influence	No influence

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Vibration phenomena in NPP components and systems due to load-follow

Vibrations in the main recirculation pumps at **nominal** load due to **rotor-fluid interaction**:

Excitation (input): Hydraulic **disturbance forces** depend on fluid flow profiles and z_i. Excitation **frequencies**: $\boldsymbol{n} \cdot \boldsymbol{z_i} \cdot \boldsymbol{\Omega}$ $(\mathrm{n} = 1,2, \dots)$, z_i:number of impeller blades

Component dynamics: Natural frequencies $\boldsymbol{\omega_j}$, damping values $\boldsymbol{\alpha_j}$ and mode shapes $\boldsymbol{\phi_j}$ depend on the system parameters $\boldsymbol{M}, \boldsymbol{K}, \boldsymbol{D}$ and $\boldsymbol{\Omega}$

Vibrations (output): The vibrations depend on the **rotor-fluid interaction forces** and on the component dynamics M, K, D and Ω. Critical operating states: $n \cdot z_i \cdot \Omega \sim \omega_j$

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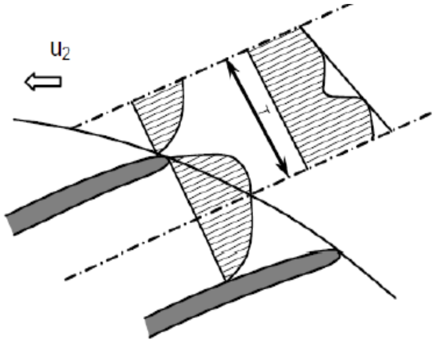
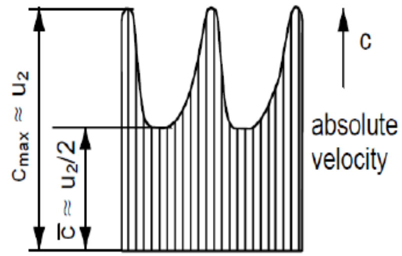
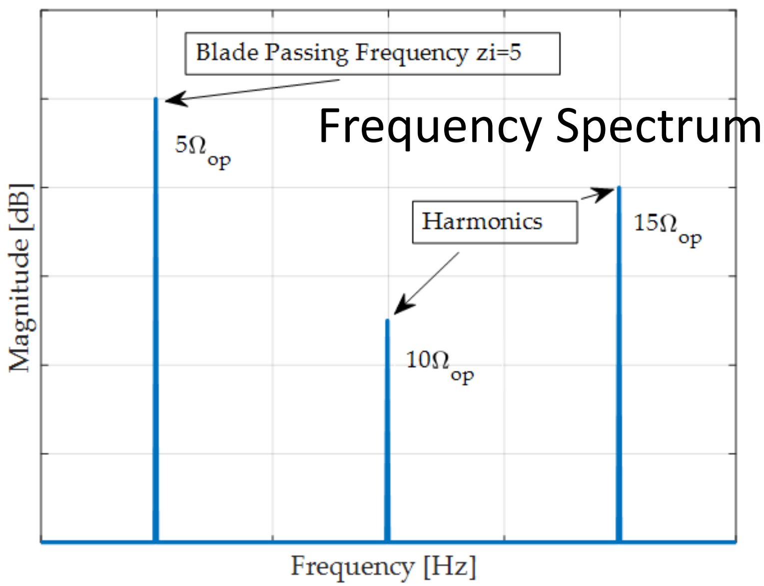
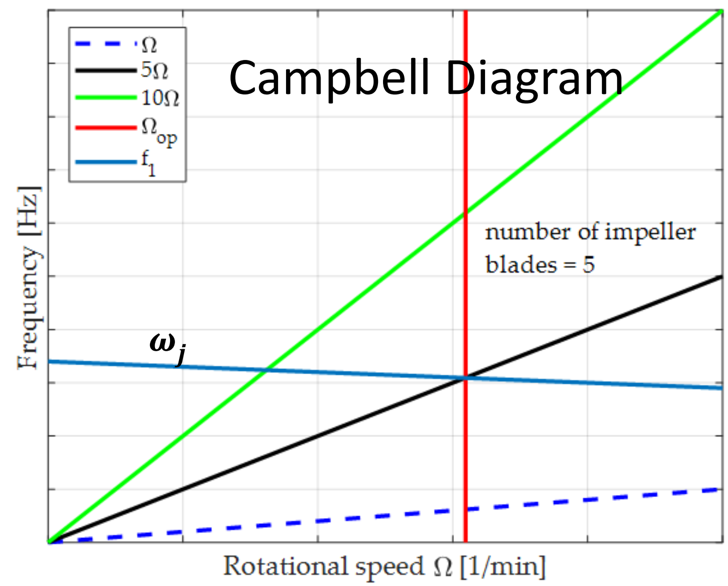
Vibration phenomena in NPP components and systems due to load-follow





Rotor-fluid-interaction at impeller outlet





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Vibration phenomena in NPP components and systems due to load-follow

Change of Vibrations in the Recirculation pumps due to Rotor-Structure Interaction in case of Load Follow	Angular Frequency of Pump Shaft Ω	Mass Flow of water m• through the pump	Pressure differences in the pump Δp	Static bearing forces in pumps F_{st}
Excitation Exc.Amplitude $\sim\Omega, m^{\bullet}, \Delta p$	Ampl. change due to Ω	Ampl. change due to m•, fluid profile	Ampl.change due to Δp, fluid profile	No change
Exc. Frequencies $n \cdot z_I \cdot \Omega$ z_I: number of blades	Change due Ω	No change	No change	No change
Dynamic Behavior Matrices M, D, K	Change due to Ω change	Damping D may change	Change of Seals: D, K	Change of Brgs.: D, K
Natural Frequencies ω_j	Change due to Ω change	Possibly no change	Small influence	Change of Brgs. D, K
Damping α_j	Change due to Ω change	Influence on damping	Positive influence	Change of Brgs. D, K
Vibration Response Response Amplitude	Influence on Amplitude	Influence on Amplitude	Influence on Amplitude	Possible influence
Response Frequencies $n \cdot z_I \cdot \Omega$	Ω is reduced at part load	No influence	No influence	No influence

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Vibration phenomena in NPP components and systems

Vibrations in the **piping system** strongly depend on the **flow conditions**:

- **Flow situation** in the **pipe** or **component** (cross-, axial, two-phase,…)
- **Fluid** flow **velocity**
- **Pressure** and **Temperature**
- **Geometry** of the **piping** system or **dead ended** side **branches**

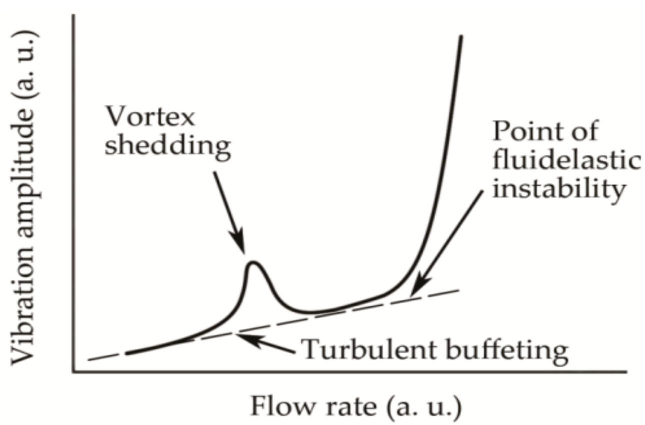
Vibration phenomena in NPP components and systems

Effect of changed process and operating parameters on flow-induced vibrations:

- The excitation frequency is proportional to the fluid flow velocity

- Excitation force is quadratic proportional into the fluid flow velocity and proportional to the density of the fluid

$$F_{fiv} = \rho \cdot v_{fluid}^2$$



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Vibration phenomena in NPP components and systems due to load-follow

Vibrations in the the **piping** system at **nominal** load due to **flow pulsations** caused by **pumps** or **fans**:

Excitation (input): **Pumps** or **fans** may cause flow pulsations (acoustic pulses) with frequency of $\Omega/60$ and higher harmonics

Component dynamics: Natural frequencies $\boldsymbol{\omega_j}$, damping values $\boldsymbol{\alpha_j}$ and mode shapes $\boldsymbol{\phi_j}$ depend on the system parameters $\boldsymbol{M}, \boldsymbol{K}, \boldsymbol{D}$

Vibrations (output): The vibrations depend on the **excitation frequencies** and on the component dynamics M, K, D and Ω. Critical operating states: $\boldsymbol{n \cdot \Omega/60 \sim \omega_j}$

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Vibration phenomena in NPP components and systems due to load-follow

Change of Vibrations in the piping system due to flow pulsations	Angular Frequency of Pump Shaft Ω	Temperature T of the fluid	Pressure p of the fluid
Excitation Exc.Amplitude	Reduced due to Ω decrease	Small influence	Small influence
Exc. Frequency	Ω reduced	No change	No change
Dynamic Behavior Matrices M, D, K	No influence	No significant influence	No significant influence
Natural Frequencies ω_j	No influence	No significant influence	No significant influence
Damping α_j	No influence	No influence	No influence
Vibration Response Response Amplitude	Probably lower Ampl.	Influence on Amplitude	Small influence
Response Frequency	Ω reduced at part load	No influence	No influence

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Vibration phenomena in NPP components and systems due to load-follow

Vibrations in the **piping** system at **nominal** load due to **vortex shedding** in **dead ended** side **branches**:

Excitation (input): In the **piping** system **vortices** are formed at the **upstreaming** edge of a **dead** ended side branch with **frequencies** of $f_{vortex} = n \cdot (S_r \cdot v_{fluid})/D_{de}$

Component dynamics: Natural frequencies $\boldsymbol{\omega_j}$, damping values $\boldsymbol{\alpha_j}$ and mode shapes $\boldsymbol{\phi_j}$ depend on the system parameters $\boldsymbol{M}, \boldsymbol{K}, \boldsymbol{D}$

Vibrations (output): The vibrations depend on the **excitation frequencies** and on the component dynamics M, K, D. Critical operating states: $f_{vortex} \sim f_j$

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Vibration phenomena in NPP components and systems due to load-follow

Change of Vibrations in the piping system due to vortex shedding	Mass flow $\dot{m}$	Temperature T of the fluid	Pressure p of the fluid
Excitation Exc.Amplitude	Small influence	Small influence	Small influence
Exc. Frequency	$\dot{m}$ reduced and therefore the excitation frequency	No change	No change
Dynamic Behavior Matrices M, D, K	No influence	No significant influence	No significant influence
Natural Frequencies ω_j	No influence	No significant influence	No significant influence
Damping α_j	No influence	No influence	No influence
Vibration Response Response Amplitude	Small influence on amplitude	No significant influence	Small influence
Response Frequency	$\dot{m}$ is reduced and therefore the response frequencies	No influence	No influence

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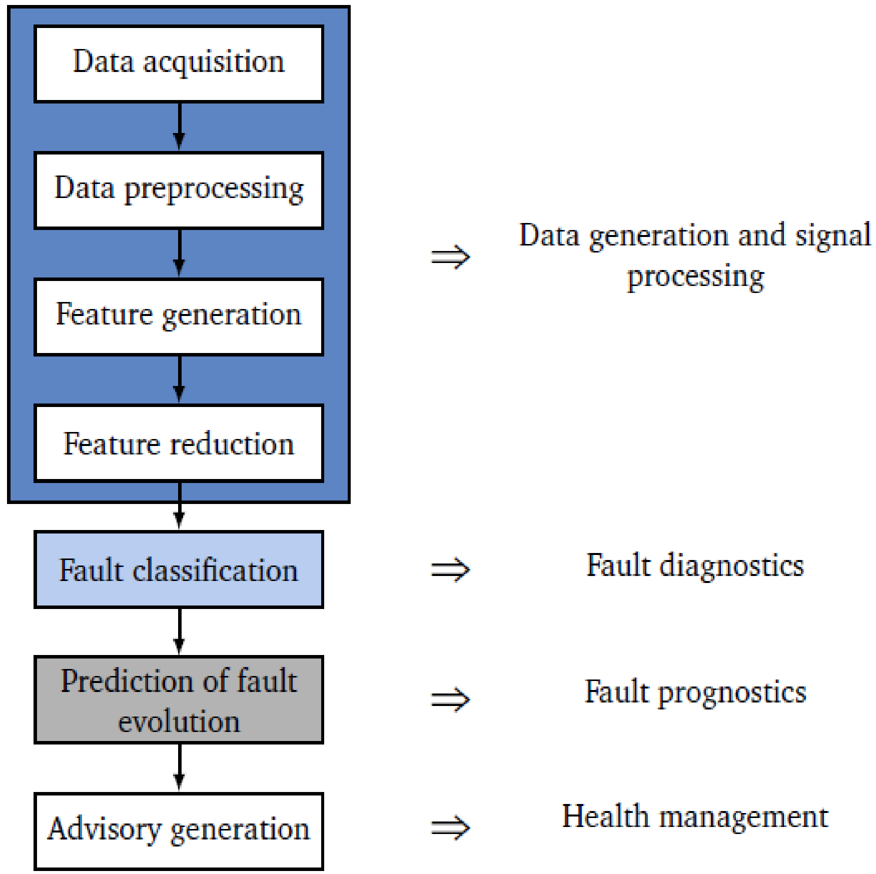
Experimental & numerical methods and evaluation criteria for vibration problems in NPPs due to load follow



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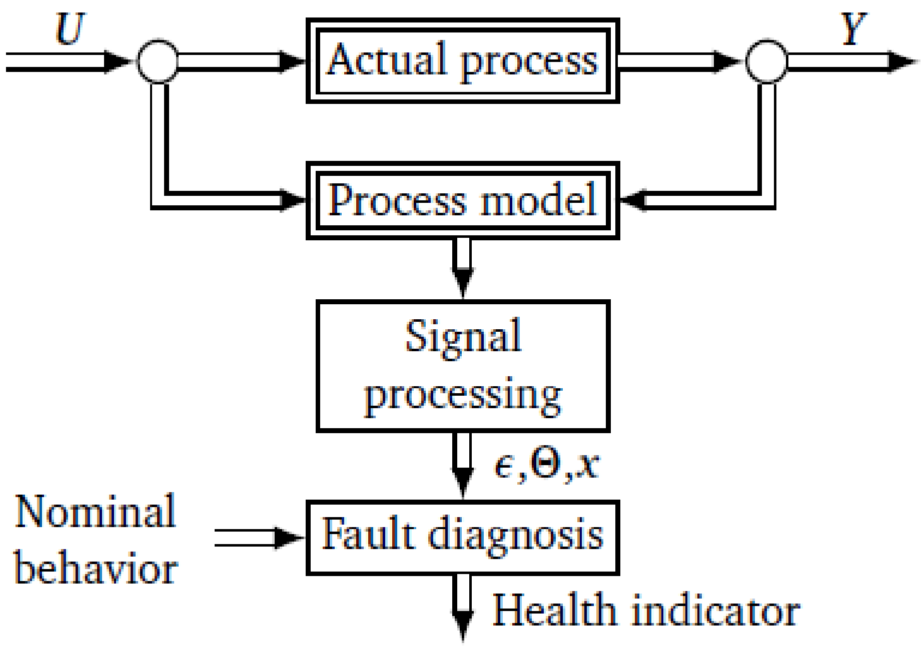
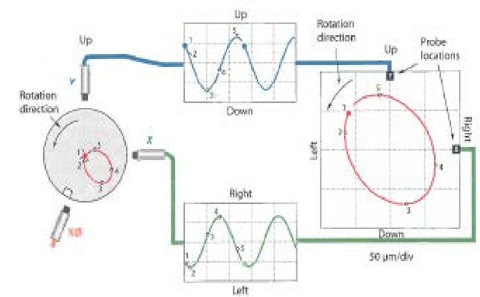


Measurement



By means of an **FEM analysis** the dynamic response can be predicted.

Fault diagnosis by **Identification methods**

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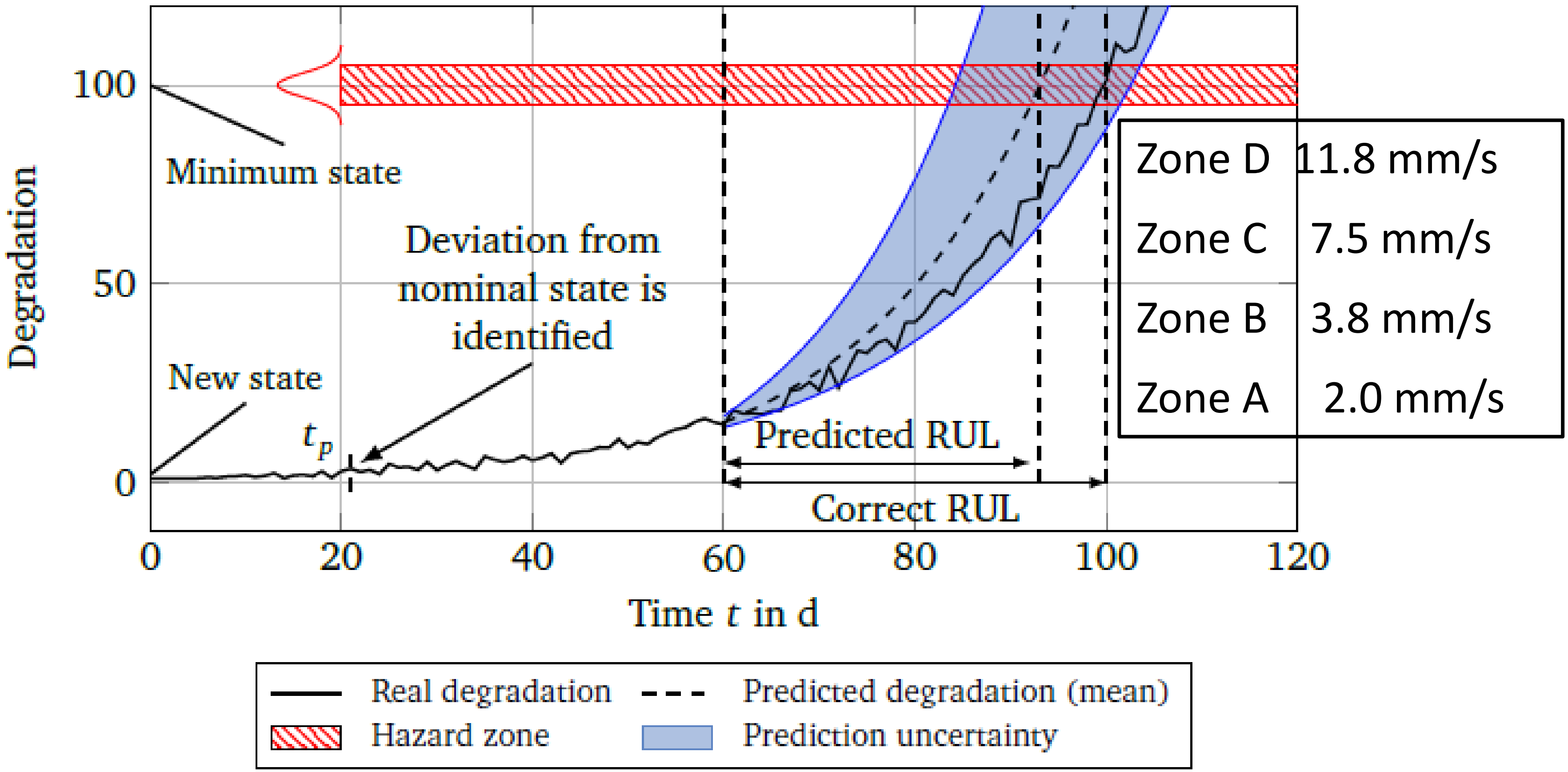
Experimental & numerical methods and evaluation criteria for vibration problems in NPPs due to load follow



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Mitigation methods for vibration problems in NPPs

- Vibrations can be mitigated by the following techniques:
  - Reduction of excitation forces
  - Tuning of the system behavior (i.e. adding mass, different materials, passive absorber, …)
  - Additional damping (i.e. shunt-damping,…)
  - Isolation of exciter or receiver (i.e. mounts,…)

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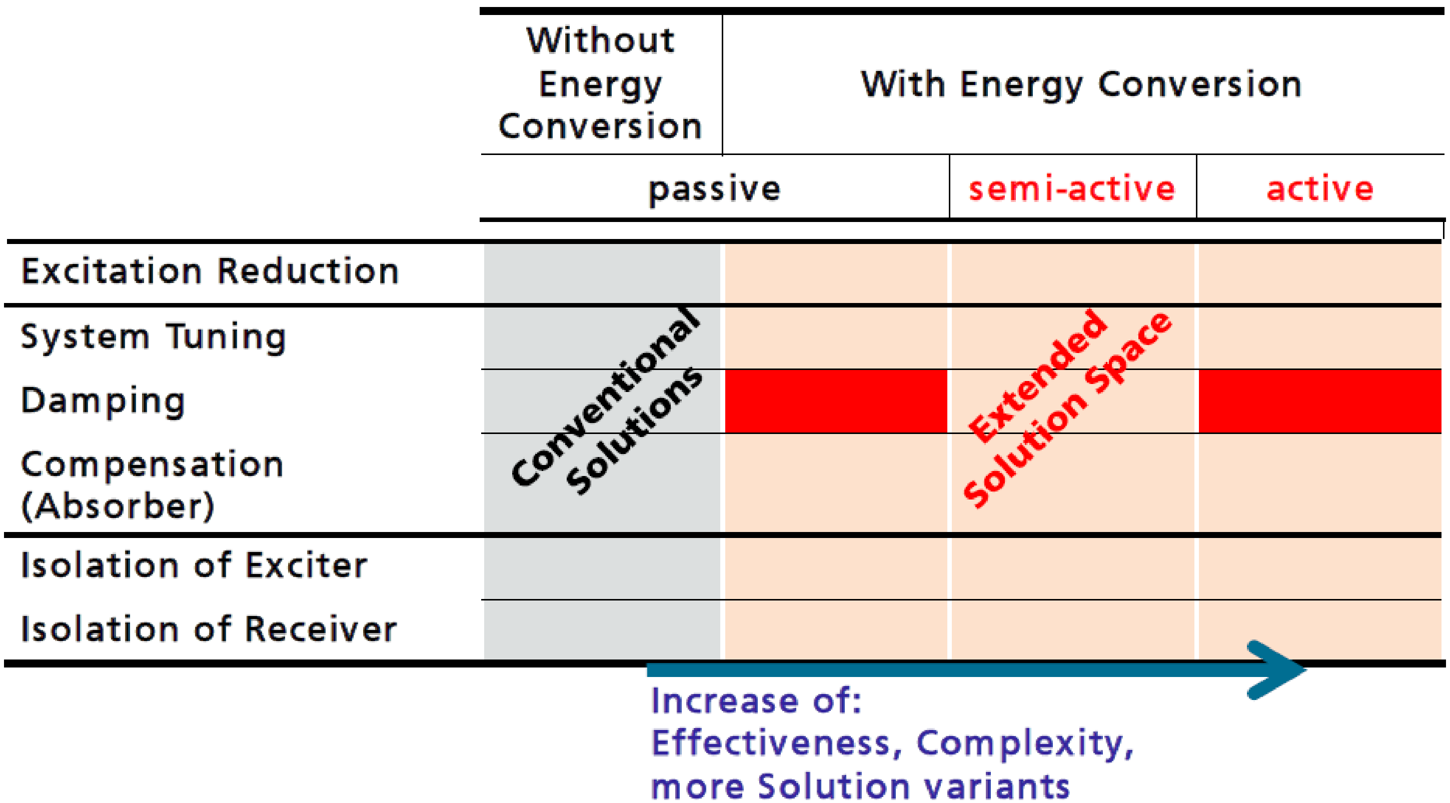
Mitigation methods for vibration problems in NPPs



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Concluison

- In this report only **qualitative statements** on vibrations due to load-follow were possible
- These statements are based on:
  - A **literature** study
  - **Expert talks** with **power** plant **engineers**
  - **Experience** from **manufacturers**

- Quantitative statements of the impact of load-follow can be gathered by means of **numerical simulations**, **field measurements** or **further expert talks**