Vorlesungen Mechatronik im Wintersemester

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

TECHNISCHE UNIVERSITÄT DARMSTADT

Vibrations of Turbines and Generators in Power Plants

Lecture I Introduction and Vibration Phenomena in Turbogenerators

Rainer Nordmann

Technische Universität Darmstadt and Fraunhofer Institute LBF

Introduction and Vibration Phenomena in Turbogenerators

- Mechanical and Electrical Components of Turbogenerators
- Lateral and Torsional Vibration Phenomena in Turbogenerators
- Lateral Vibration Phenomena demonstrated by Gustav de Laval
- Laval Shaft: Modelling and Equations of (Lateral) Motion
- Laval Shaft: Natural Frequency, Unbalance Response, Resonance
- Influence of Stiffness and Damping Characteristics in Bearings
- From Simple Rotor Systems to Large Turbogenerators

Mechanical and Electrical Components of Turbogenerators

Steam Turbines, Generator and Pipe System in the Plant

Lateral and Torsional Vibration Phenomena in Turbogenerators

Mechanics and other different Disciplines of Physics

Disciplines : Thermodynamics **Mechanics** Electrodynamics

Stresses
Strength of material

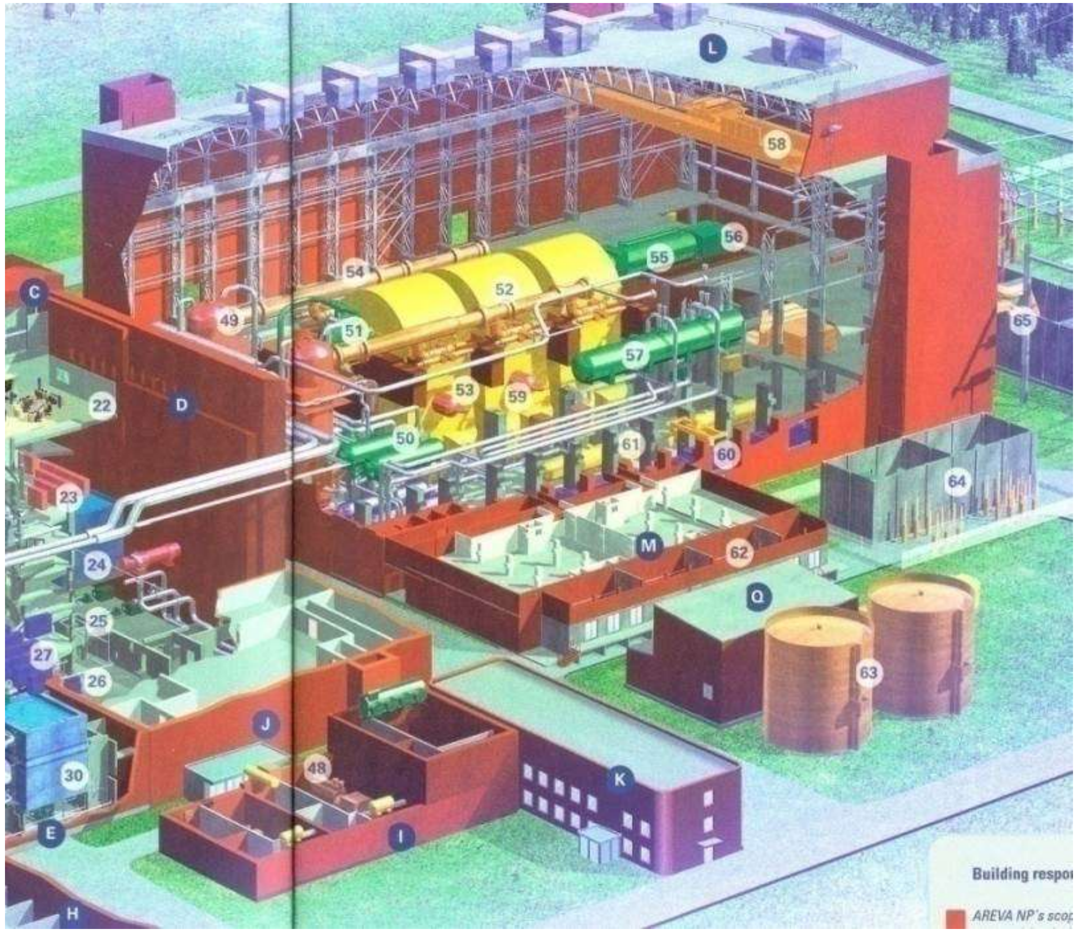
Lateral and Torsional Rotordynamics

Critical speeds
Unbalance Response
Air Gap Torques

Stability

Mechanical and Electrical Components of Turbogenerators

Machine Building with Steam Turbines, Generator and Pipes (OL3)



Power: 1600 MW
Speed: 1500 1/min (25 Hz)

Rotating Components

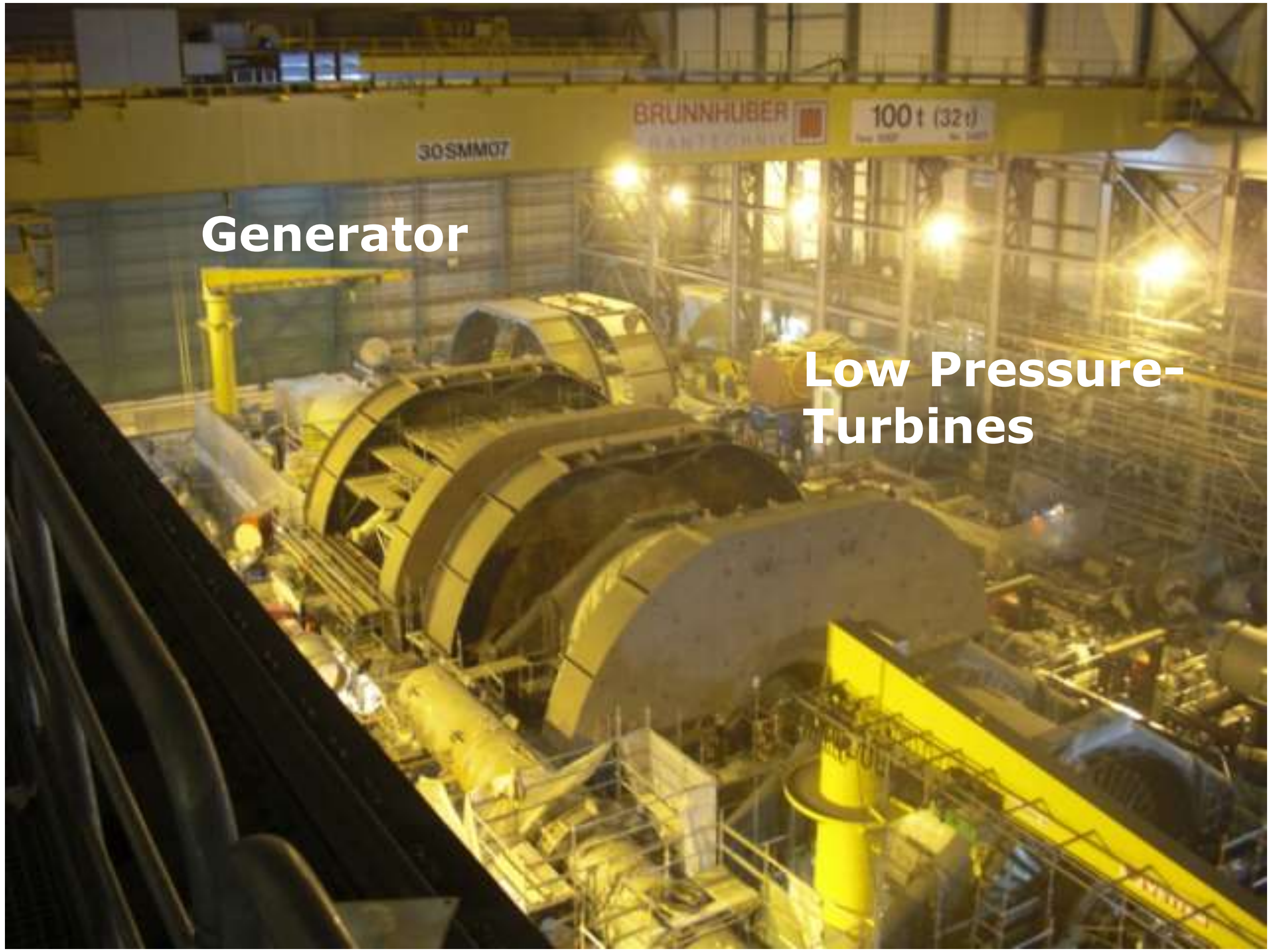
- 1 High Pressure Turbine
- 3 Low Pressure Turbines
- 1 Generator

running in Oilfilm-Bearings

Length of Machine: 68 m

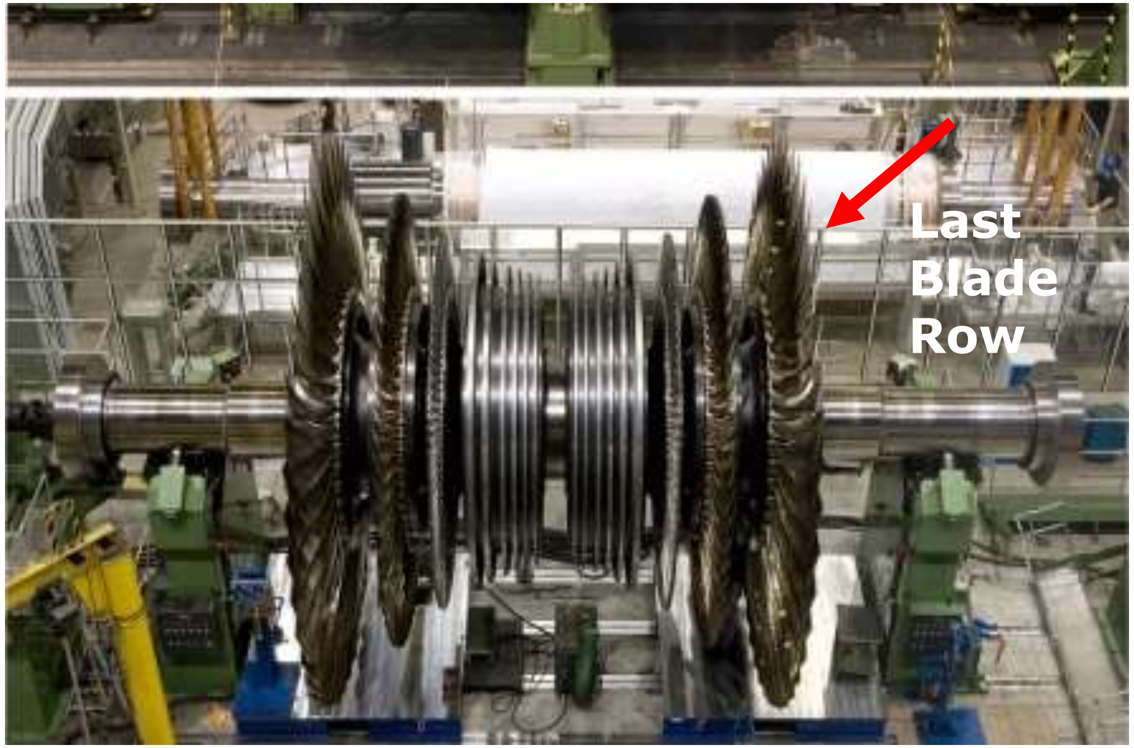
Mechanical and Electrical Components of Turbogenerators

Mounting of Steam Turbines and Generator in Machine Building (OL3)



Mechanical and Electrical Components of Turbogenerators

Low Pressure Turbine Shaft with Blades



Weight 320 t

Length: 12,5 m

Diameter of Last Blade Row: 6,7 m

Blade length:up to 1,8 m

Blade weight: up to 230 kg

Bearing diameter: 850 mm

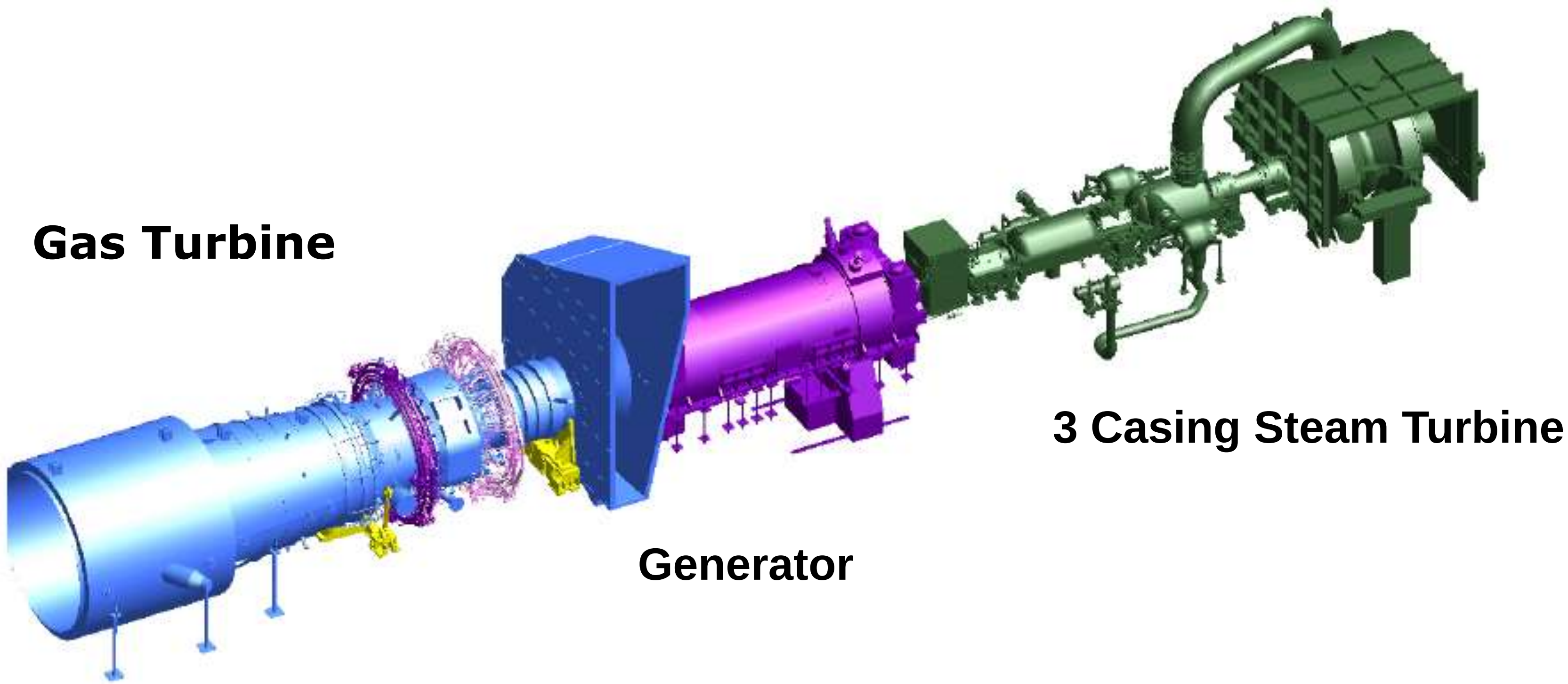
Mechanical and Electrical Components of Turbogenerators

Conventional Steam Turbine Shaft Train with Oil Film Bearings

Power: 1000 MW
Shaft Length: 55,8 m
Shaft Weight: 426 to
Bearing Diameter: 600mm

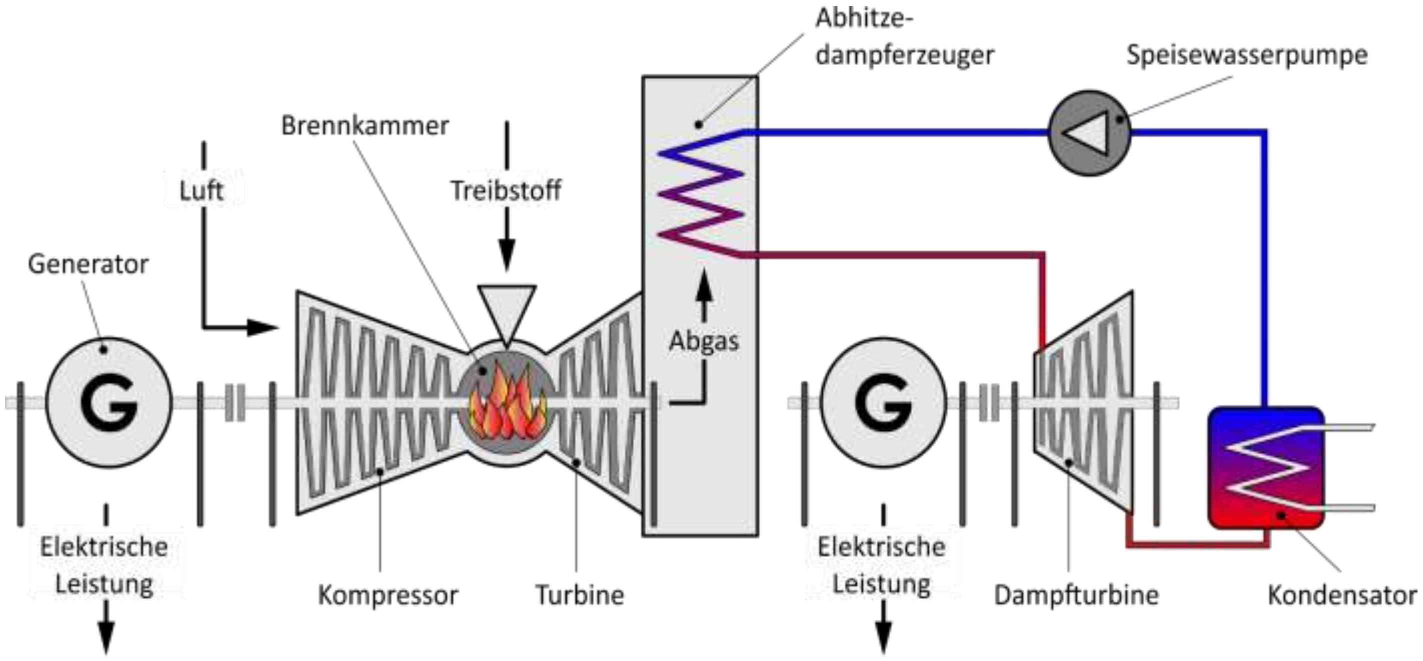
Mechanical and Electrical Components of Turbogenerators

Combined Cycle Single Shaft Train with Steam and Gas Turbines



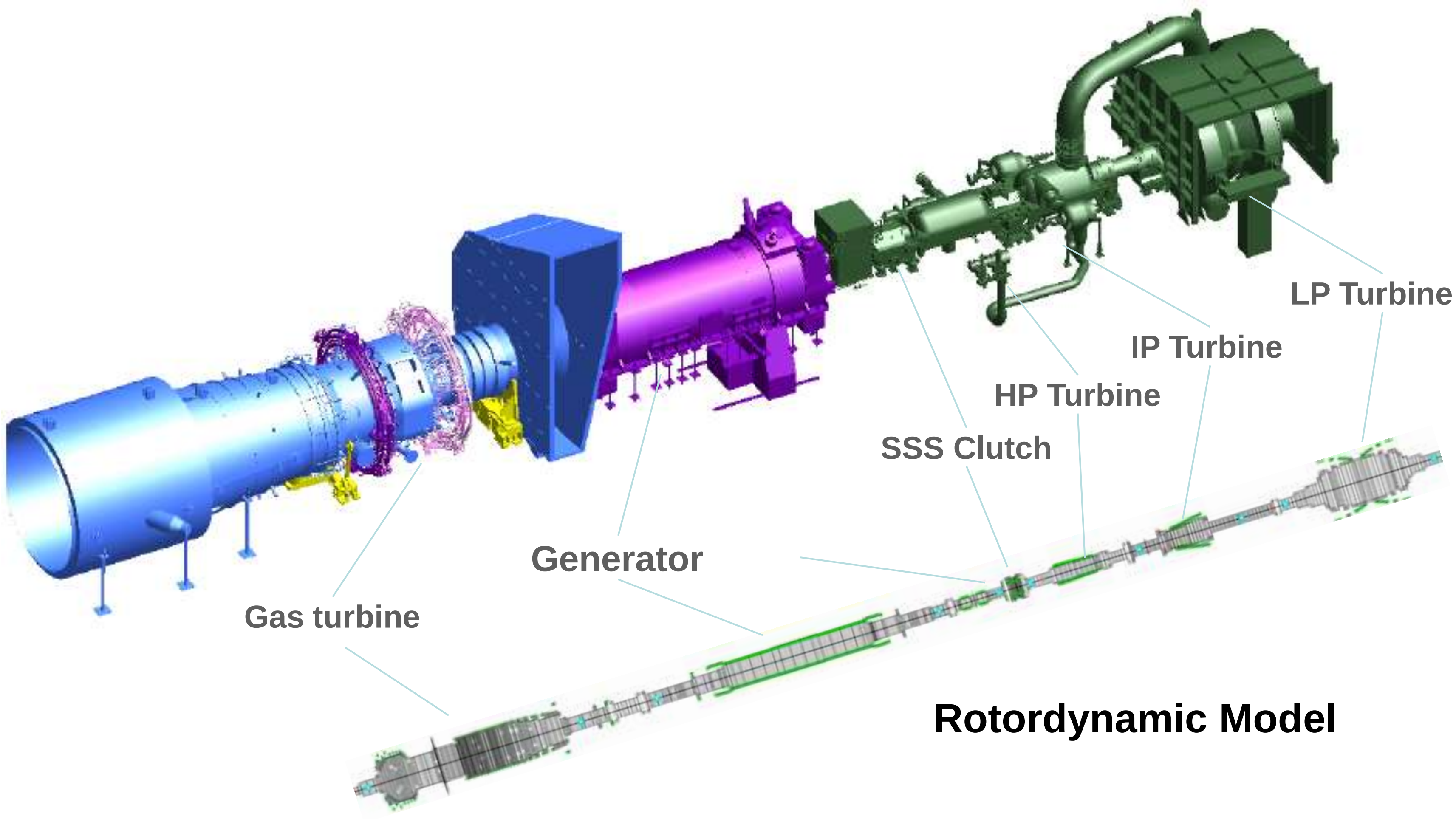
Mechanical and Electrical Components of Turbogenerators

Combined Cycle Single Shaft Train with Steam and Gas Turbines



Mechanical and Electrical Components of Turbogenerators

Combined Cycle Single Shaft Train with Steam and Gas Turbines



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Lateral and Torsional Vibration Phenomena in Turbogenerators

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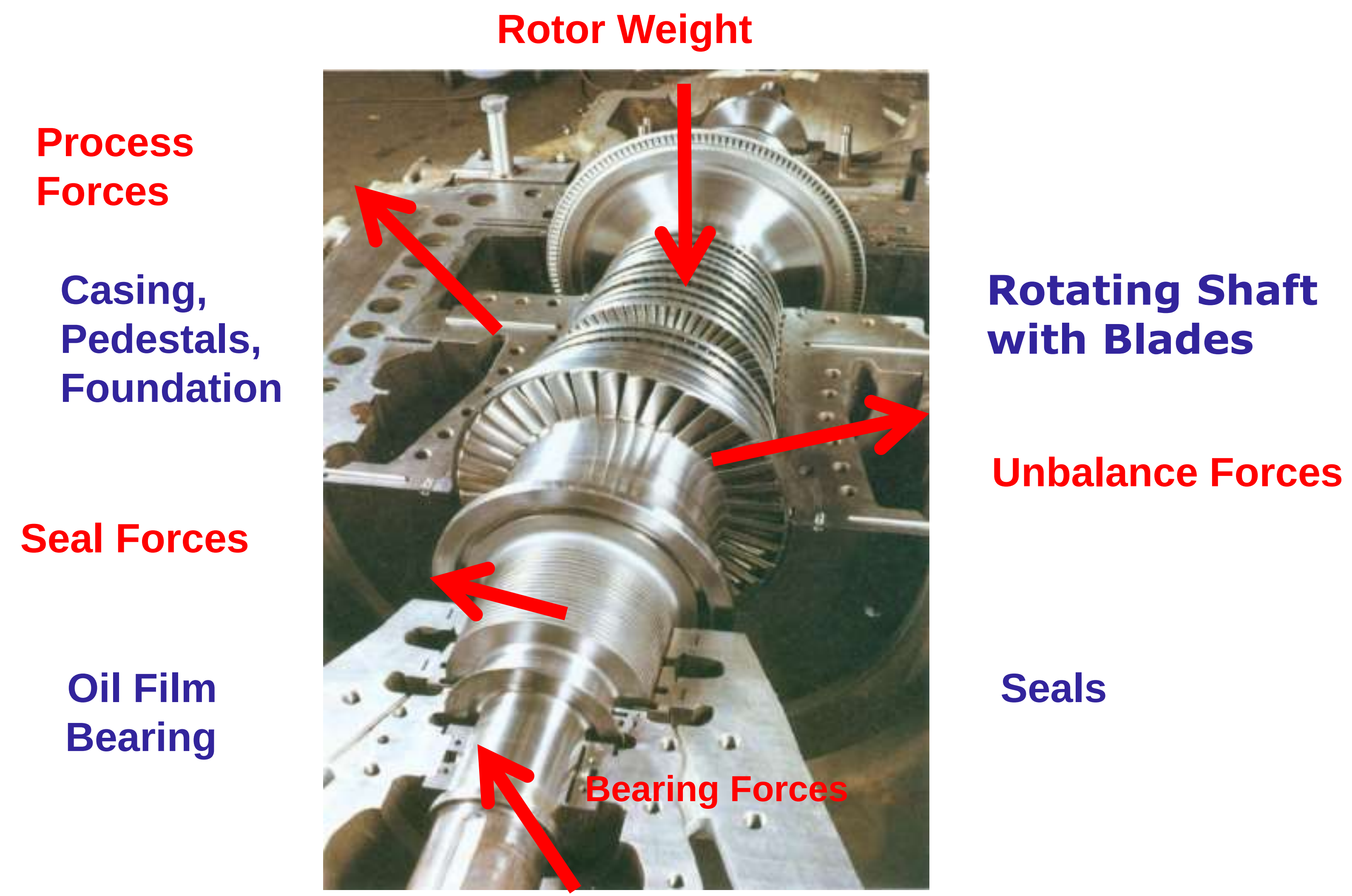
Lateral and Torsional Vibration Phenomena in Turbogenerators

Static and Dynamic Forces for Lateral Vibrations of Turbines



Lateral and Torsional Vibration Phenomena in Turbogenerators

Topics for the Investigation of Vibrations

- **How is the influence of time dependent Forces and Moments on the dynamic behavior of a Machine?**
- **Which Motions of Vibration and which internal Stresses act on the rotating and on the non-rotating Machine Parts?**
- **Are Critical Conditions (Resonances, Instabilities) possible?**
- **Can Vibrations destroy Machine Parts?**
  Rubbing, Blade Loss, Shaft Cracks, Bearing Failures, large Deformations,…
- **Which Interactions have to be considered?**
  Fluid Structure Interaction, Rotor Structure Interaction, Rotor Blade Interaction, Electromechanical Interaction

Lateral and Torsional Vibration Phenomena in Turbogenerators

Topics for the Investigation of Vibrations

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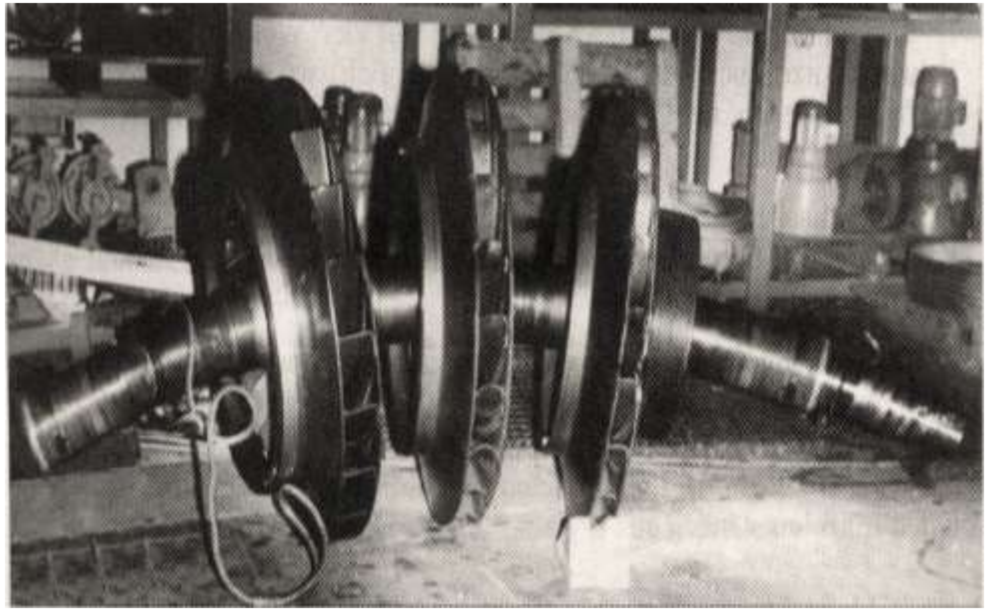


Lateral and Torsional Vibration Phenomena in Turbogenerators

Lateral and Torsional Vibrations of Shaft Trains

Shaft Train with Oil Film Bearings

Lateral

Torsional

Coupling of Lateral and Torsional Vibrations usually negligible

Which Phenomena are of Practical Relevance?

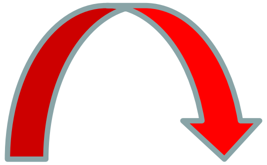
Lateral Vibrations: **Lateral Vibrations perpendicular to the Shaft axis with Bending along the Shaft line. Physical Effects: Inertia (masses), Siffness and Damping of System Components (Shaft, Bearings).**

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

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

Which Phenomena are of Practical Relevance?

Torsional Vibrations: Torsional Vibrations around the Shaft axis with torsional deformations along the Shaft line, Physical Effects: Moments of Inertia, Torsional Stiffness and Damping of the System components



Dynamic Characteristics: Natural Frequencies, Natural Modes, Modal Damping, Amplitudes and Phase angles of the Vibration Response due to Excitations.

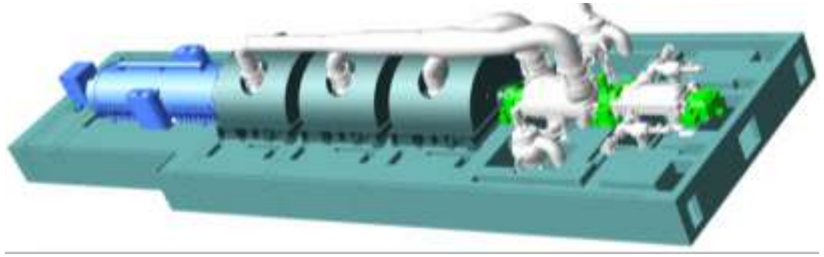
Excitation: Air Gap Torques in Electrical Machines due to Electromagnetic Coupling in the Generator and the Grid.

Lateral and Torsional Vibration Phenomena in Turbogenerators

Different Interactions have an Influence on the Vibrations

Rotor-Fluid Interaction: Oil Film Bearings, Seals

Rotor-Blade Interactions



Rotor-Structure Interaction: Casing, Foundation

Elektromechanical Interaction: Generator,Grid

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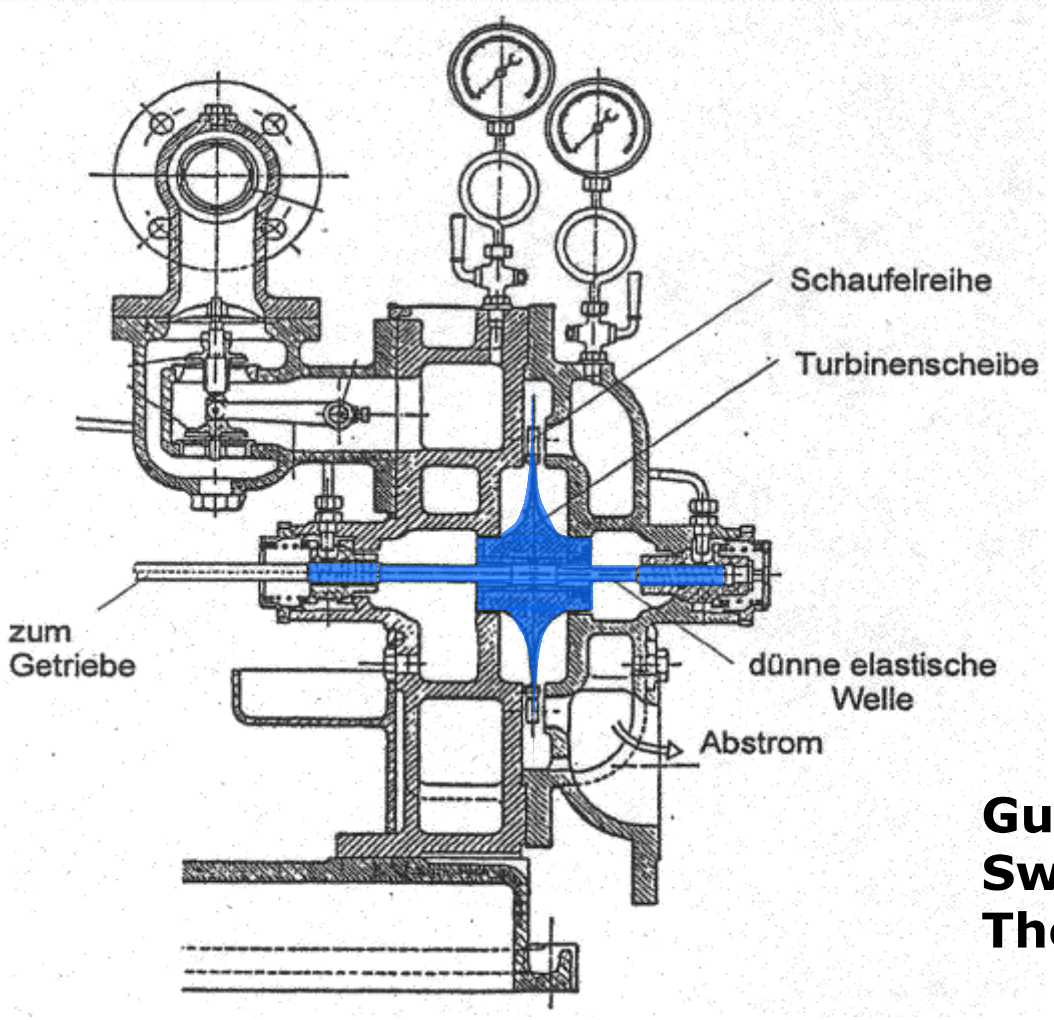
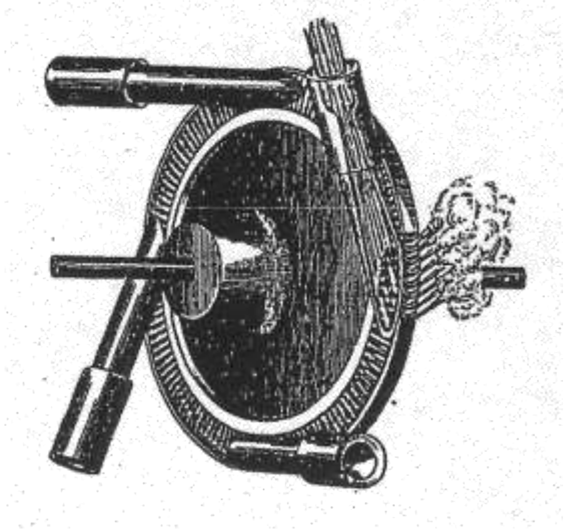
Lateral Vibration Phenomena demonstrated by Gustav de Laval

Experimental Investigations with a simple Steam Turbine



Laval - Laufrad

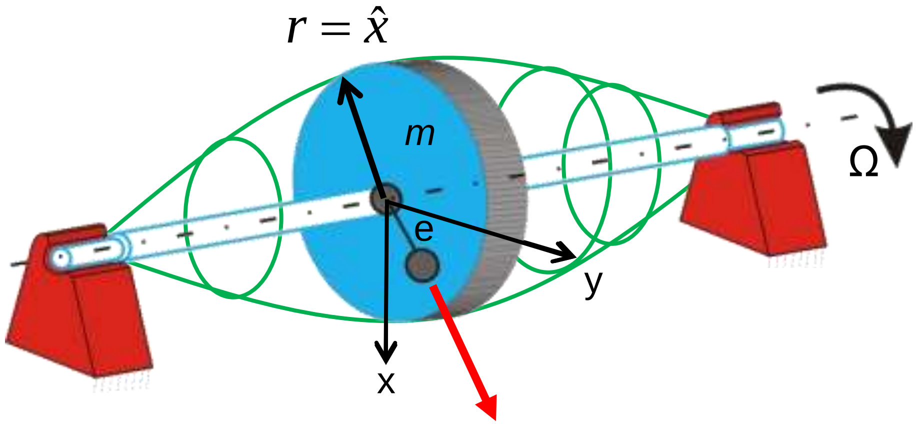


Gustav de Laval (1845 – 1913)
Swedish Engineer,
Theory by Föppl 1895

Lateral Vibration Phenomena demonstrated by Gustav de Laval

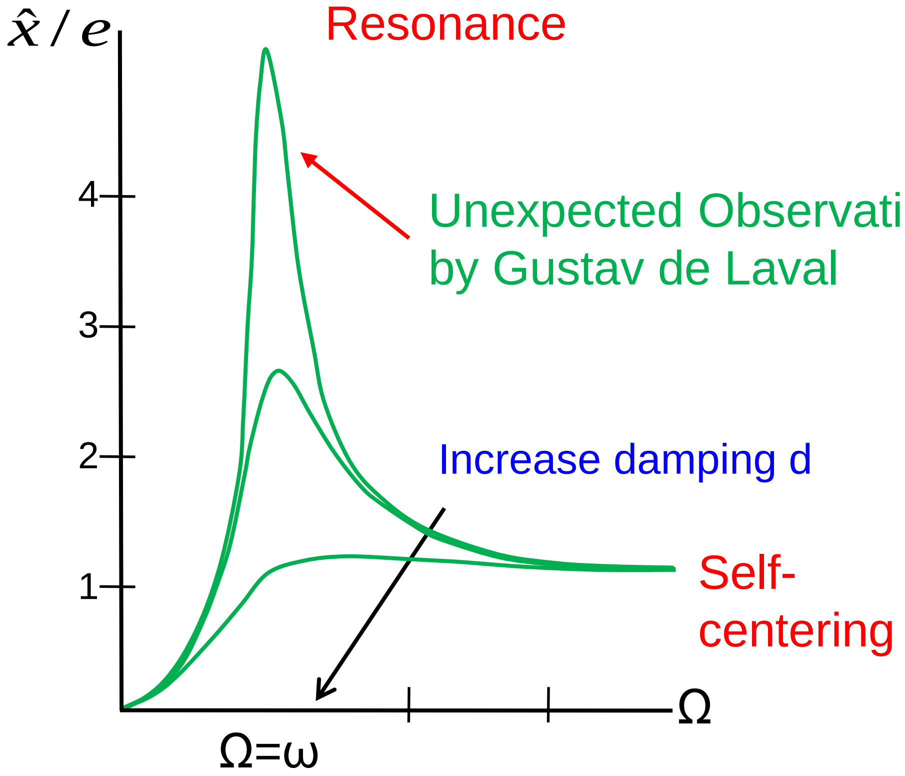
Experimental Investigations with a simple Steam Turbine

Shaft vibrations with circular orbit,



Unbalance Force: $me\,\Omega^2$

Amplitude $\hat{x}$ of unbalance vibration



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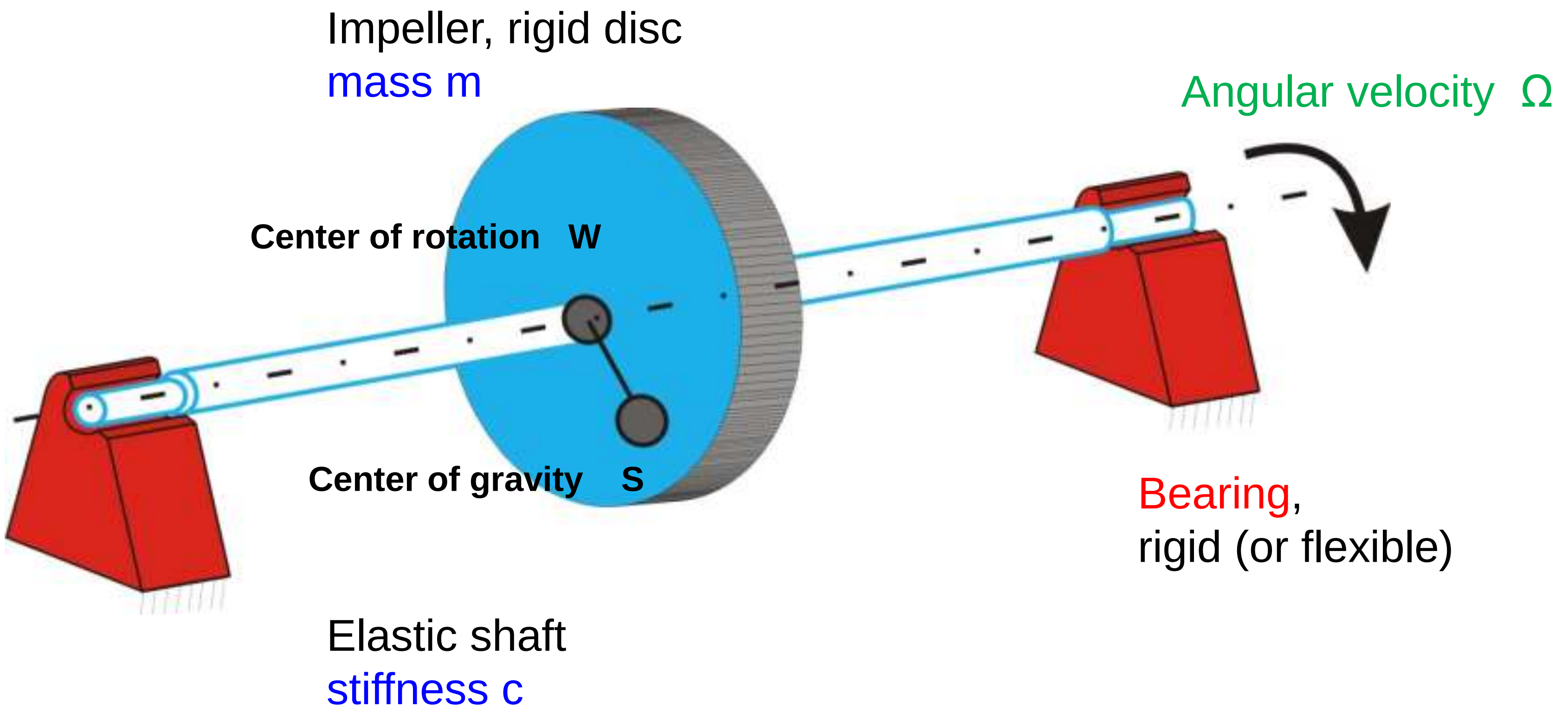
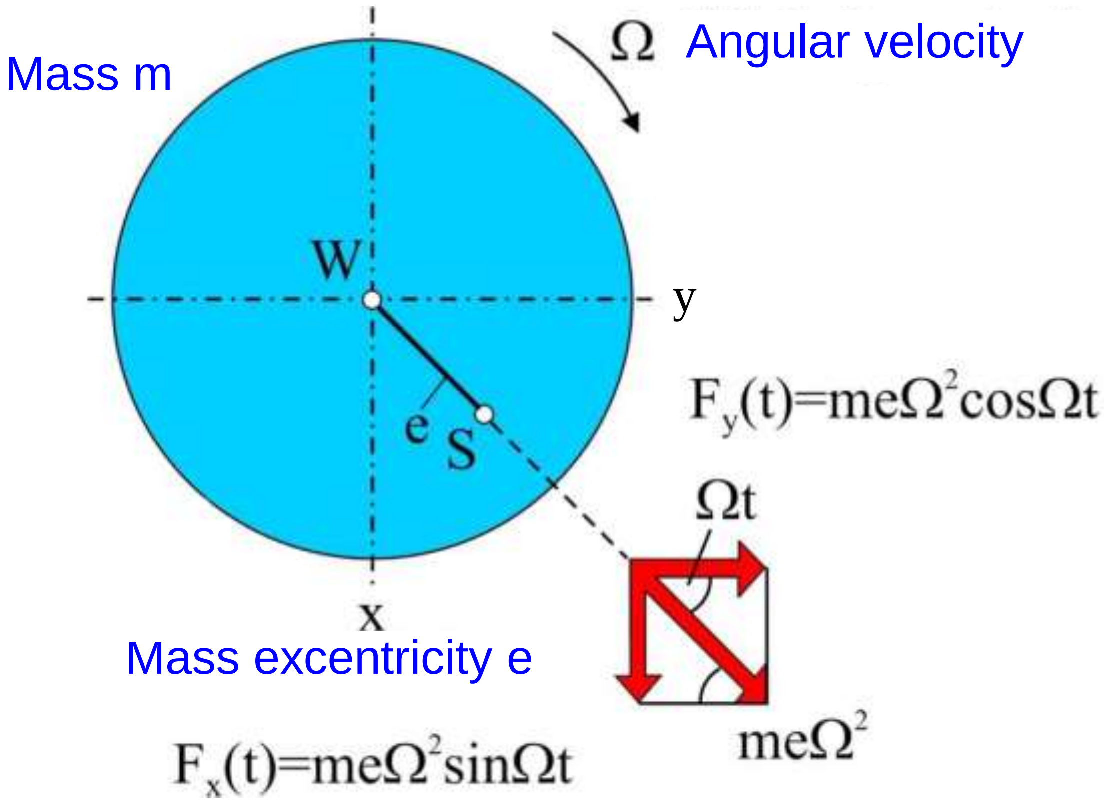
Laval Shaft: Modelling and Equations of Motion

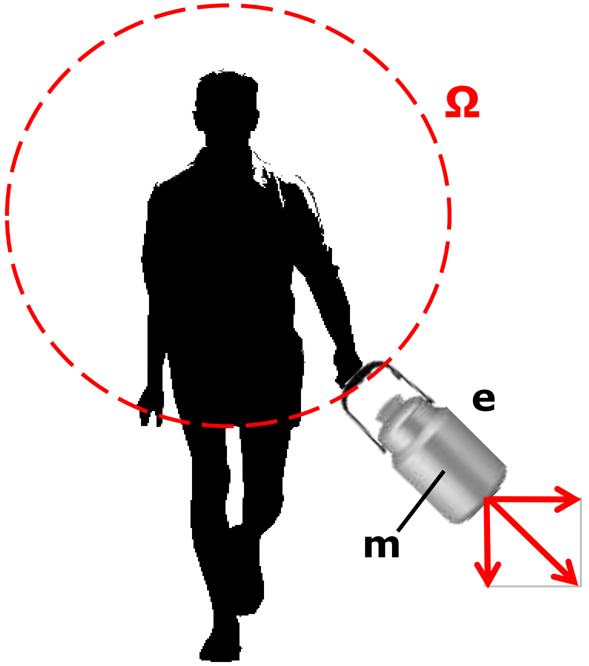
Simple Laval Shaft with Rigid Bearings



Laval Shaft: Modelling and Equations of Motion

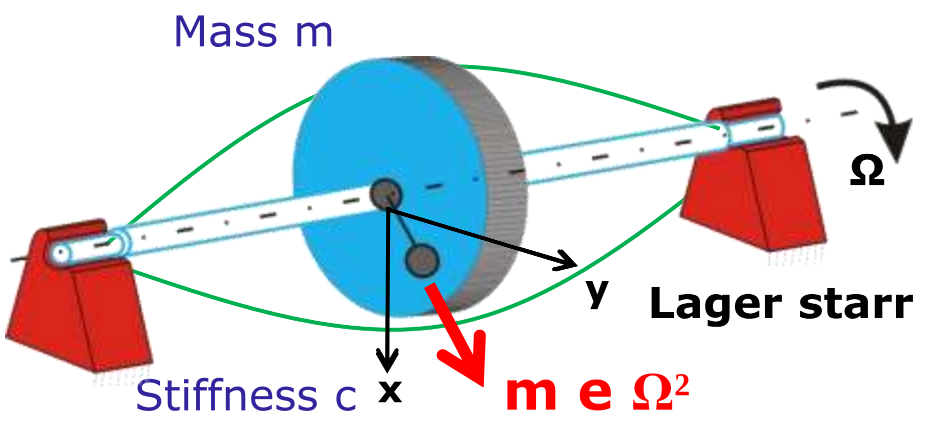
Excitation due to Harmonic Unbalance Forces

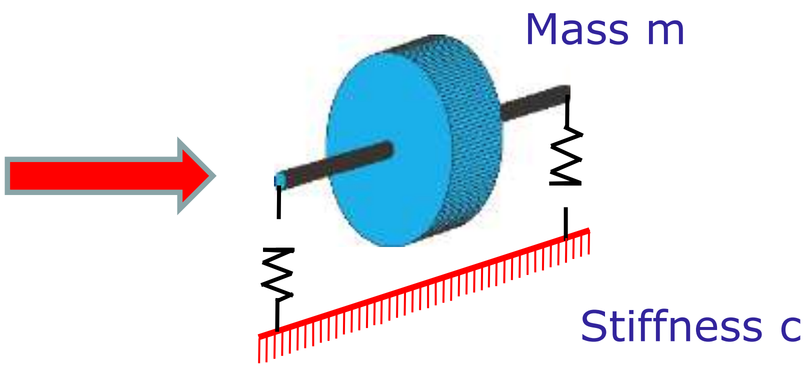




Laval Shaft: Modelling and Equations of Motion

Equations of Motion for x- and y-direction





$$m\,\ddot{x} + d\,\dot{x} + c\,x = m\,e\,\Omega^2\ \sin\Omega t$$

$$m\,\ddot{y} + d\,\dot{y} + c\,y = m\,e\,\Omega^2\ \cos\Omega t$$

Inertia Damping Stiffness Unbalance

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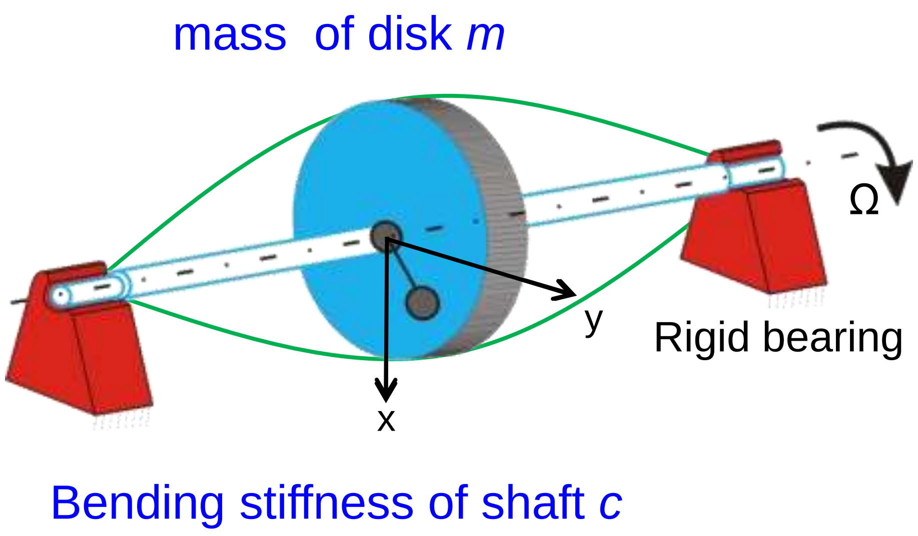
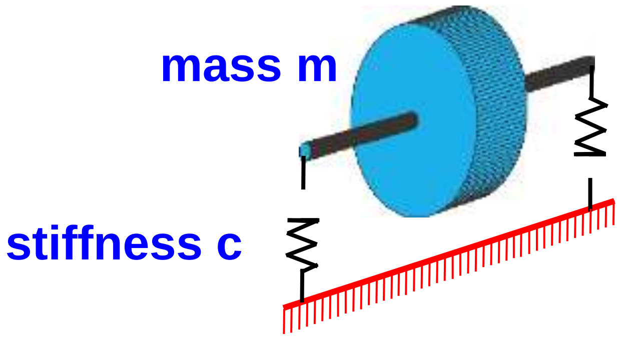
Laval Shaft: Natural Frequency, Resonance, Unbalance Response

Natural Frequency and Resonance



Natural frequency of Laval's shaft

$$\omega = \sqrt{c / m}$$

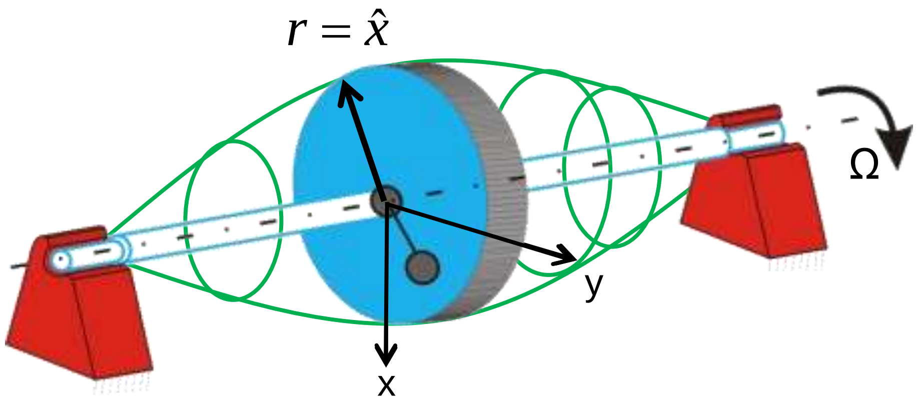


External excitation with this frequency leads to **Resonance!**

Laval Shaft: Natural Frequency, Resonance, Unbalance Response

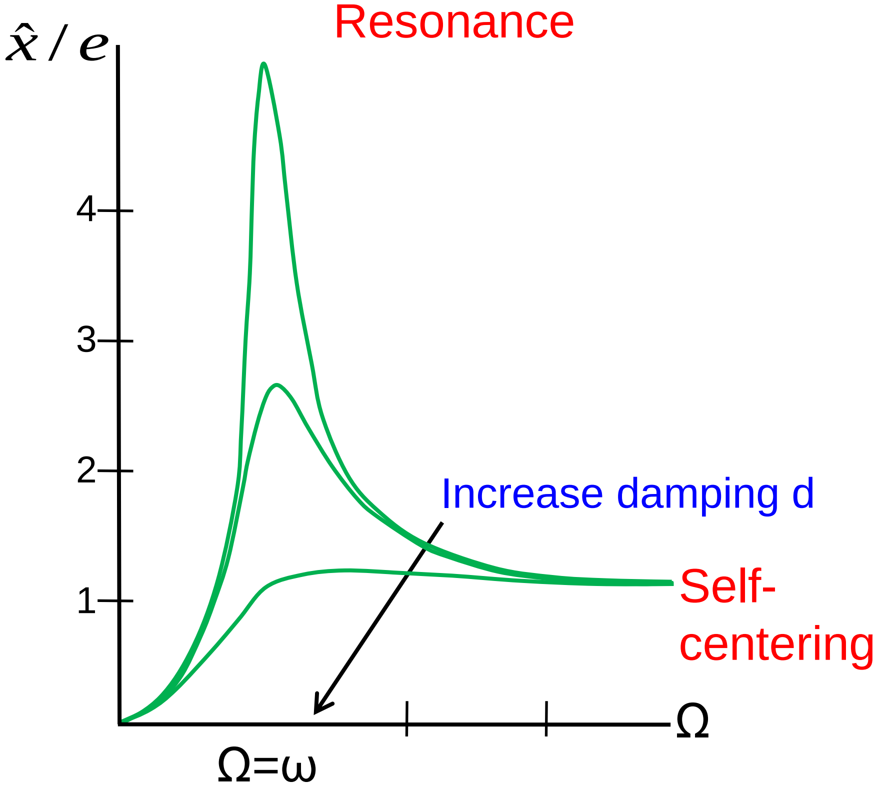
Unbalance Response with Resonance and Self Centering

Shaft vibrations with circular orbit,



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

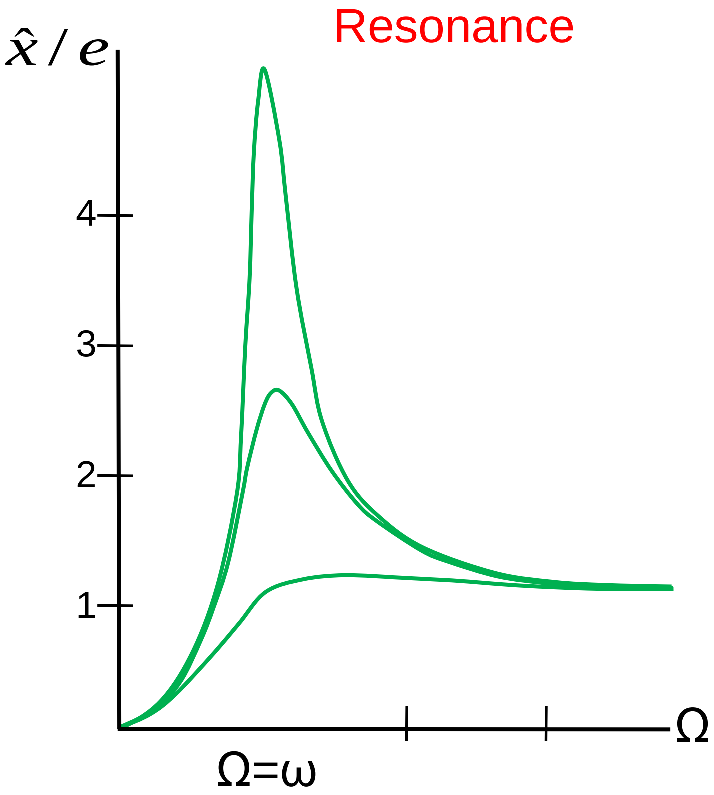
Amplitude $\hat{x}$ of unbalance vibration



Laval Shaft: Natural Frequency, Resonance, Unbalance Response

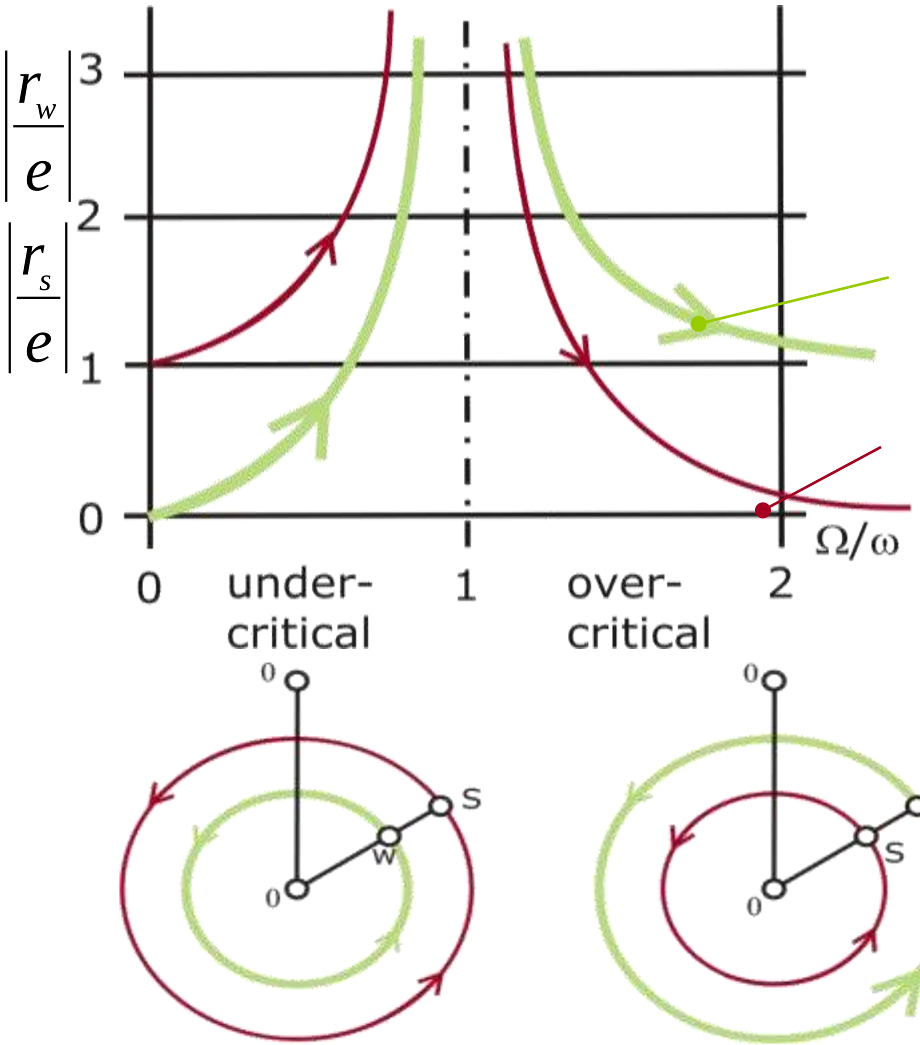
Unbalance Response with Resonance

Resonance:
Child on a swing



Laval Shaft: Natural Frequency, Resonance, Unbalance Response

Unbalance Response for Disk Center W and Center of Gravity S

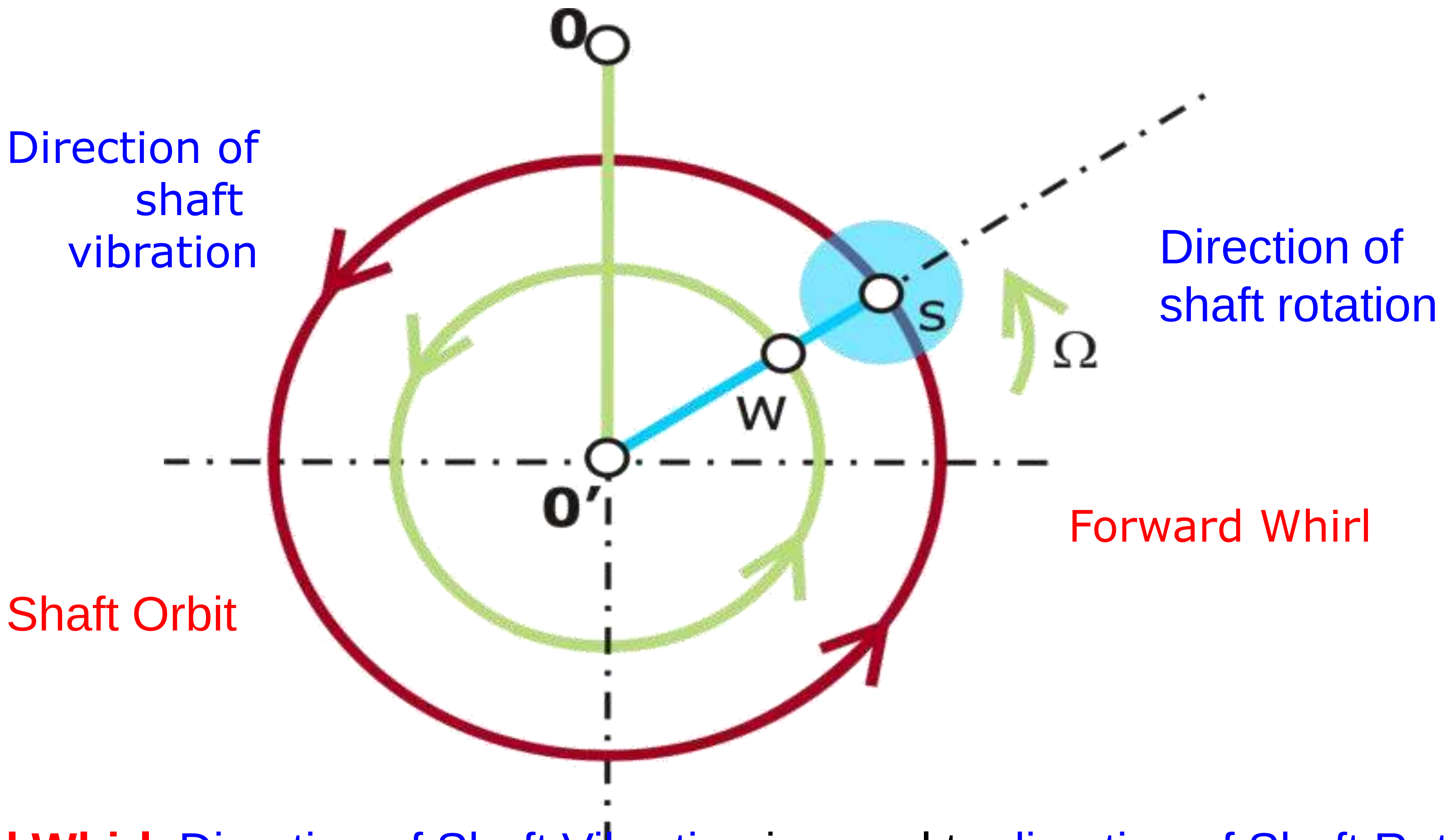


$$\frac{r_w}{e} = \frac{(\Omega/\omega)^2}{1-(\Omega/\omega)^2}$$

$$\frac{r_s}{e} = \frac{1}{1-(\Omega/\omega)^2}$$

Laval Shaft: Natural Frequency, Resonance, Unbalance Response

Unbalance Response with Forward Whirl Vibrations

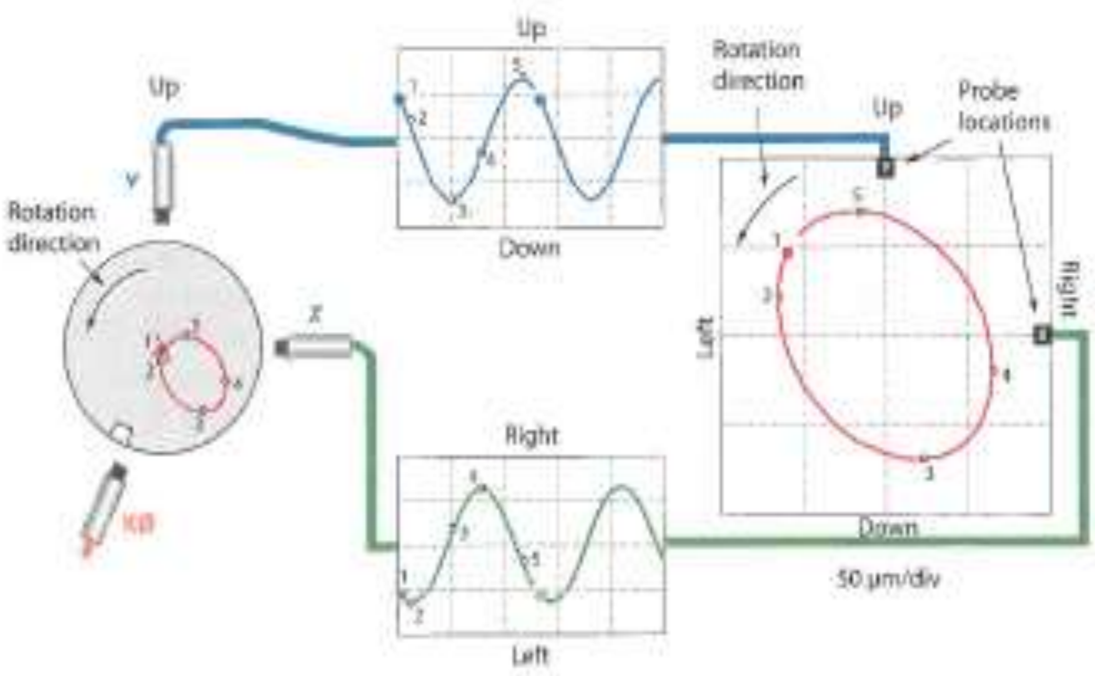


Forward Whirl: Direction of Shaft Vibration is equal to direction of Shaft Rotation

Laval Shaft: Natural Frequency, Resonance, Unbalance Response

Relative Shaft Vibrations show Orbits of a Shaft

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



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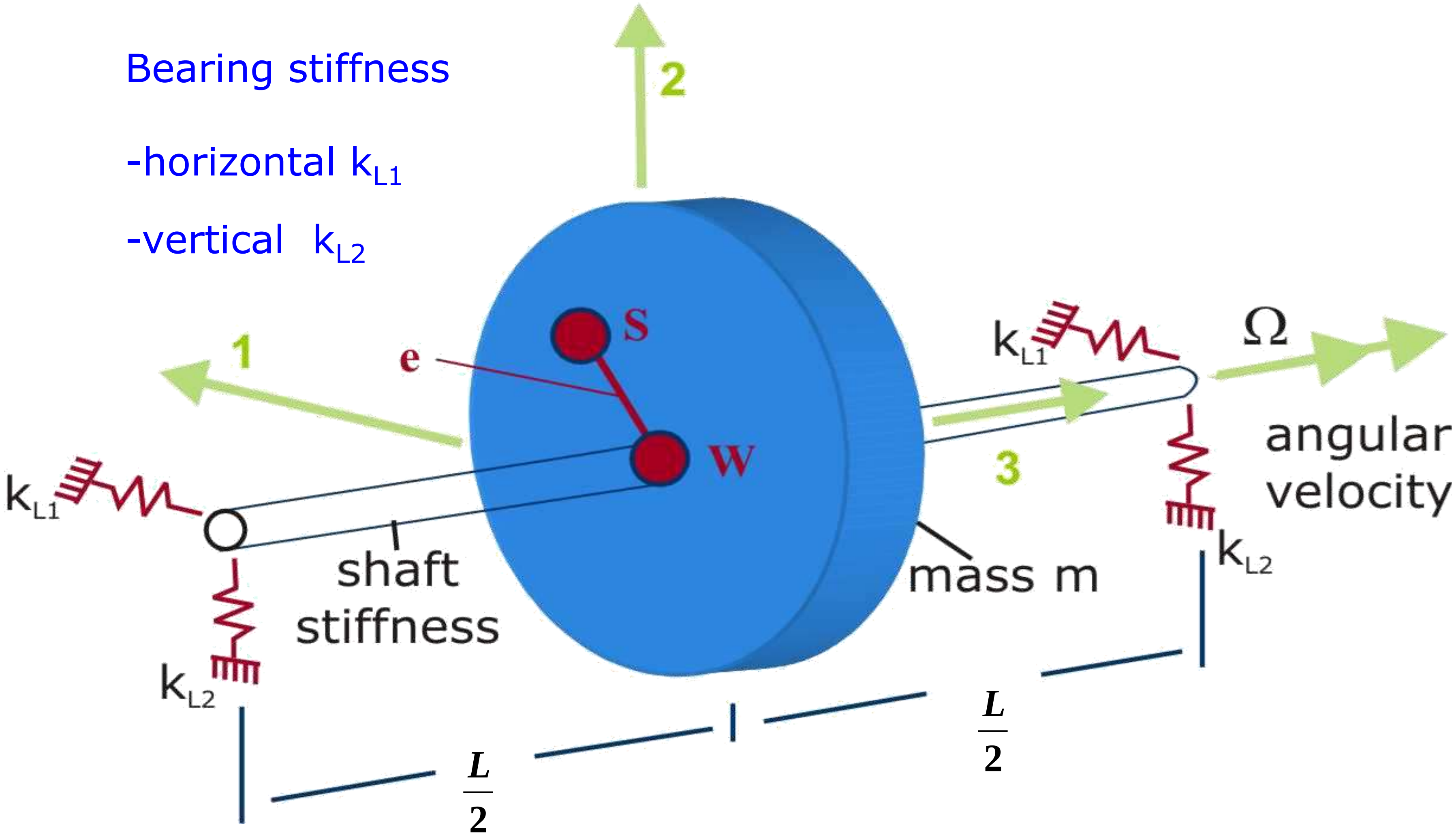
Influence of Stiffness and Damping Characteristics in Bearings

Laval Shaft with Bearing Stiffness Coefficients k_{L1}, k_{L2}

Bearing stiffness

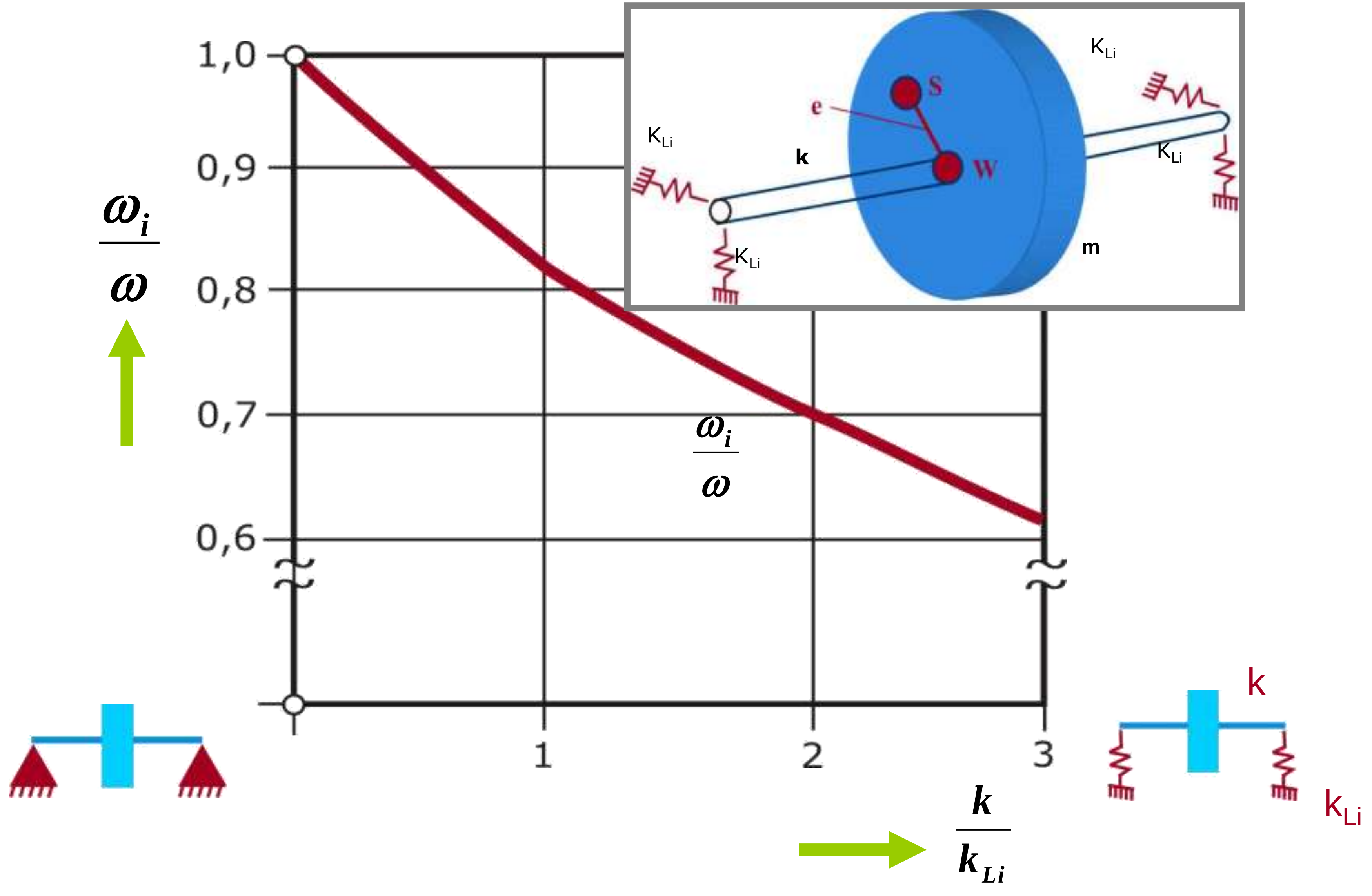
-horizontal k_{L1}

-vertical k_{L2}



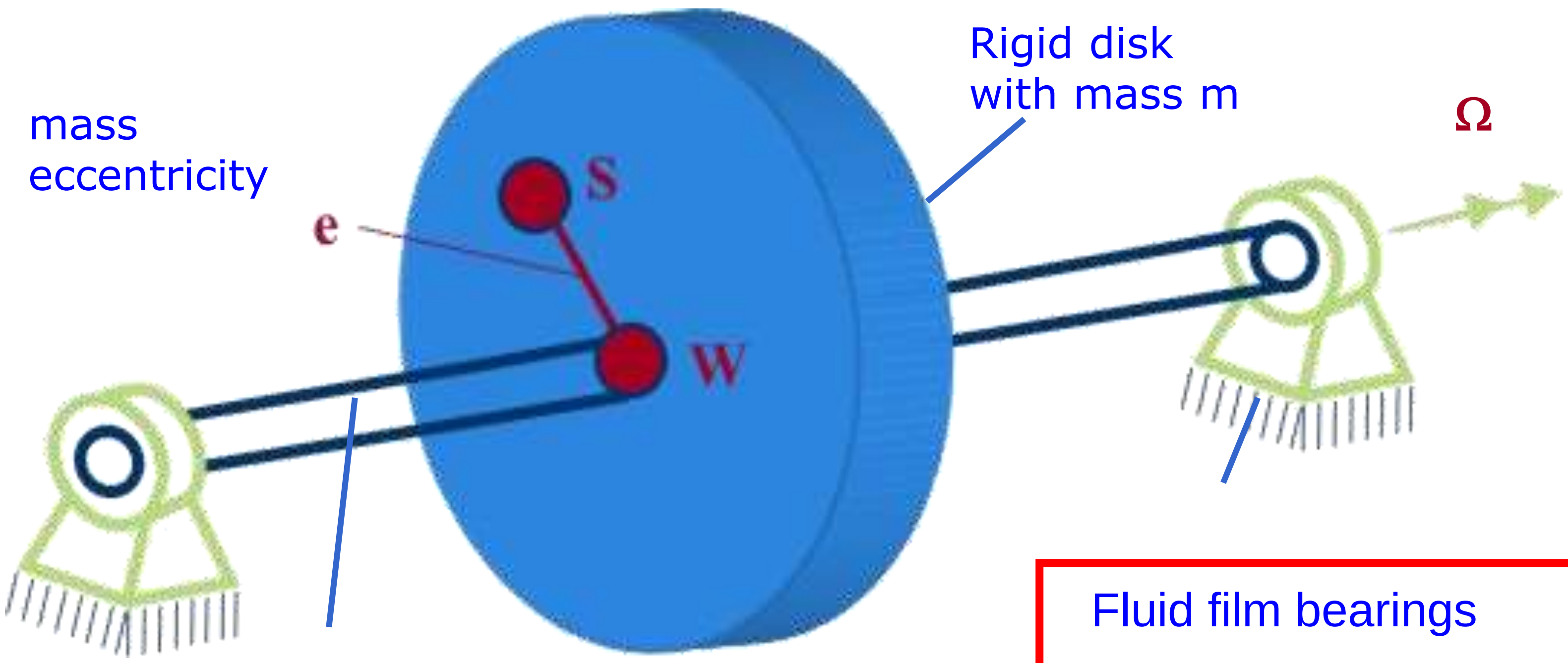
Influence of Stiffness and Damping Characteristics in Bearings

Natural Frequencies as Function of Stiffness Ratio k/ k_{Li}



Influence of Stiffness and Damping Characteristics in Bearings

Stiffness and Damping Coefficients of Oil Film Bearings



Fluid film bearings

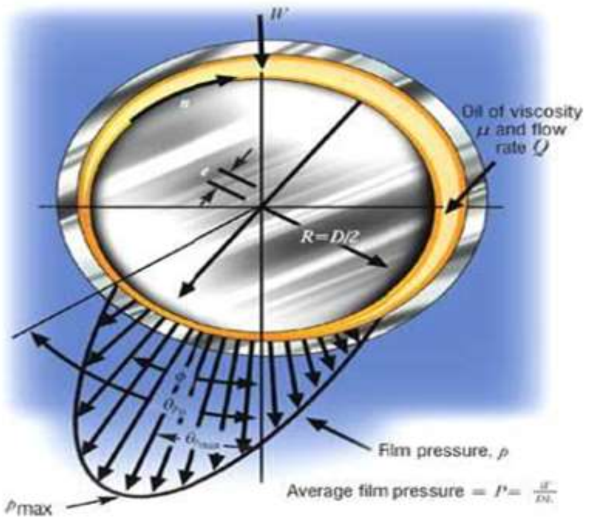
So-number

Stiffness Coefficients

Damping Coefficients

Influence of Stiffness and Damping Characteristics in Bearings

Stiffness and Damping Coefficients of Oil Film Bearings



Stiffness- and damping coefficients of the Oil Film Bearings

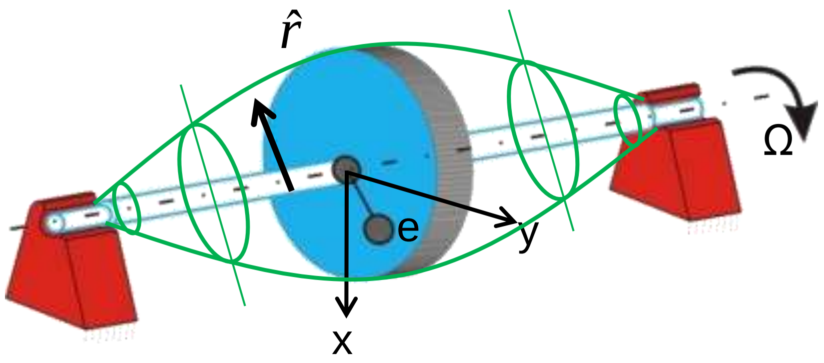
$$F_x = k_{xx}x + k_{xy}y + d_{xx}\dot{x} + d_{xy}\dot{y}$$

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

Influence of Stiffness and Damping Characteristics in Bearings

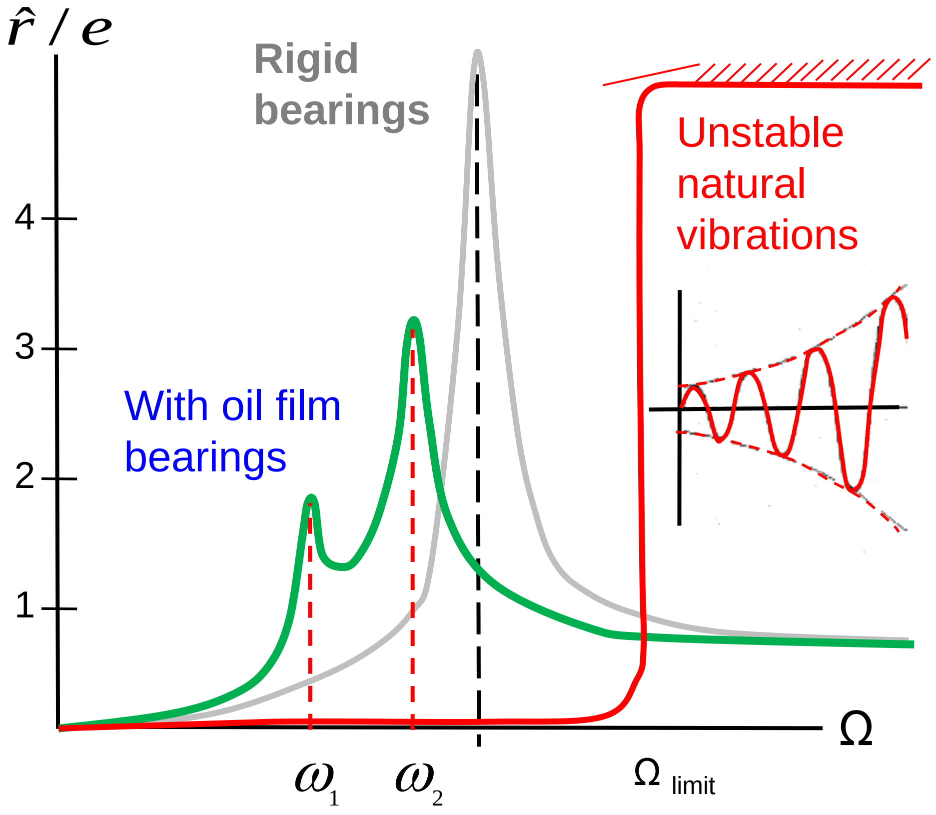
Comparison of Vibrations: Oil Film Bearings versus Rigid Bearings

Shaft vibration with elliptical orbits



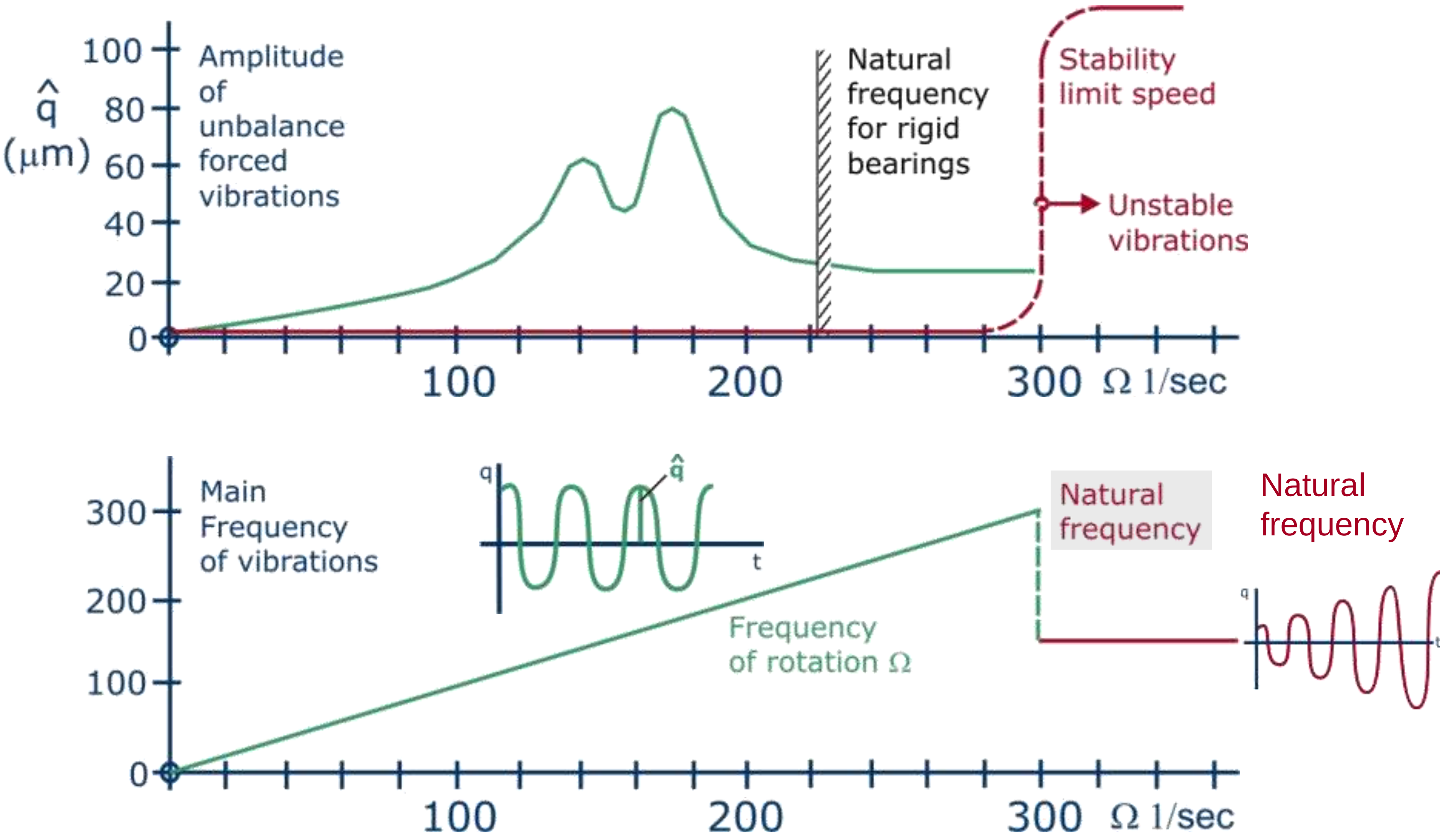
Influence of Oil film bearings:

Stiffness, Damping, Anisotropy
Danger of self-excitation



Influence of Stiffness and damping Characteristics in Bearings

Vibration Behavior of a Simple Laval Shaft with Oil Film Bearings (Tondl)



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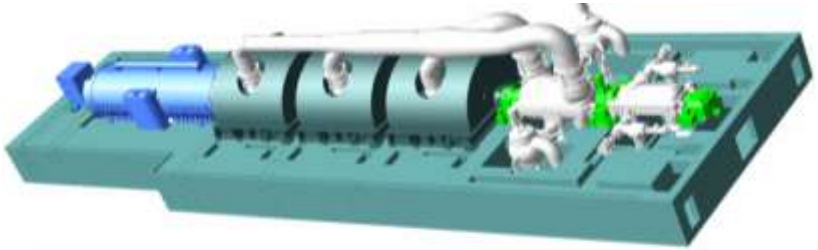
From Simple Rotor Systems to Large Turbogenerators

Different Interactions in Rotordynamics

Rotor-Fluid Interaction: Oil Film Bearings, Seals

Rotor-Blade Interactions

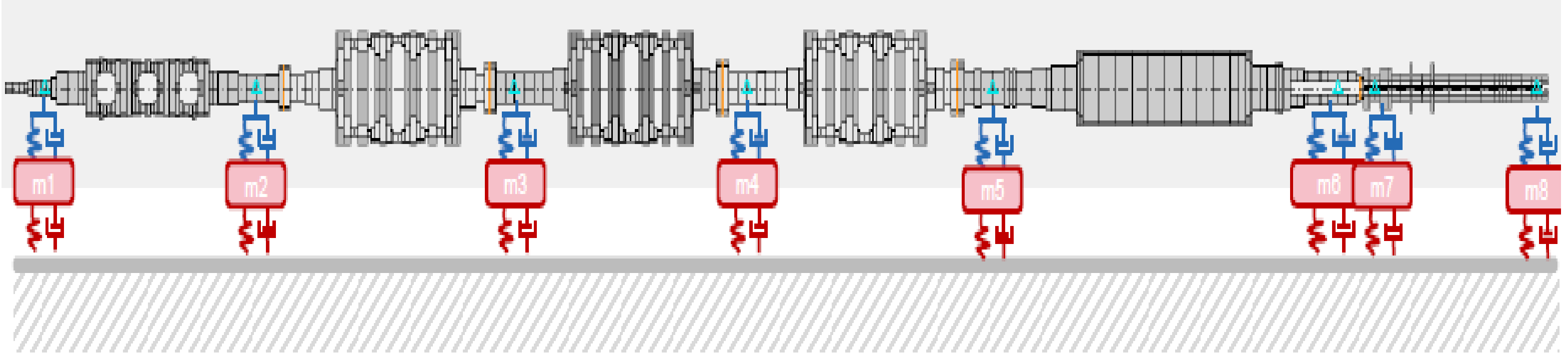


Rotor-Structure Interaction: Casing, Foundation

Elektromechanical Interaction: Generator,Grid

From Simple Rotor Systems to Large Turbogenerators

FE-Model and Equations for Lateral Vibrations of Turbine Shaft Trains

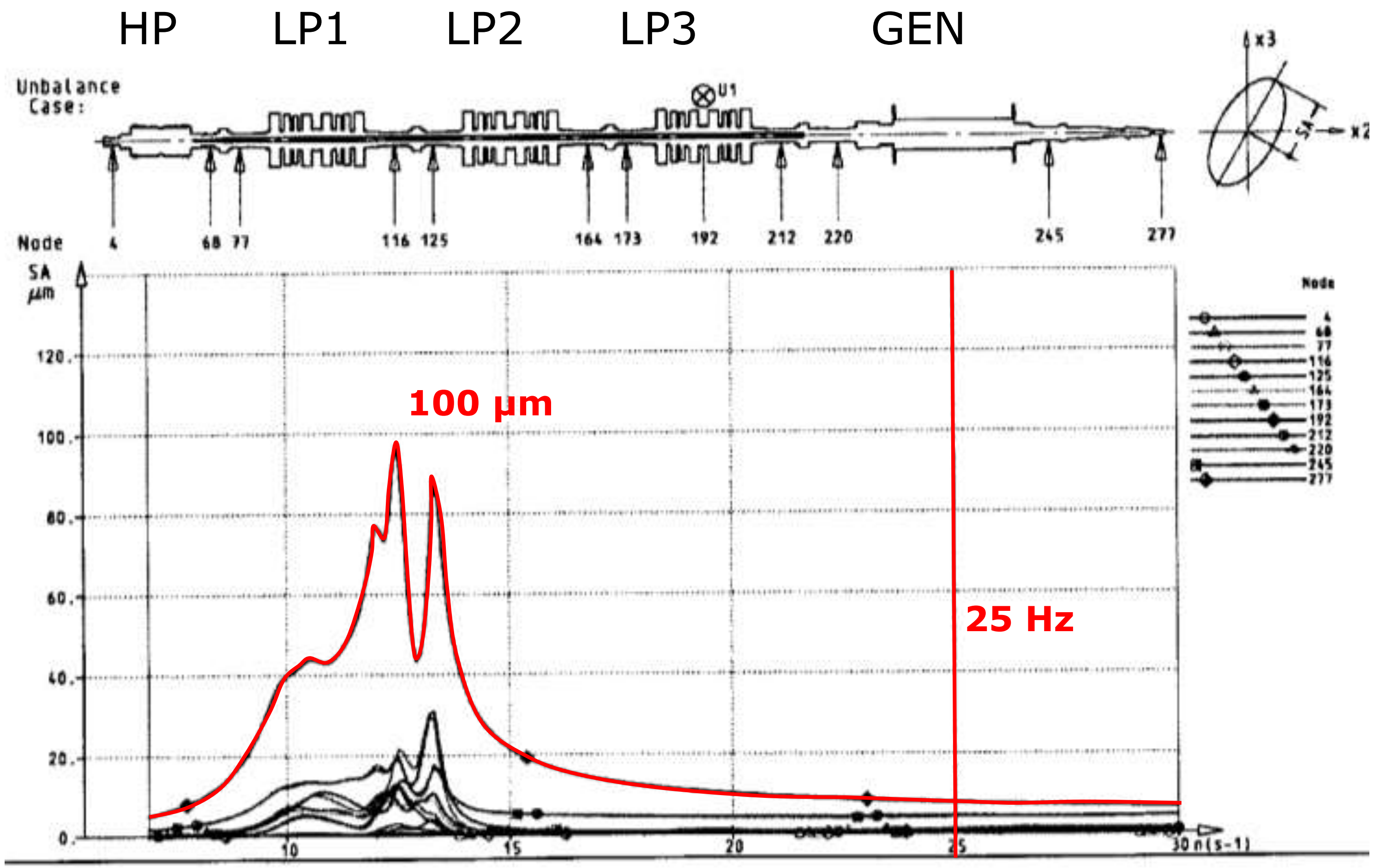


$$\mathbf{M}\,\ddot{x}(t)+(\mathbf{D}(\Omega)+\mathbf{G}(\Omega))\,\dot{x}(t)+\mathbf{K}(\Omega)\,\mathbf{x}(t)=\mathbf{F}(t)$$

The **Equations of Motion** for **Lateral Vibrations** of the **Turbogenerator** contain the stiffness and damping information of the shaft train, the bearings and the supports (pedestals and foundation)

From Simple Rotor Systems to Large Turbogenerators

Unbalance Vibration Response of a Turbine Shaft Train versus Speed



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

TECHNISCHE UNIVERSITÄT DARMSTADT

Vibrations of Turbines and Generators in Power Plants

Lecture I Introduction and Vibration Phenomena in Turbogenerators

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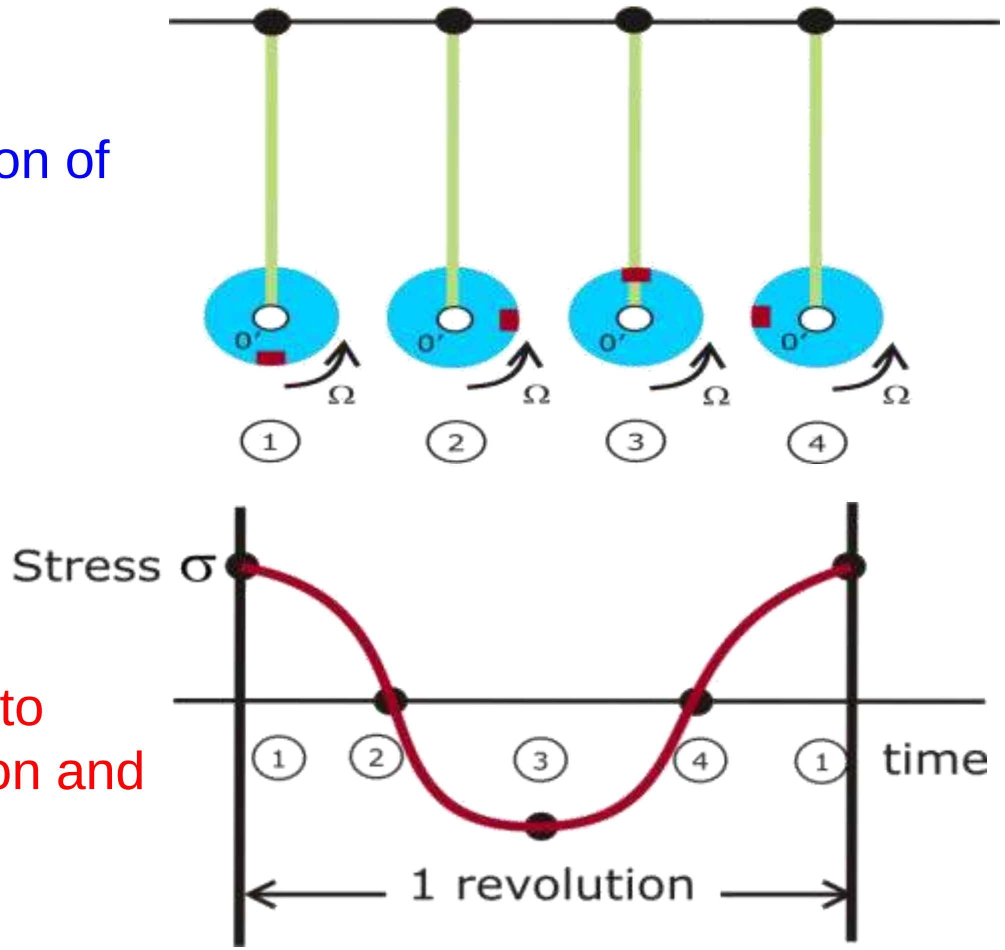
Technische Universität Darmstadt and Fraunhofer Institute LBF

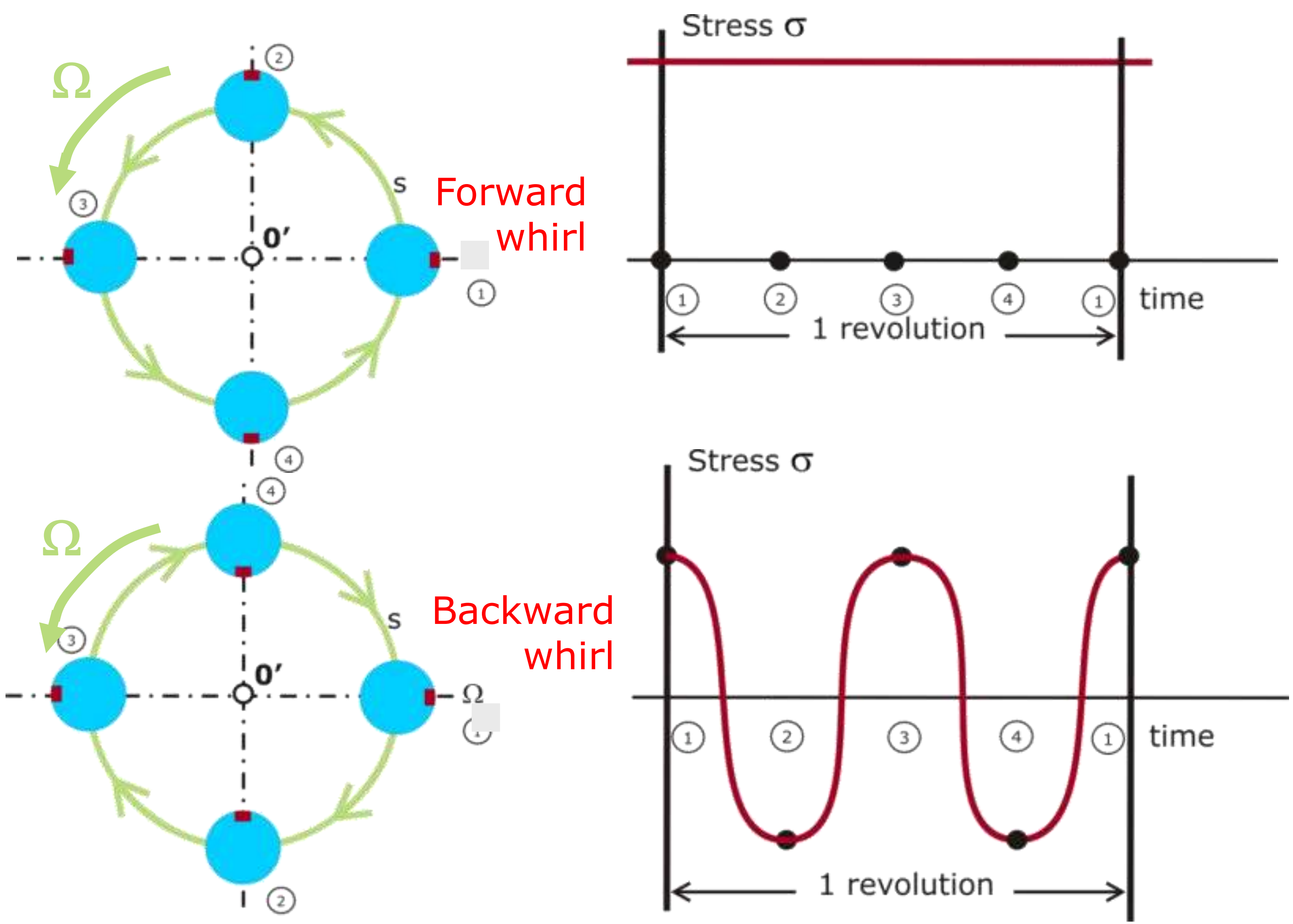
Vibrations of Laval's Shaft with Rigid Bearings
Shaft stress due to static deflection

Static deflection of the shaft

Stresses due to static deflection and rotation



Vibrations of Laval's shaft with Rigid Bearings
Shaft stresses for Forward and Backward whirl



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