Vorlesungen Mechatronik im Wintersemester

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

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Vibrations of Turbines and Generators in Power Plants

Lecture IV Vibrations in Generators of Turbogenerators

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Vibrations in Generators of Turbogenerators

- Some Vibration Problems in Generators
- End Winding Vibrations in Generators
- Lateral Vibrations due to Time Variant Stiffness of the Generator Shaft
- Sub Synchronous Resonance (SSR)

Some Vibration Problems in Generators

Turbogenerator System with Components

Generator

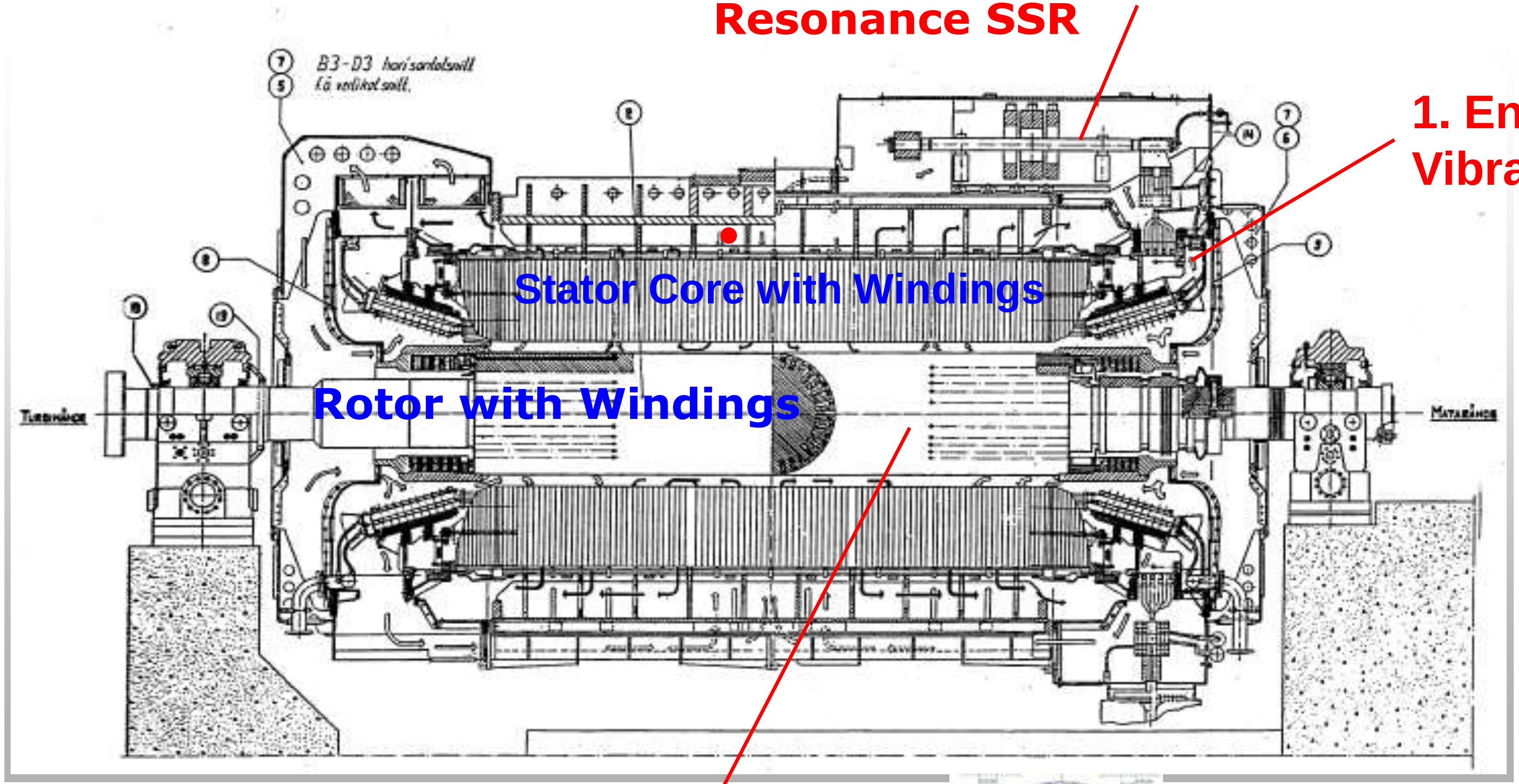
Pipe
System

Low Pressure
Turbines LPT

High Pressure
Turbine HPT

Some Vibration Problems in Generators

Generator Cross Section with Rotor and Stator Core

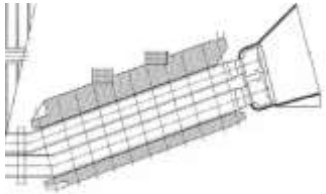


3. Sub Synchronous Resonance SSR

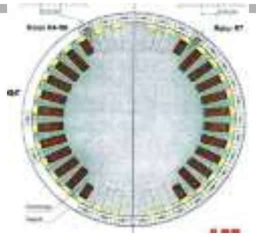
1. End Winding Vibrations of Core

Stator Core with Windings

Rotor with Windings



2. Time Variant Shaft Stiffness



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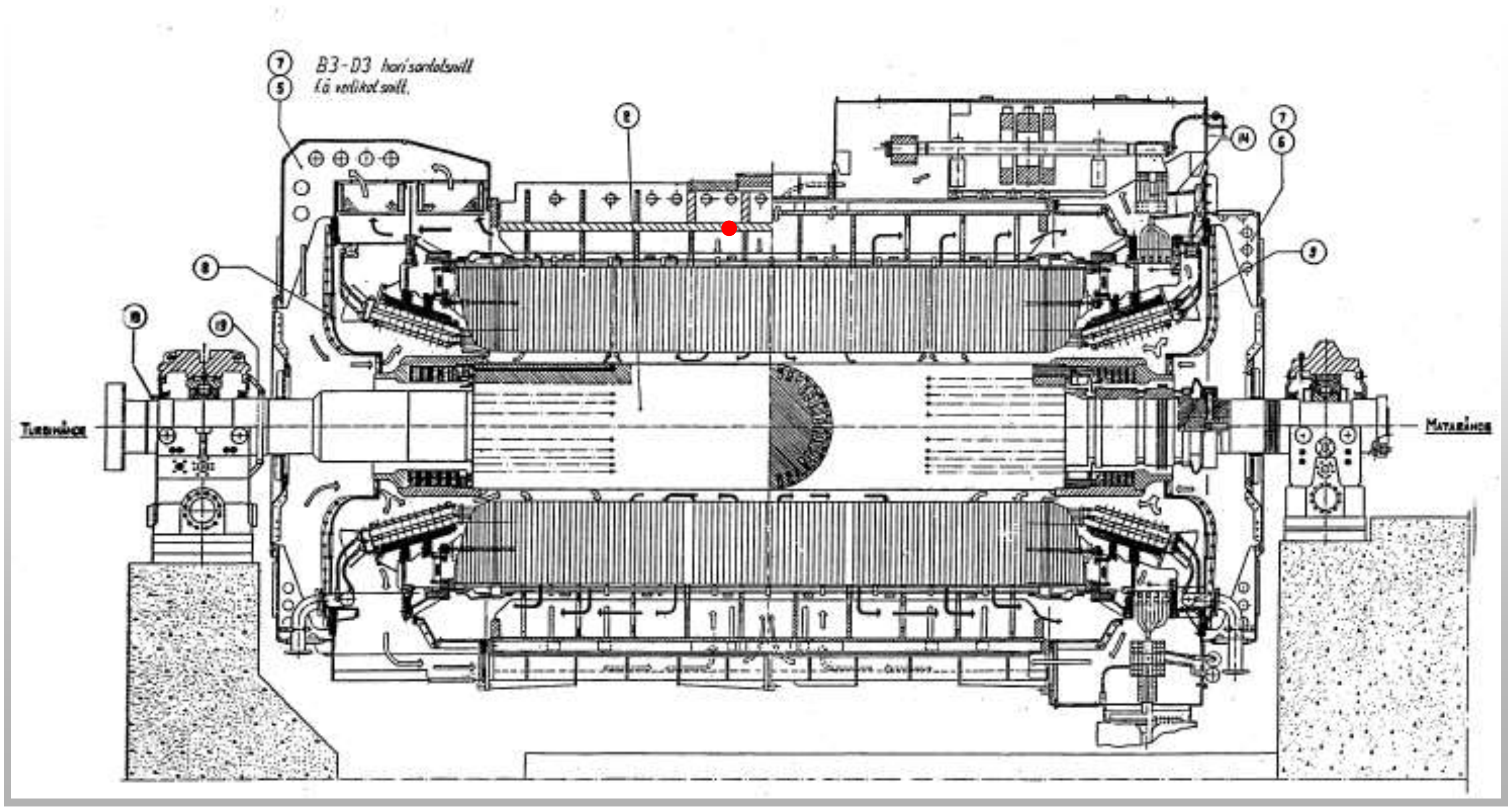
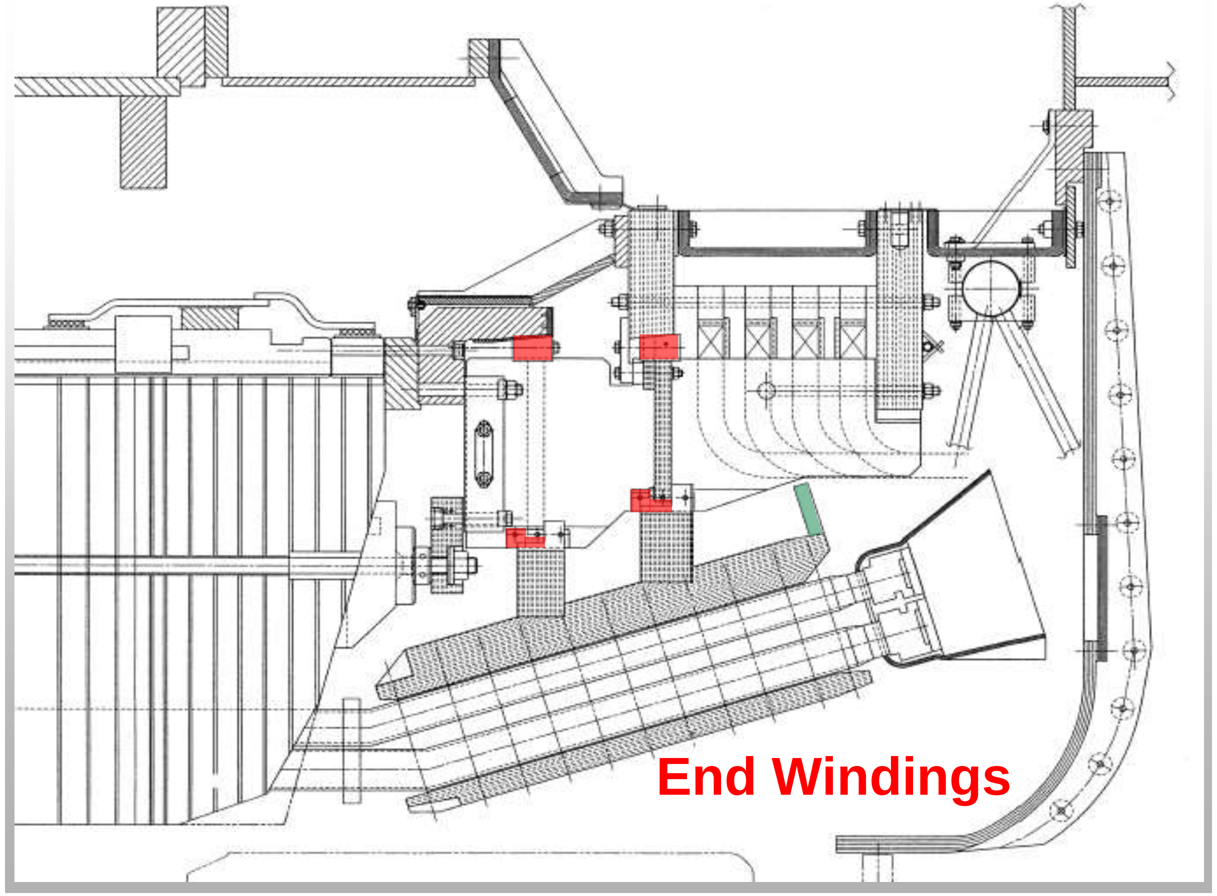
End Winding Vibrations in Generators

Generator Cross Section

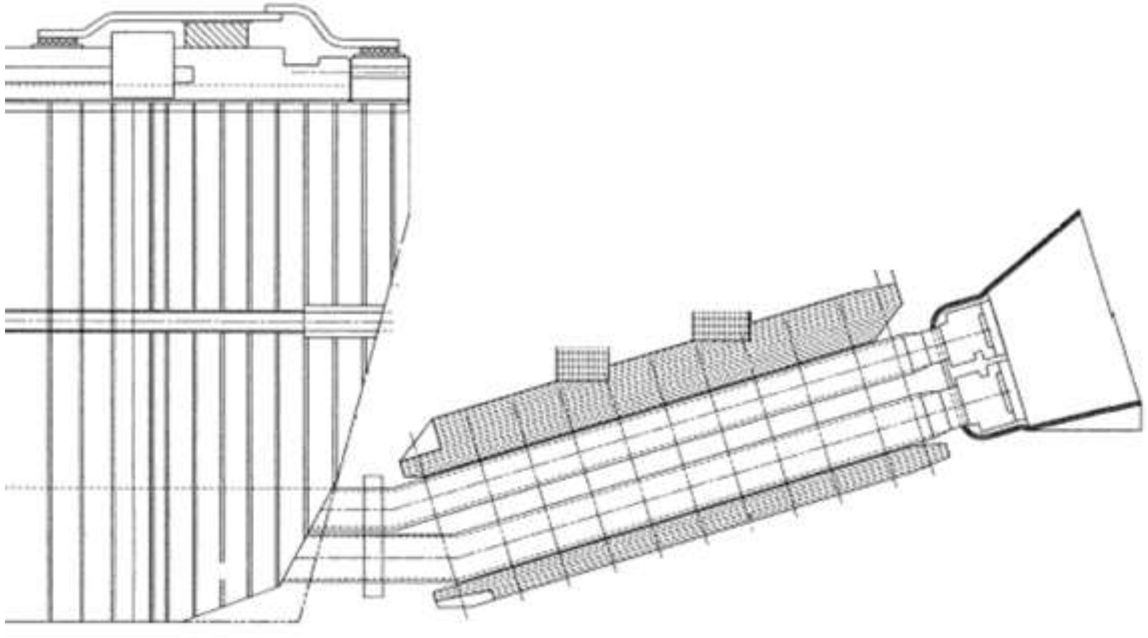


- **End Winding Vibrations** have been one of the problems in generators
- They are excited **at 100 Hz** by Electro-Magnetic forces and amplified due to **resonances close to 100 Hz**
- The **mode shape** has often an **elliptical form**

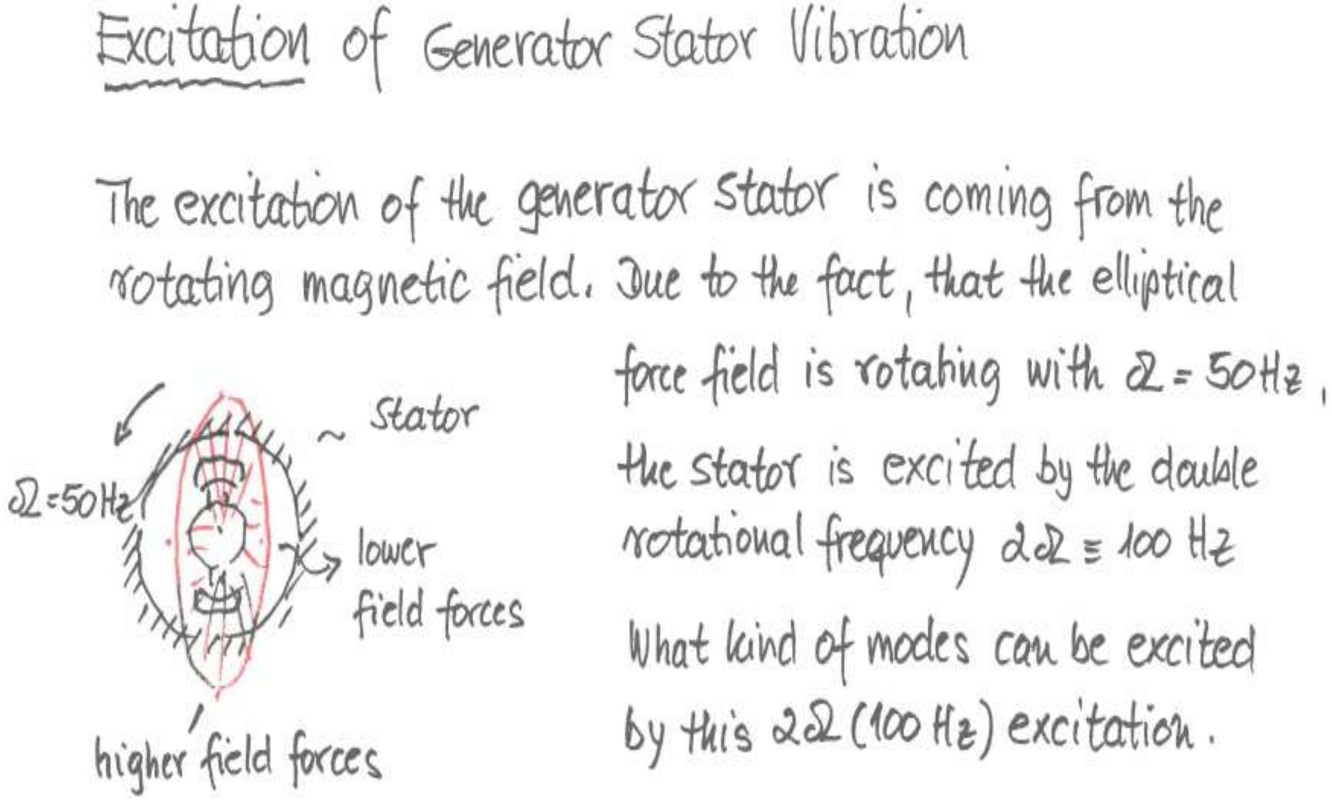


Concepts: End Windings have supports

or are designed as Free End Windings



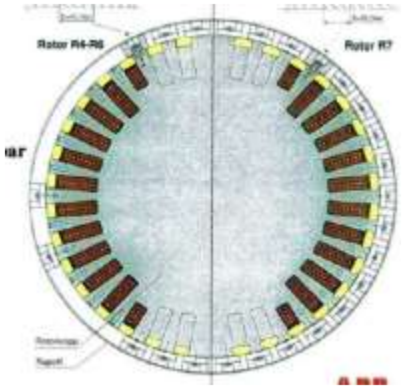
- Free Endwinding Solution
- Resonance behavior:
- Short circuit: safety, stress analysis



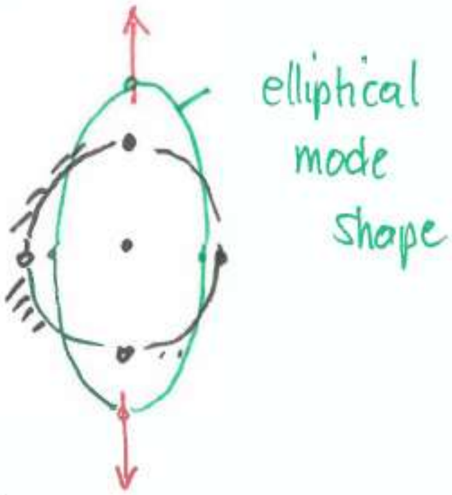
Excitation of Generator Stator Vibration

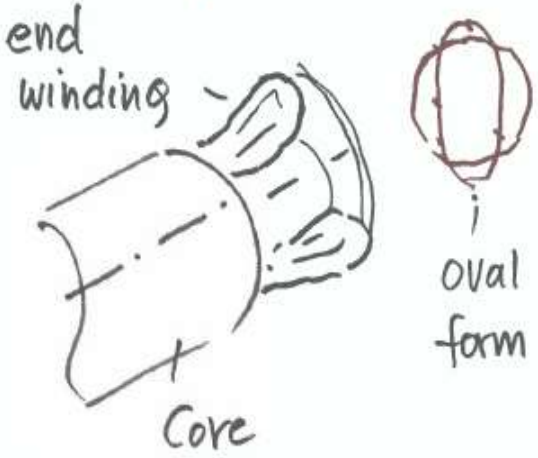
The excitation of the generator stator is coming from the rotating magnetic field. Due to the fact, that the elliptical force field is rotating with $\Omega = 50\,Hz$, the stator is excited by the double rotational frequency $2\Omega = 100\,Hz$

What kind of modes can be excited by this 2Ω (100 Hz) excitation.



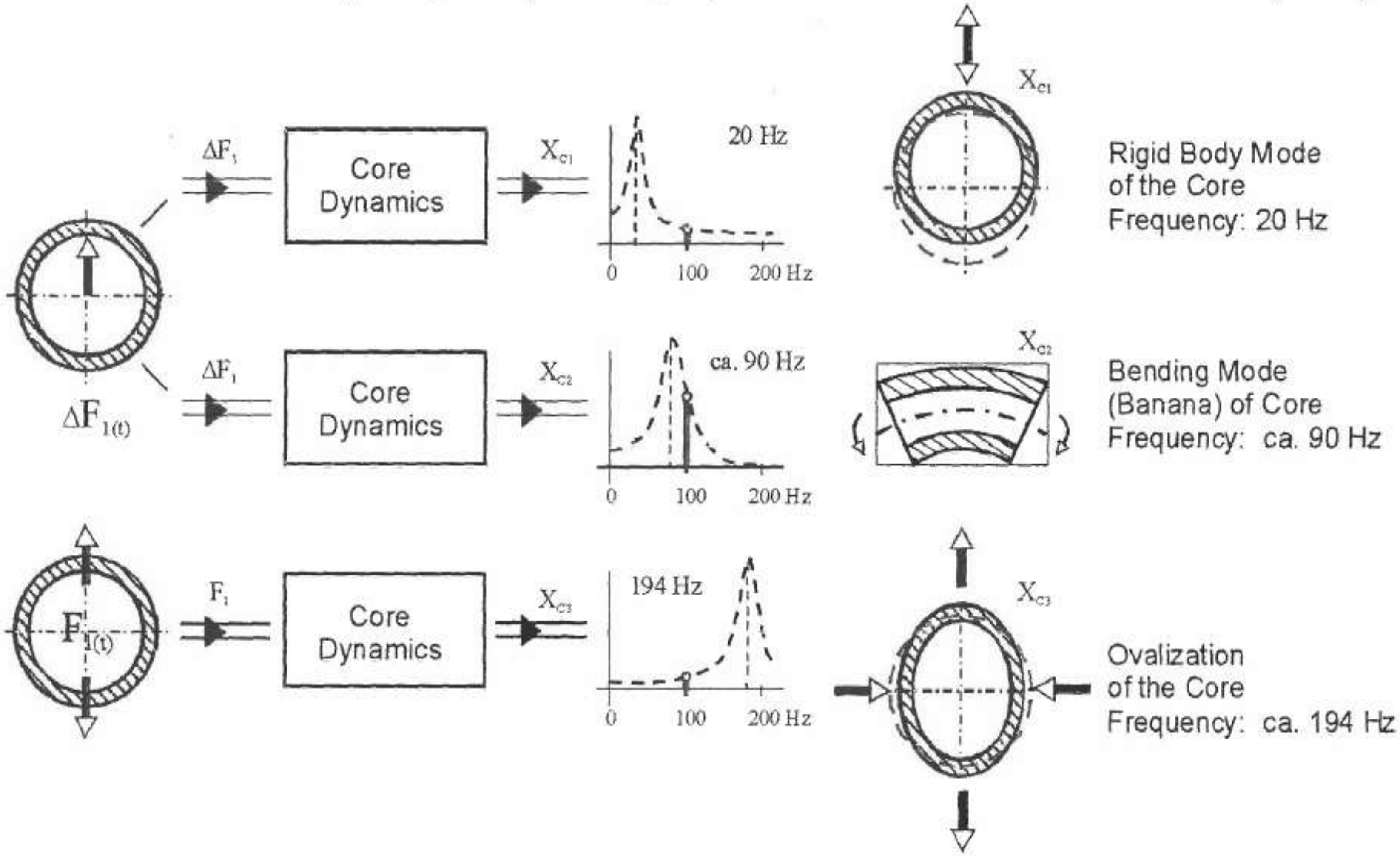
Rotor with rotating **Magnetic Field** in a Two Pole Generator





The natural frequency of the core with an elliptical mode ~~is~~ has been calculated at a frequency of 190 Hz. This is far away from 100 Hz excitation and there should be no problem.

However, the question arises, whether the end windings can also be excited by 100 Hz frequency on both sides of the stator. In the measurement results we see a very clear oval mode shape.



Excitation

Frequency Response - Output

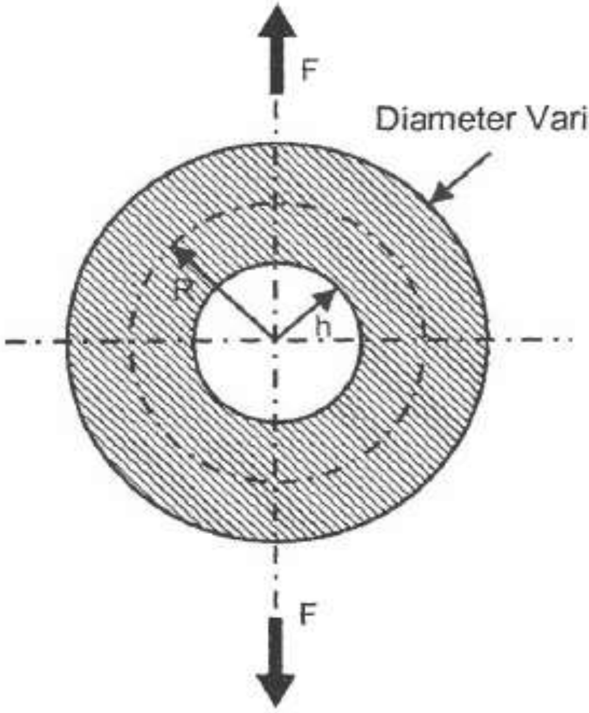
Vibration Mode and Frequency

Rigid Body Mode
of the Core
Frequency: 20 Hz

Bending Mode
(Banana) of Core
Frequency: ca. 90 Hz

Ovalization
of the Core
Frequency: ca. 194 Hz

Core Deformation due to a **Static Load**



Diameter Variation (Static Solution)

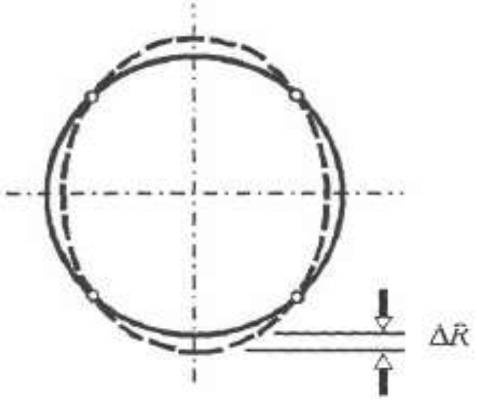
$$\Delta D = 0{,}148\frac{FR^3}{EJ}$$

$$\Delta D_{stat} = 8{,}05\,\mu m$$

$$\Delta R_{stat} = 4{,}02\,\mu m$$

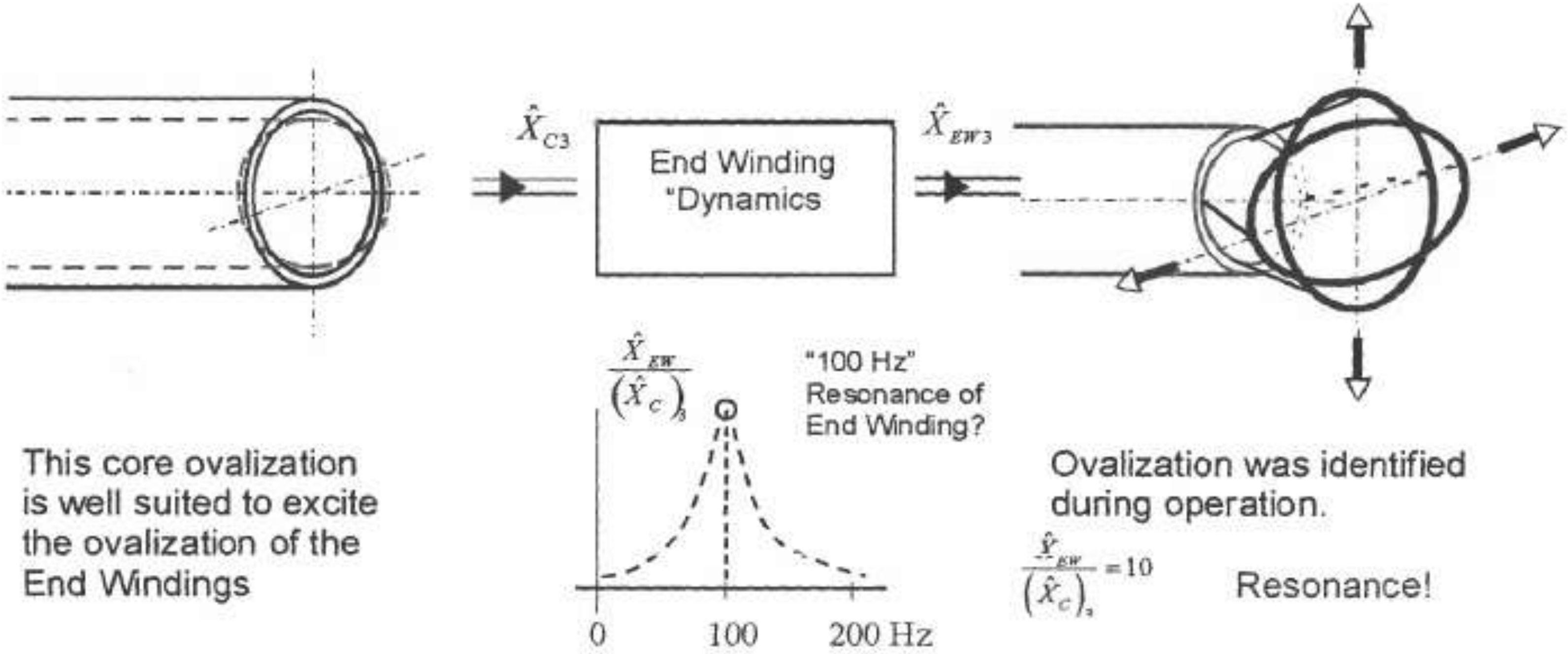
$$\Delta R_{dyn} \approx 1{,}25 * \Delta R_{stat} = 5\,\mu m$$

Force: F = 2370 KN
Radius: R = 1,2 m
Thickness: h = 0,9 m
E-Modul: $E = 2{,}1 * 10^{11}$ N/m²
Moment of Inertia: $J = Lh^3/12$
Length L = 5,9 m



“Excitation” due to
Core Ovalization $X_{C3}(t)$ - 100 Hz

“Vibration Response” of
End Windings is an
“Ovalization”. Oval form
rotates with 100 Hz



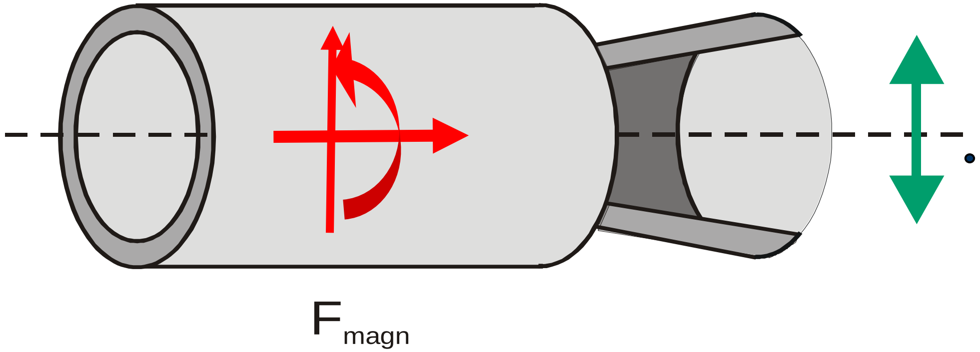
This core ovalization
is well suited to excite
the ovalization of the
End Windings

Ovalization was identified
during operation.

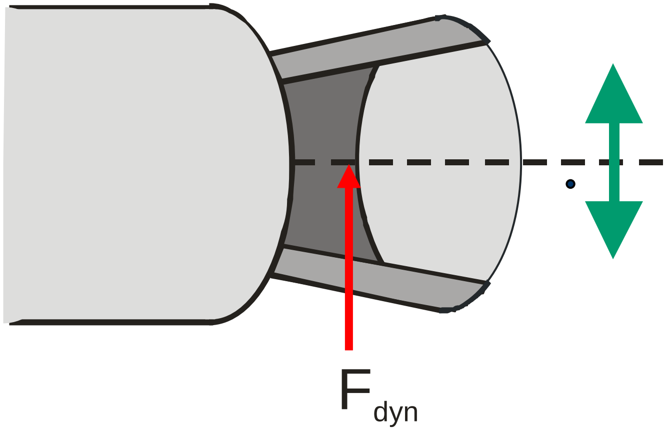
$\frac{\hat{X}_{EW}}{(\hat{X}_C)_3} = 10$ Resonance!

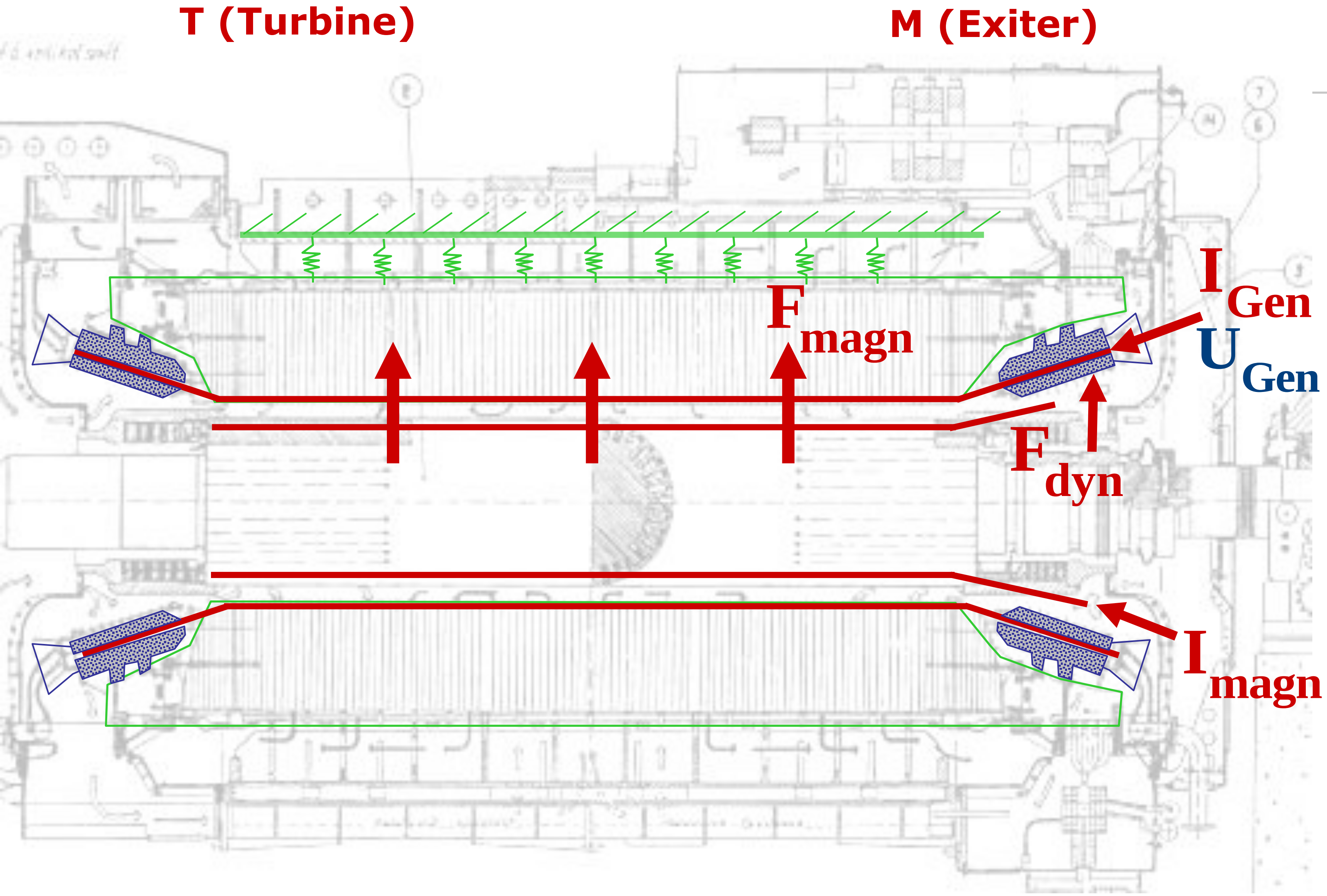
- There are two ways to excite the End Winding Vibrations

Indirect Excitation via Magnetic
Forces and the the Core



Direct Excitation
due to currents




T (Turbine)
M (Exiter)
I_{Gen}
U_{Gen}
F_{magn}
F_{dyn}
I_{magn}

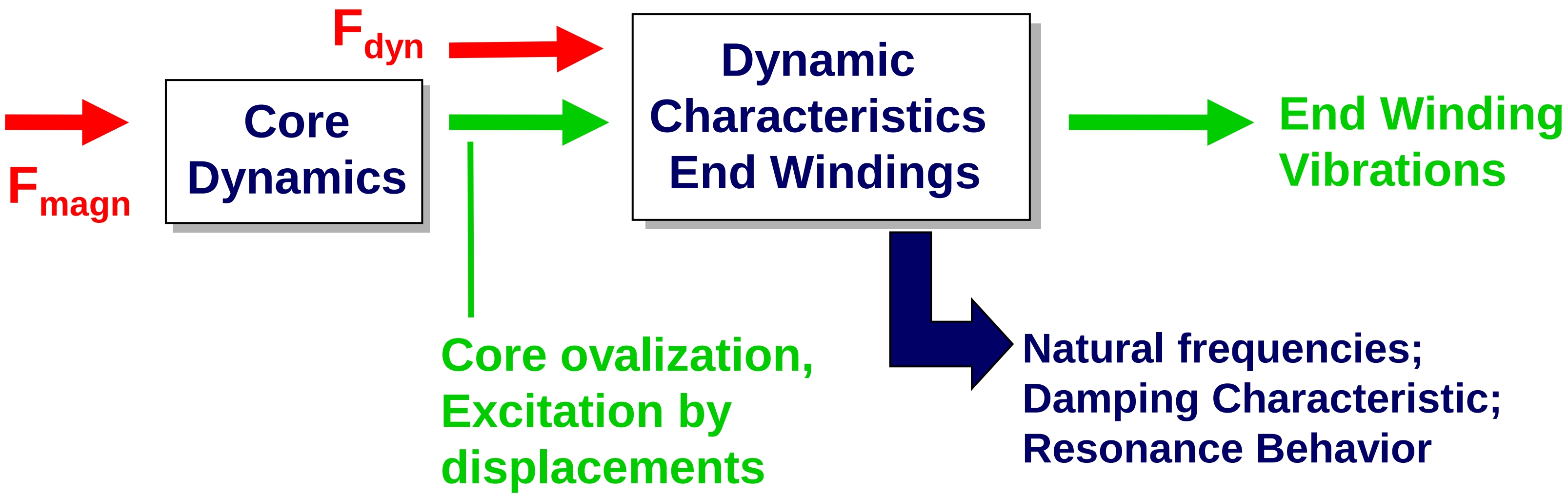
End Winding Vibrations

depend on

Electrodynamic Force F_{dyn}

Electromagnetic Forces F_{magn}

Dynamic Characteristics of End Windings



F_{dyn}

F_{magn}

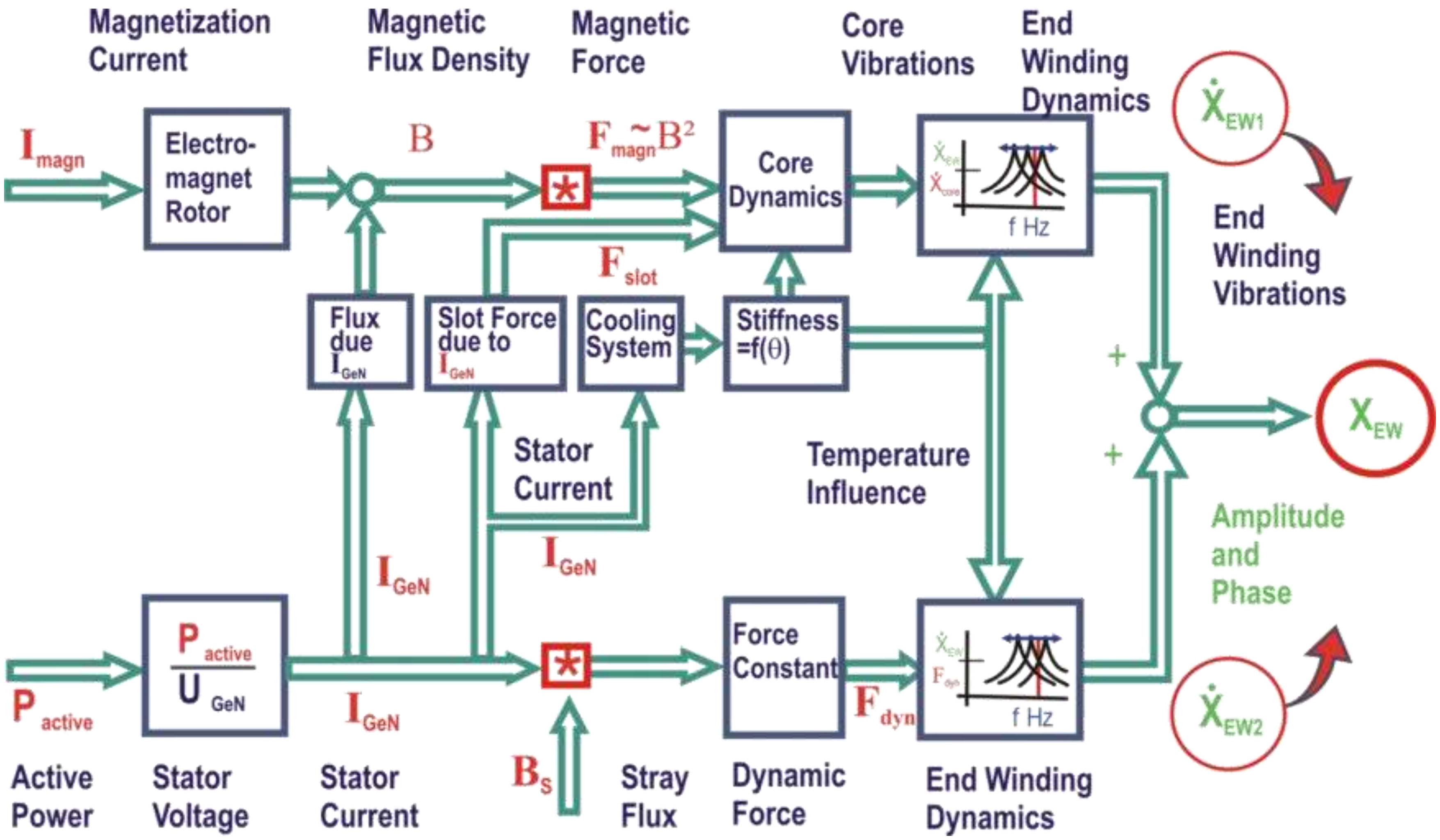
Core Dynamics

Dynamic Characteristics End Windings

End Winding Vibrations

Core ovalization, Excitation by displacements

Natural frequencies;
Damping Characteristic;
Resonance Behavior



Magnetization Current

Magnetic Flux Density

Magnetic Force

Core Vibrations

End Winding Dynamics

I_{magn}

Electro-magnet Rotor

B

$F_{magn} \sim B^2$

$*$

Core Dynamics

$\dot{X}_{EW}$

$\dot{X}_{core}$

f Hz

$\dot{X}_{EW1}$

End Winding Vibrations

F_{slot}

Flux due I_{GeN}

Slot Force due to I_{GeN}

Cooling System

Stiffness $=f(\theta)$

+

+

X_{EW}

Stator Current

Temperature Influence

I_{GeN}

I_{GeN}

Amplitude and Phase

P_{active}

$\frac{P_{active}}{U_{GeN}}$

I_{GeN}

$*$

Force Constant

F_{dyn}

$\dot{X}_{EW}$

F_{dyn}

f Hz

$\dot{X}_{EW2}$

B_S

Active Power

Stator Voltage

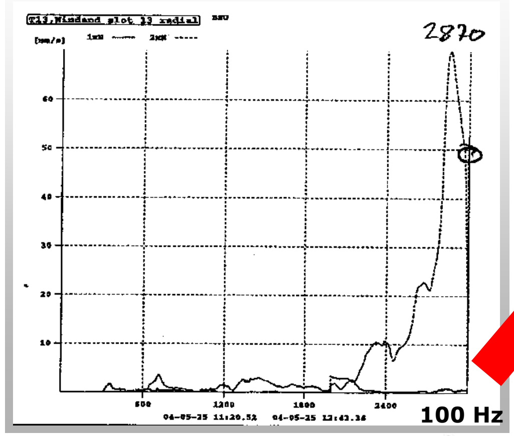
Stator Current

Stray Flux

Dynamic Force

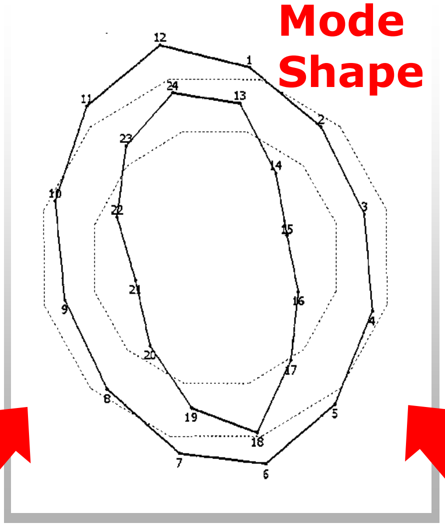
End Winding Dynamics

Resonance Turbine Side

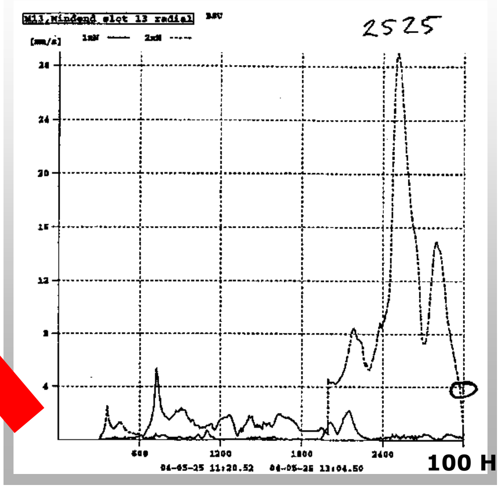


100 Hz

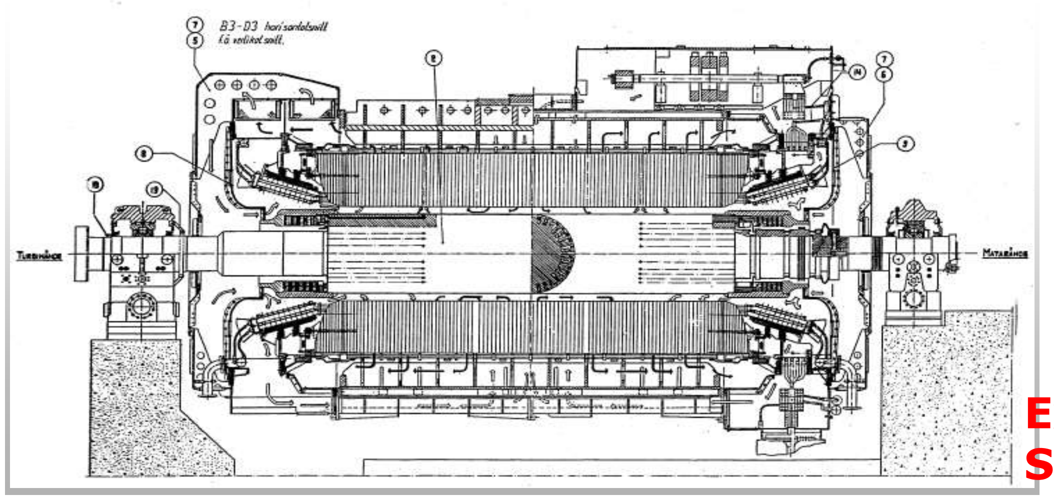
Mode Shape



Resonance Exciter Side



100 Hz



Turbine Side

Exciter Side

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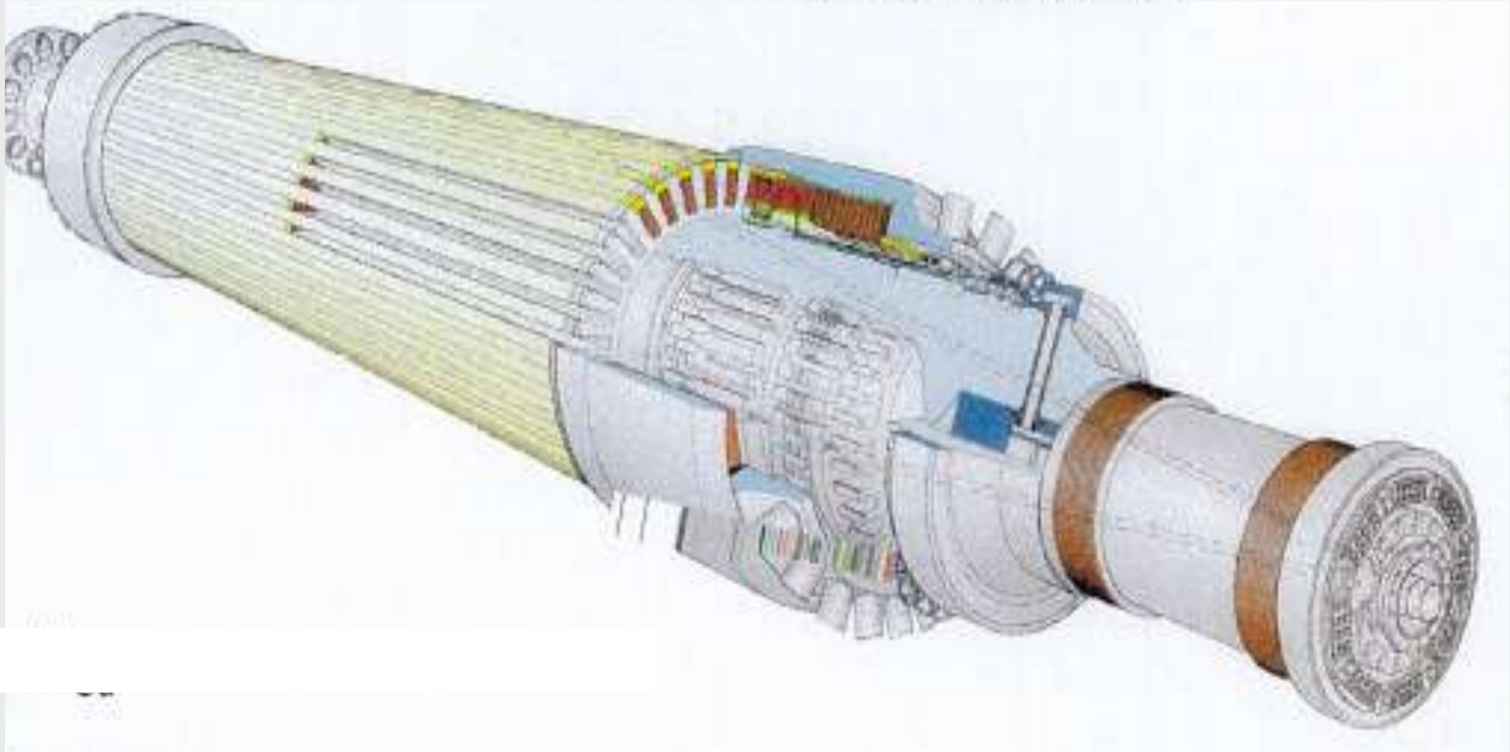
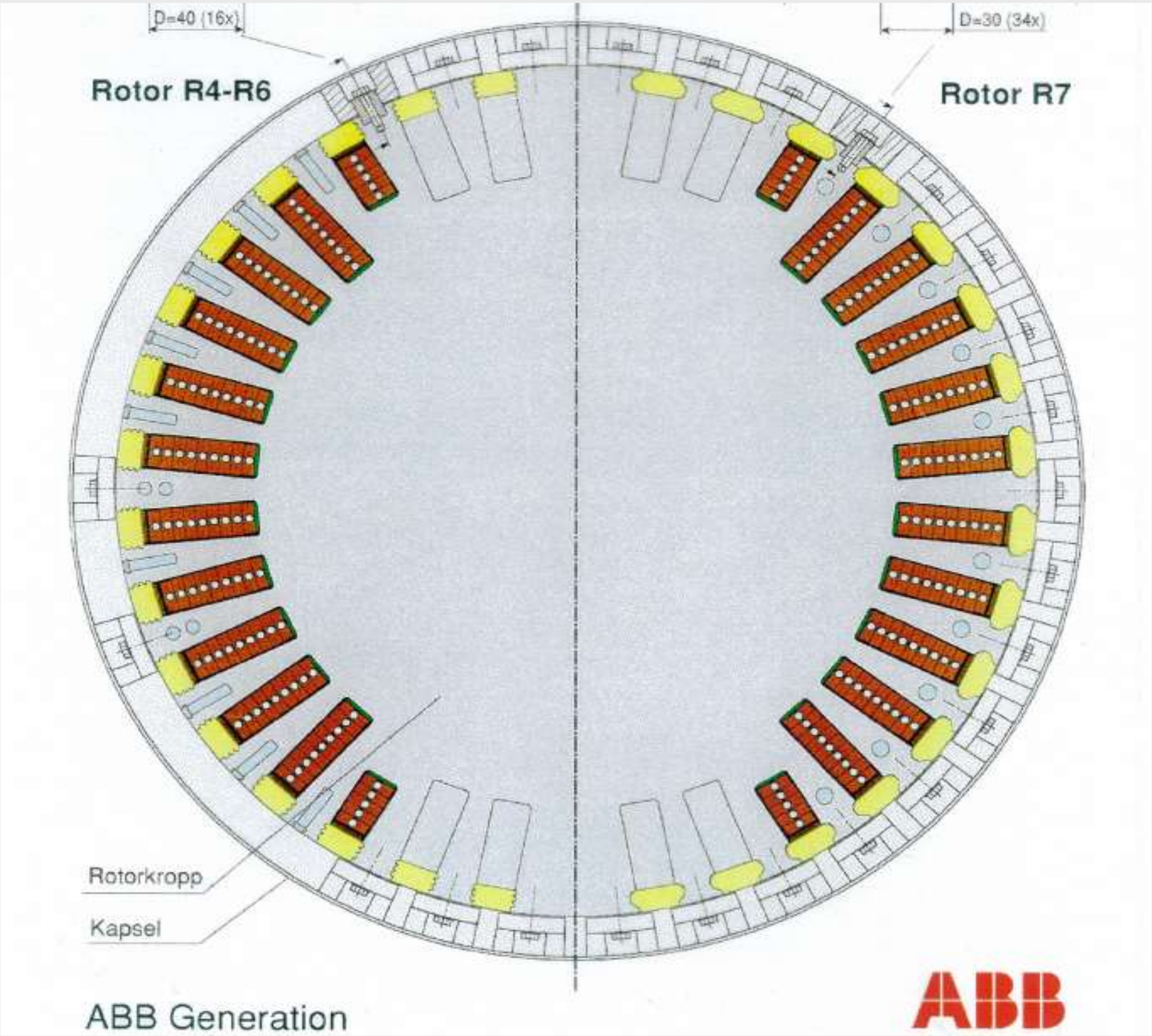
Laval Rotor, unequal moments of inertia

Two Pole Generator



Laval Rotor, unequal moments of inertia

Two Pole Generator, cross section

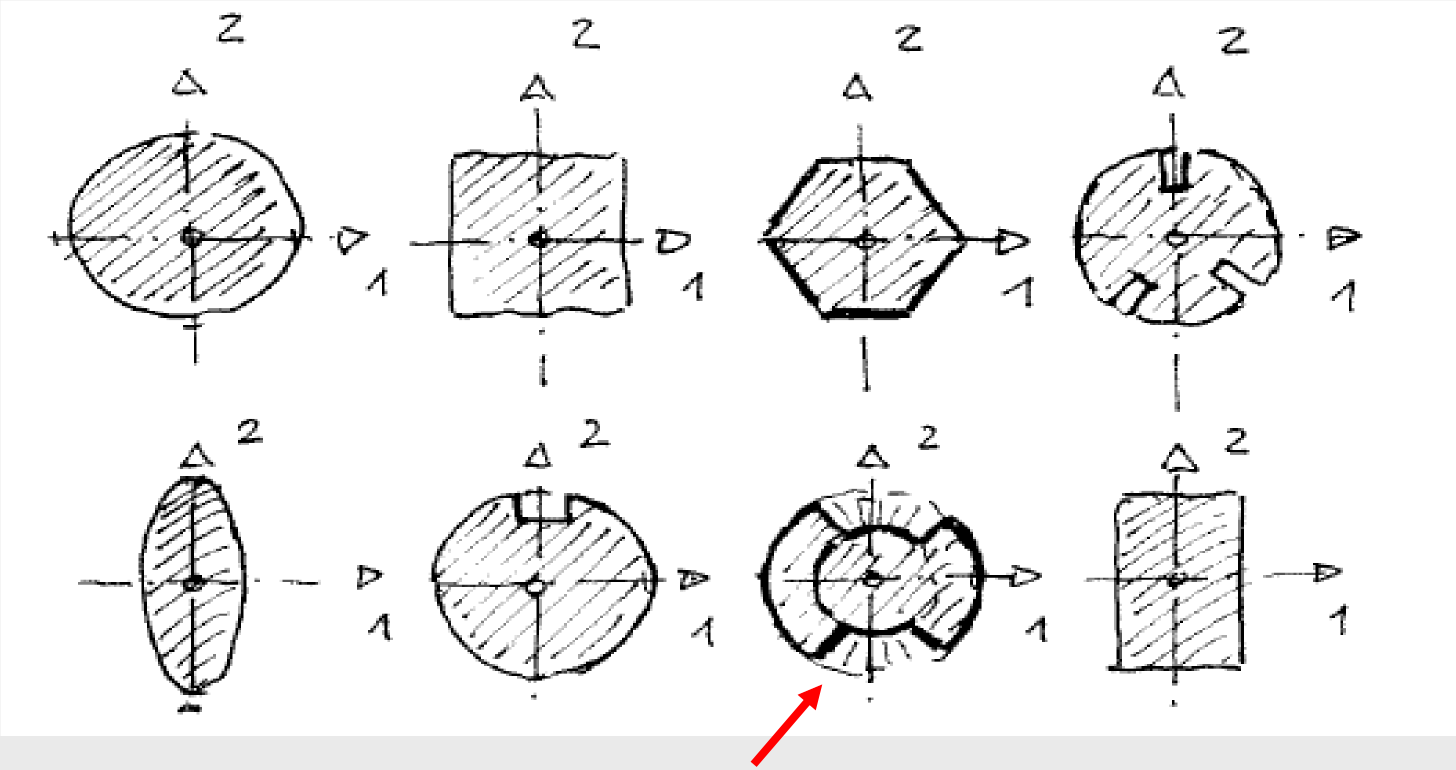


Laval Rotor, unequal moments of inertia

Different cross sections

Cross Section | **Circular** | **Quadratic** | **Hexagonal** | **With 3 slots**

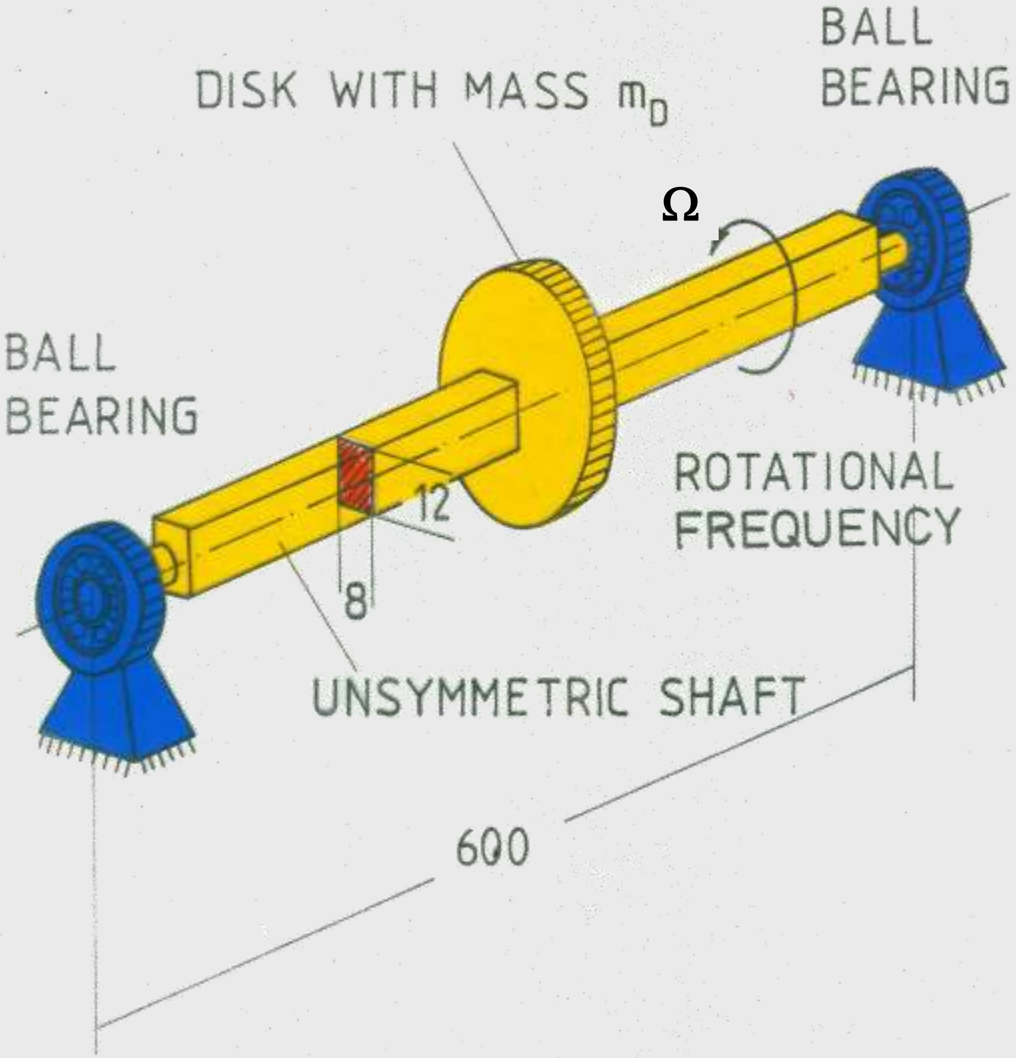
Equal Moments of Inertia



Unequal Moments of Inertia

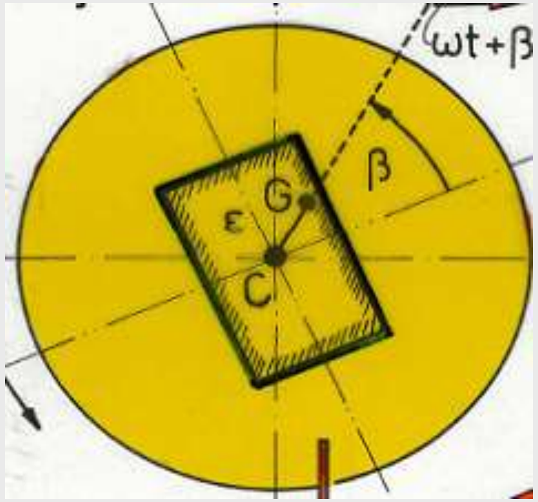
Cross Section | **Elliptical** | **With a Groove** | **Two Pole Generator** | **Rectangular**

Laval Rotor, unequal moments of inertia
Model of rotor with rectangular cross section



Laval Rotor, unequal moments of inertia
Minimum and maximum Stiffness

Direction of Maximum Stiffness kmax

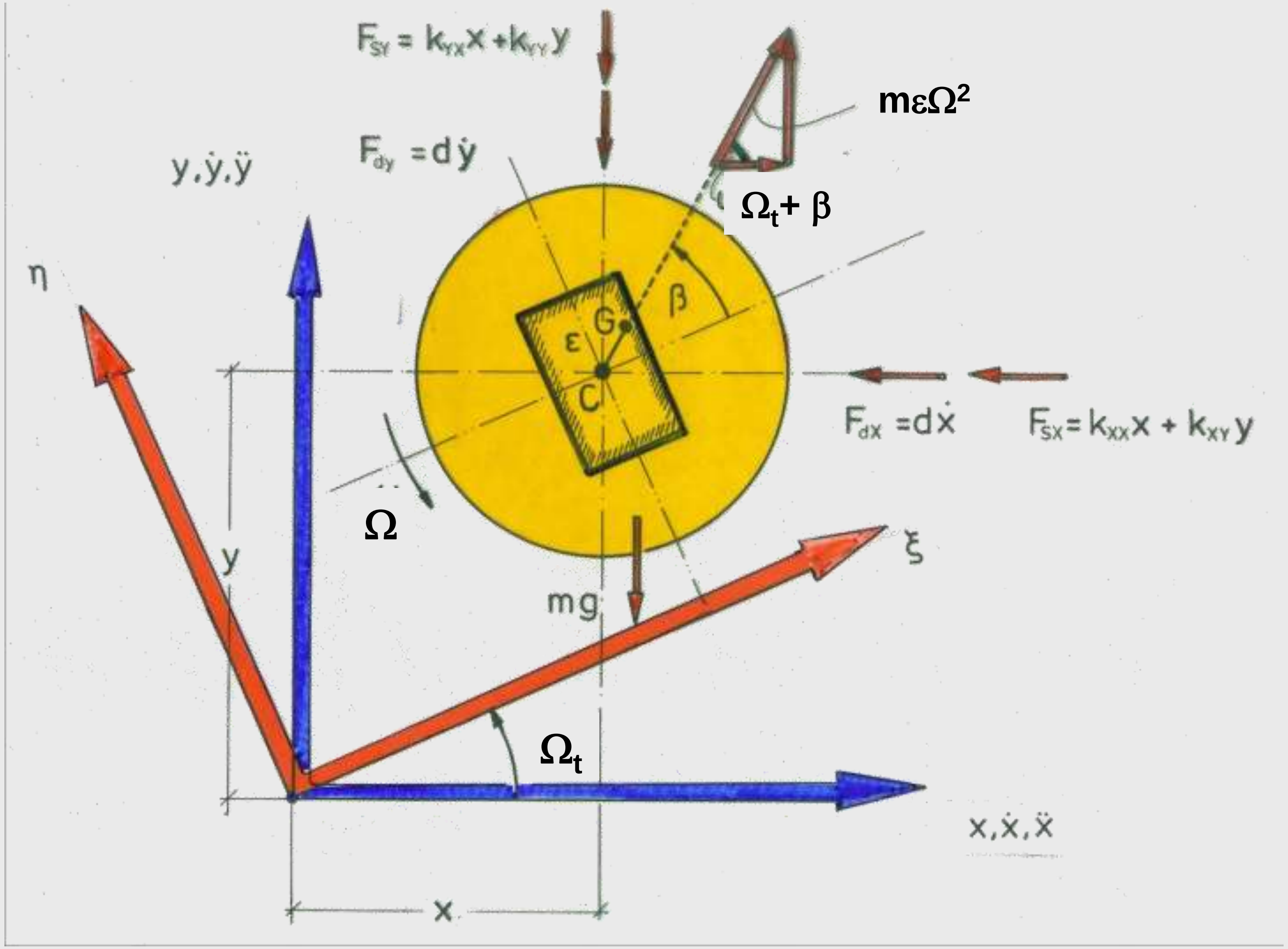


Direction of Minimum Stiffness kmin

Definition of the dimensionless Inequality of the Shaft Stiffnesses

$$\boxed{u = k_{max} - k_{min} \;/\; k_{max} + k_{min}}$$

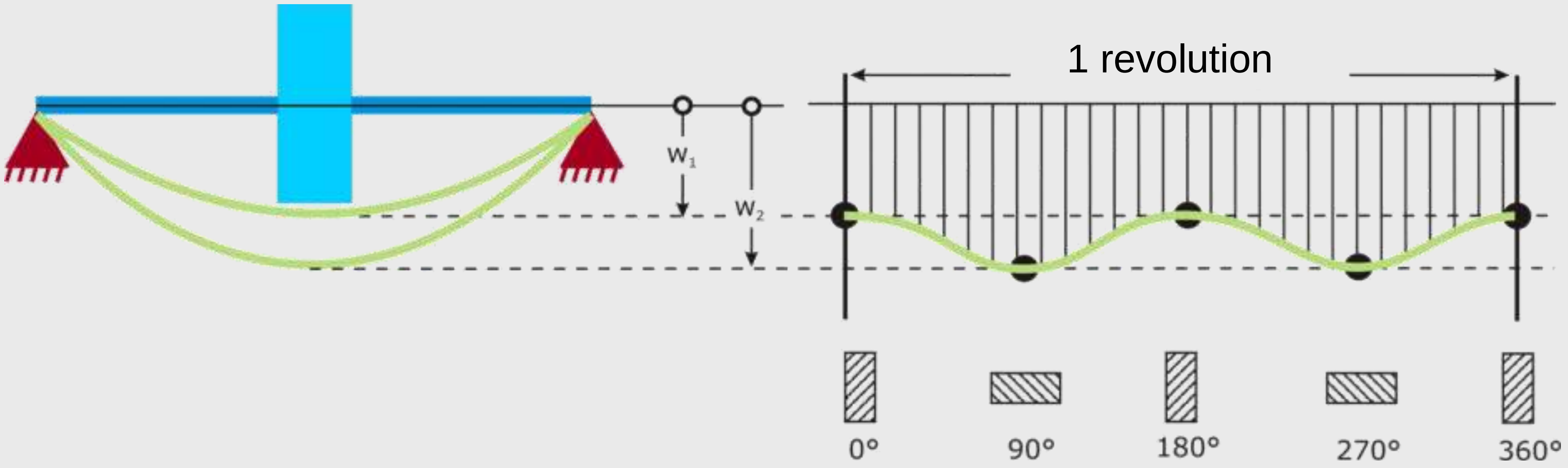
Laval Rotor, unequal moments of inertia
Fixed and rotating coordinate system



Laval Rotor, unequal moments of inertia

Shaft deflection for one revolution

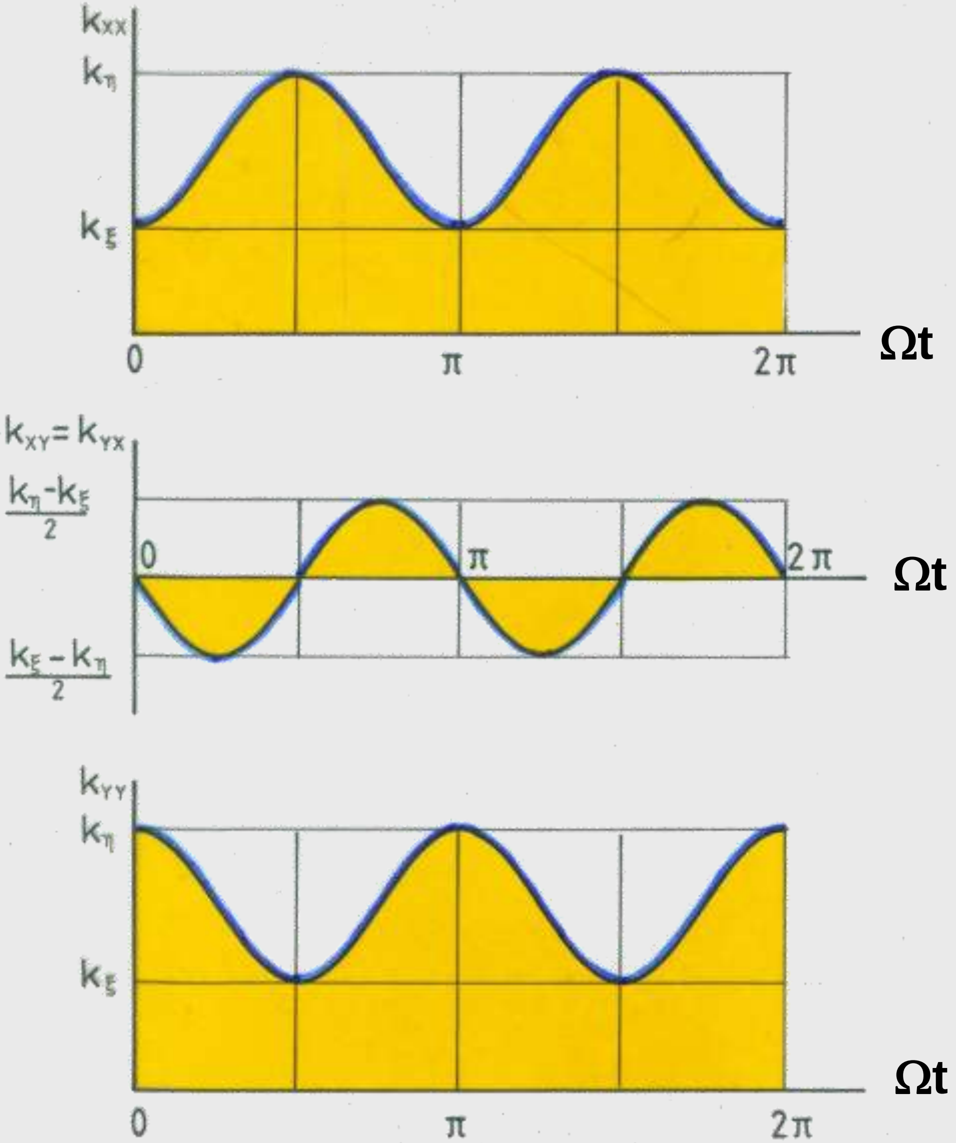
Weight, lifted twice per revolution



IFToMM
2006

Laval Rotor, unequal moments of inertia

Time dependent shaft stiffness



Laval Rotor, unequal moments of inertia

Equations of motion in fixed coordinate system

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} + \begin{bmatrix} d & 0 \\ 0 & d \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} + \begin{bmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} = m\varepsilon\,\Omega^2 \begin{bmatrix} \cos(\Omega t + \beta) \\ \sin(\Omega t + \beta) \end{bmatrix} + \begin{bmatrix} 0 \\ -mg \end{bmatrix}$$

$$\underline{M}^F \cdot \ddot{\underline{x}} + \underline{D}^F \cdot \dot{\underline{x}} + \underline{K}^F(t) \cdot \underline{x} = f_\varepsilon^F(t) + f_G^F$$

$$\underline{K}^F(t) = \frac{k_\eta + k_\xi}{2} \cdot \begin{bmatrix} 1 - \mu\cos 2\Omega t & -\mu \sin 2\Omega t \\ -\mu \sin 2\Omega t & 1 + \mu\cos 2\Omega t \end{bmatrix}$$

k_η, k_ξ	Principal stiffness
$\mu = \dfrac{k_\eta - k_\xi}{k_\eta + k_\xi}$	Dimensionless stiffness unequality

Laval Rotor, unequal moments of inertia

Dynamic Behavior

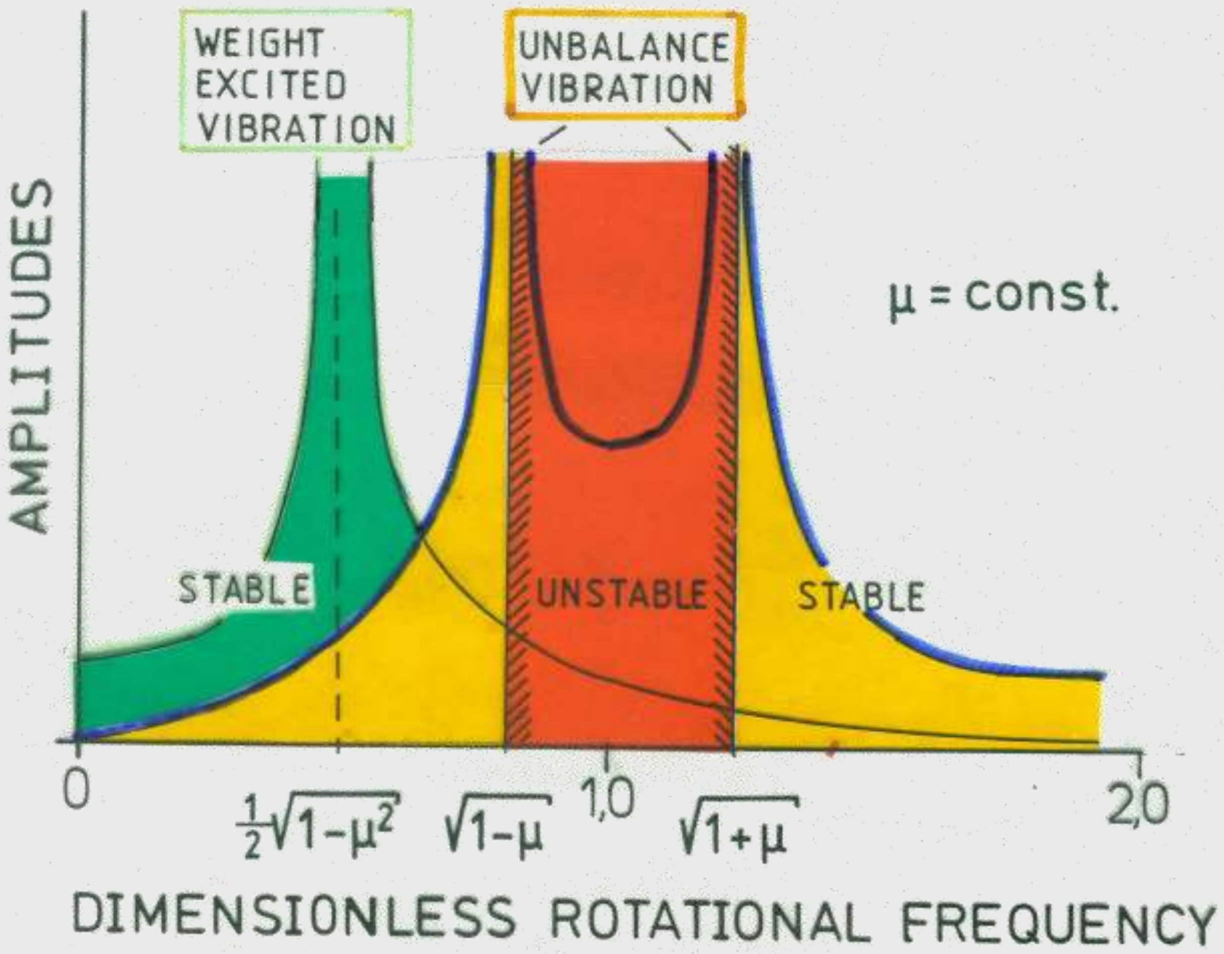
The shaft of the considered Laval Rotor has Unequal Moments of Inertia. Due to the different stiffnesses in the two directions we expect two Natural Frequencies or two Critical Speeds due to Unbalance.

When the shaft rotates the weight of the disk is lifted two times per revolution. For the rotational frequency omega a Frequency of excitation 2xomega is expected. When this Frequency of excitation is equal to a Natural Frequency of the Laval Rotor the Weight Resonance appears.

Between the two Critical Speeds instability may occur.

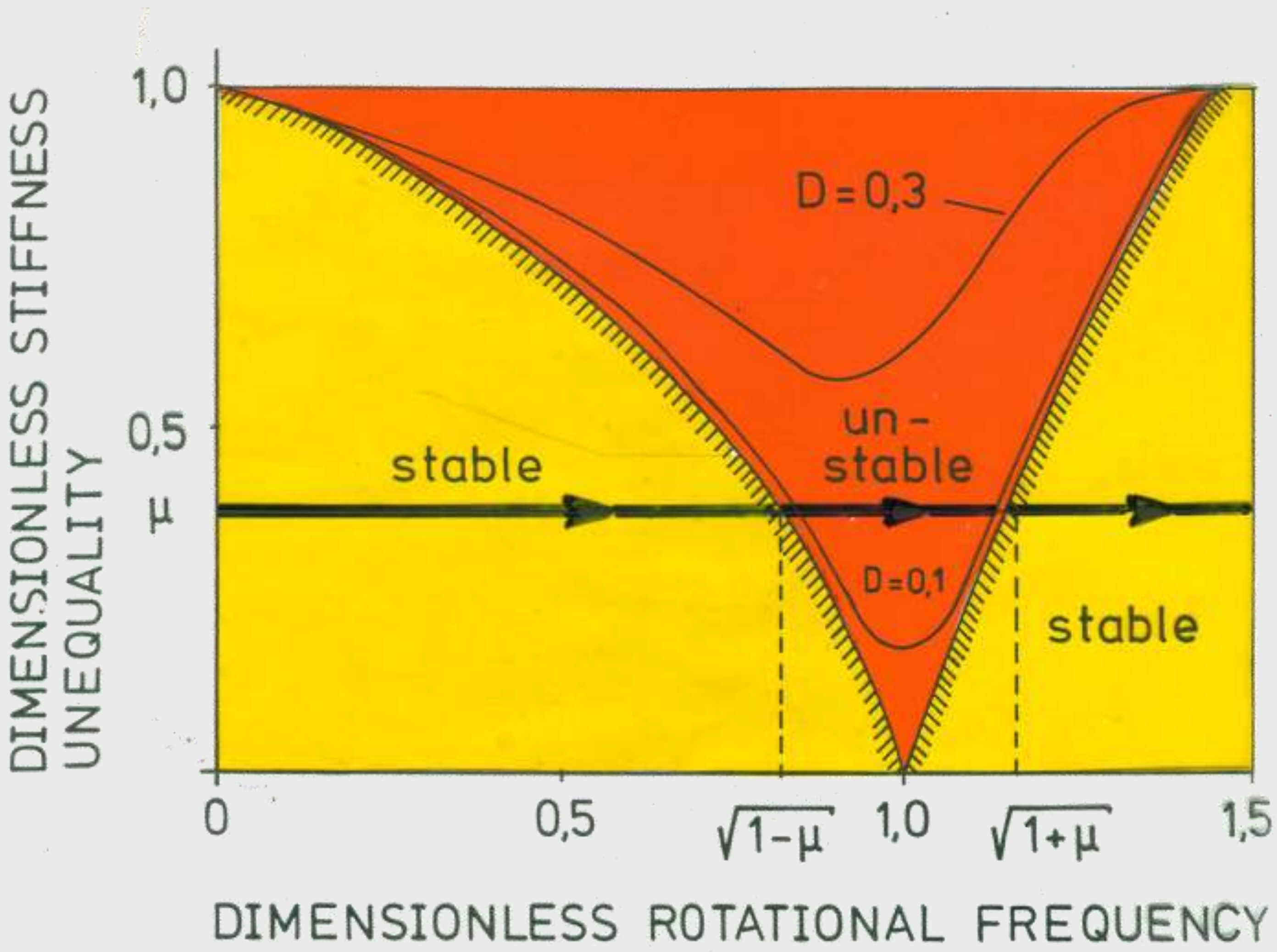
Laval Rotor, unequal moments of inertia

Amplitudes of forced vibrations



Laval Rotor, unequal moments of inertia

Stability map in dependence of damping



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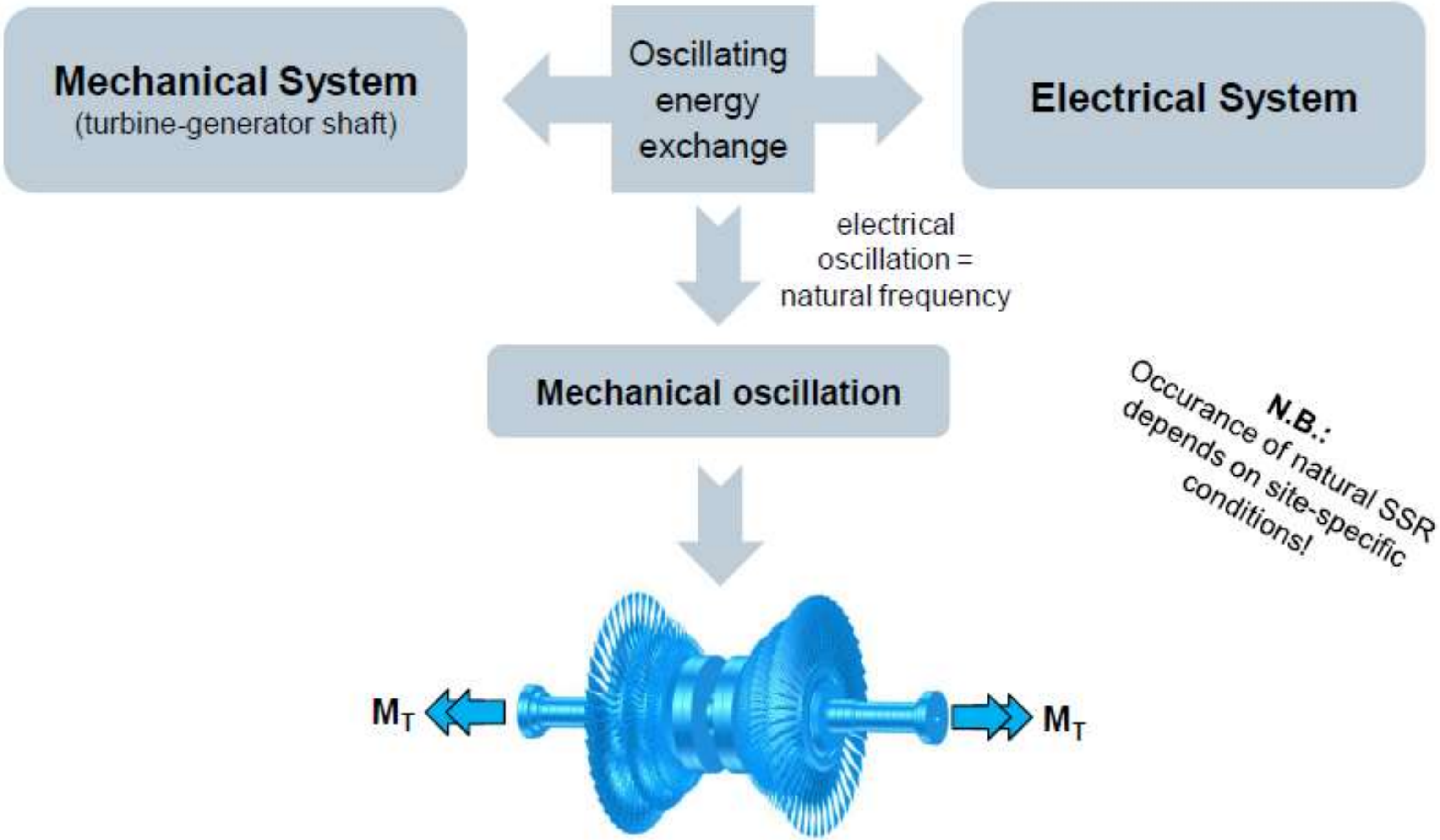
Sub Synchronous Resonance (SSR)

Introduction

Sub Synchronous Resonances are oscillations in the electrical and mechanical systems which occur, when the turbogenerator units feed into a network, the long lines of which are compensated by series capacitors.

An electrical resonant circuit can be triggered by a fault in the electrical system and an exchange of energy can occur between the shaft and the inductive and capacitive elements of the “Generator-Transformer-Line-Network” circuit.

The resulting currents generate low Frequency Electrical Torques in the Generator air gap.



Mechanical System
(turbine-generator shaft)

Oscillating energy exchange

Electrical System

electrical oscillation = natural frequency

Mechanical oscillation

N.B.:
Occurance of natural SSR depends on site-specific conditions!

Sub-synchronous resonance is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system.

(IEEE SSR Working Group, "Proposed Terms and Definitions for Subsynchronous Resonance," IEEE Symposium on Countermeasures for Subsynchronous Resonance, IEEE Pub. 81TH0086-9-PWR, 1981,p 92-97.)

Natural frequencies
below the synchronous frequency

If these frequencies are in the vicinity of one of the lowest Natural Torsional frequencies of the shaft line, the shaft assembly may be excited to strong Resonant Vibrations.

These in turn are transmitted into the electrical system by the electromechanical coupling. The electro-mechanical damping of the coupled system may be low or even negative.

If the damping is negative, there is an increase in the torsional vibrations and in the electrical torque, which may lead to high stresses and even to damage.

In order to protect the mechanical system of the shaft train against Sub Synchronous Resonances, control systems have been developed.

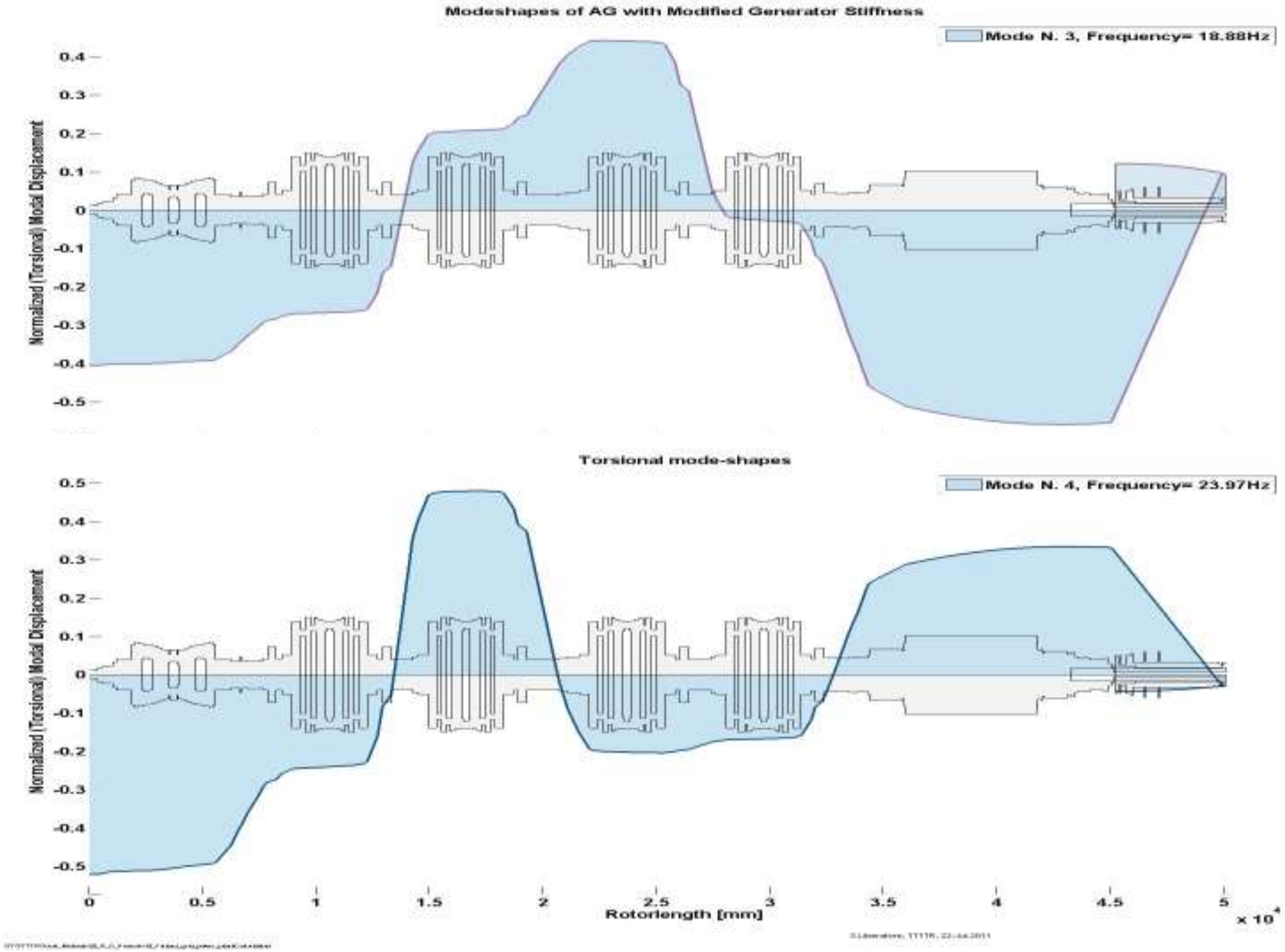
Such control systems need as input data the torsional natural frequencies of the shaft train in the low frequency range (sub synchronous) and in addition the maximum allowable angular displacements of the sub synchronous oscillation modes for the generator angle (measurement location) before any part of the shaft system has reached its fatigue limit.

These numerical data have to be delivered by the manufacturer. As an example the following shows the torsional natural frequencies of the shaft train in a Finish power plant in the low frequency range.

Eigenfrequencies - Modeshapes

Mode N.	Frequency (Hz)	Description of modes
1	7.7	Exciter quill-shaft
2	9.3	Shaft-line 1st (quill-shaft in antiphase)
3	18.9	Shaft-line 2nd (LP3–HP–Gen.)
4	24.0	Shaft-line 3rd (LP2–HP–LP4+Gen.)
5	29.1	LP4-LP3-Gen.
6	35.7	HP-LP1
7	119.3	Exciter 1st mode
8	124.5	Generator 1st mode

Eigenfrequencies - Modeshapes



Vorlesungen Mechatronik im Wintersemester

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

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Lecture IV Vibrations in Generators of Turbogenerators

Rainer Nordmann
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