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EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Selected Topics in Electrical Machines (KEV/VPS)

Noise and vibration in electrical machines

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Noise and vibration in electrical machines

- Unwanted, but usually common effect of machine operation
- Causes of origin
  - Work principle => side effect of main physical processes
  - Manufacturing process – construction, technology, tolerance, imperfections, assembly
  - Founding of the machine or other drive components
  - Faults

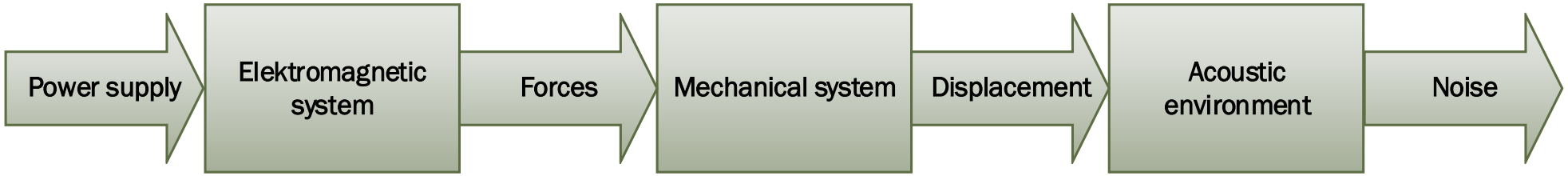
Noise and vibration in electrical machines

- **e-NVH** = *electromagnetically-excited Noise, Vibration and Harshness*

- Why noise and vibration?
  - High torque / power density (EV/HEV) ==> higher excitation
  - Material savings (less robust structure) ==> lower stiffness of structures
  - Robust design ==> long-term operation (energy & industry sector)
  - Health & Environment ==> Hygienic standards for noise and vibration
  - Comfort ==> Psychoacoustics

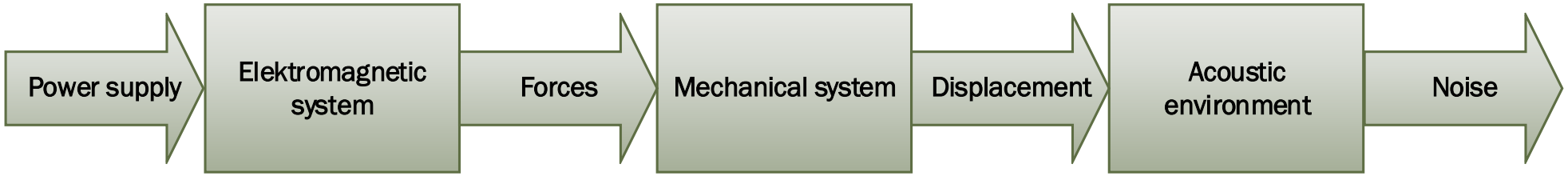
Noise and vibration in electrical machines

- Origin of electromagnetically-excited noise and vibration
  - Time variant magnetic forces
  - Set of energy conversions from electrical to acoustic one



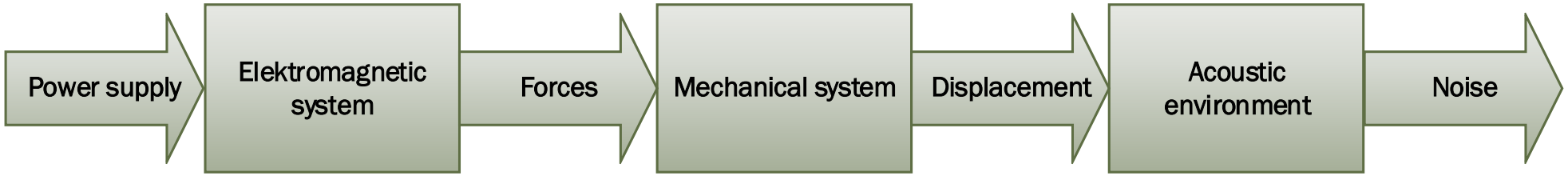
Noise and vibration in electrical machines

- Electromagnetic system
  - Winding and magnetic circuit
  - AC current or rotating DC field / PM => time variant magnetic forces



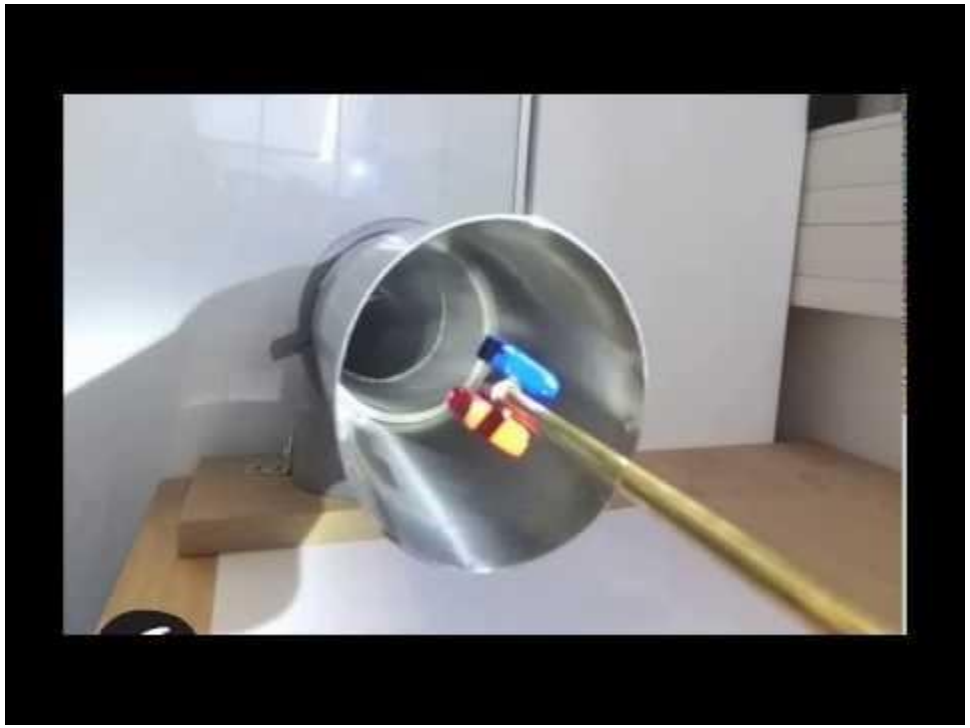
Noise and vibration in electrical machines

- Mechanical system
  - Stator lamination, winding incl. insulation system, machine frame (+ possibly columns for mounting of stator sheets etc.)
  - Time variant magnetic forces => vibration (elastic deformation) of stator teeth and other structural parts



Noise and vibration in electrical machines

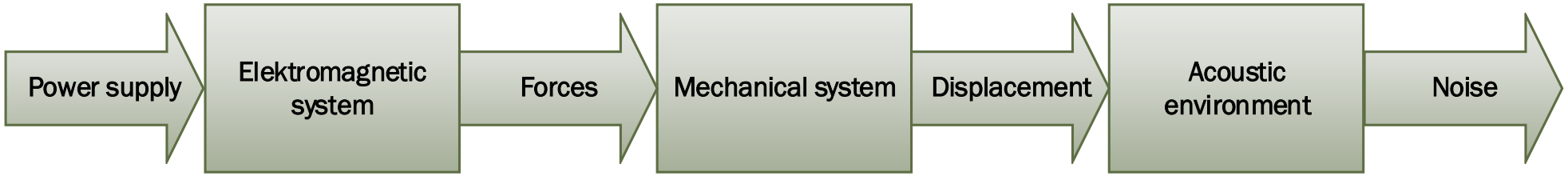
- Time variant magnetic forces => vibration (elastic deformation) of stator teeth and other structural parts



- Video link

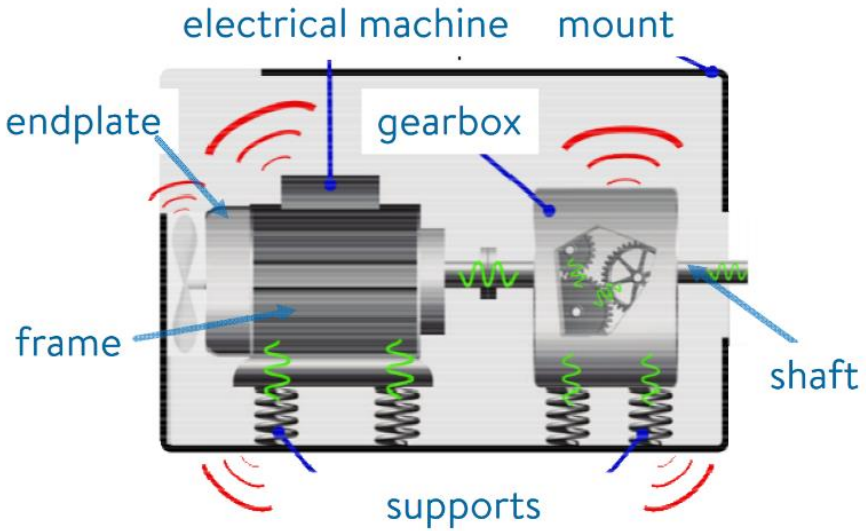
Noise and vibration in electrical machines

- Acoustic environment
  - Fluid surrounding the machine – usually air
  - Vibration of structural parts surrounded by air => acoustic energy radiation (noise)



Noise and vibration in electrical machines

- Noise transfer paths
  - Airborne noise = movement of large amount of air under a high pressure
  - Structure-borne noise = transfer in solid bodies via vibrations



Source: EOMYS Engineering

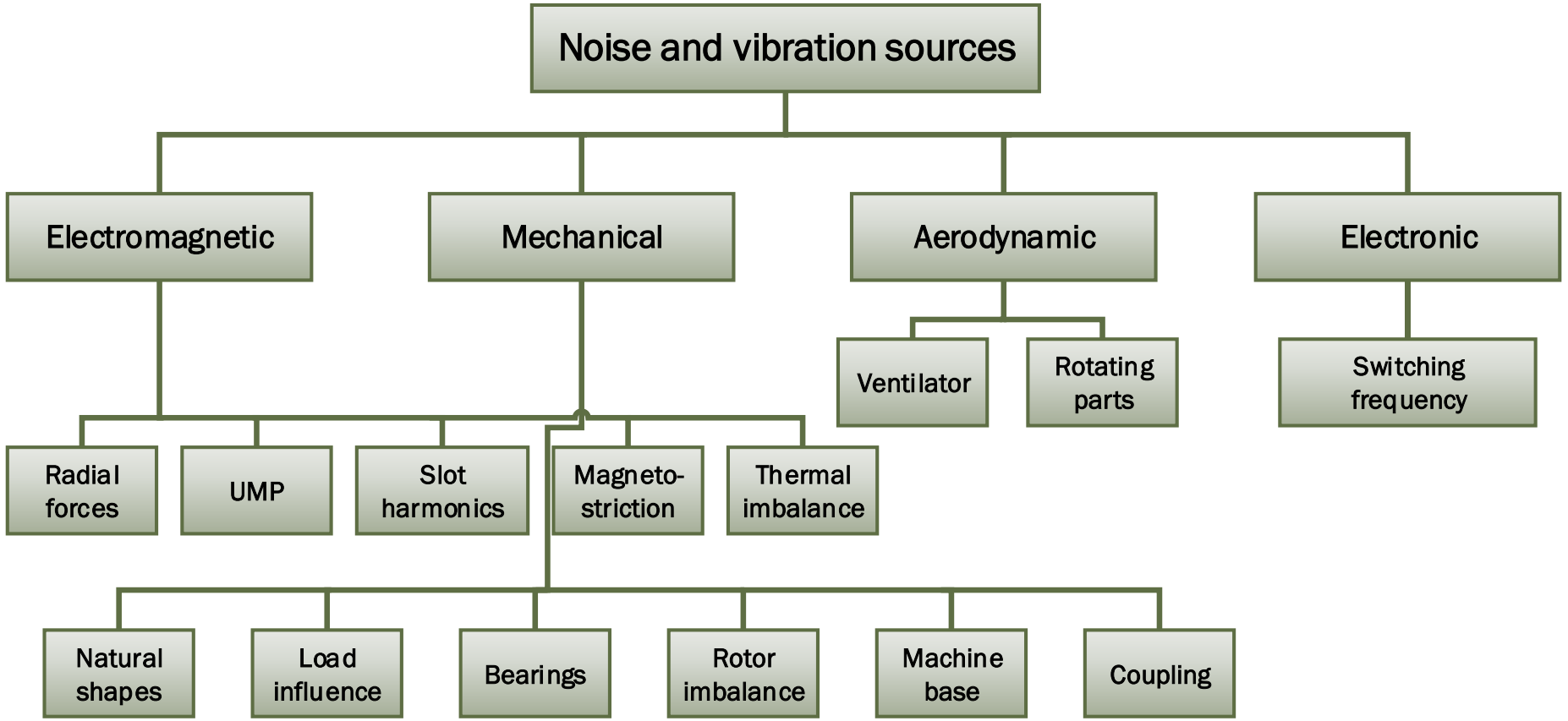
Noise and vibration in electrical machines

- **Noise and vibration sources**

- According to location
  - Inner
  - Outer

- According to the cause
  - Electromagnetic
  - Mechanical
  - Aerodynamic
  - Electronic

Noise and vibration in electrical machines



Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**

- Magnetic force value proportional to the square of air gap flux density

$$\Delta p(\xi,t) = \frac{B^2(\xi,t)}{2\mu_0}$$

- Force change in both time and space

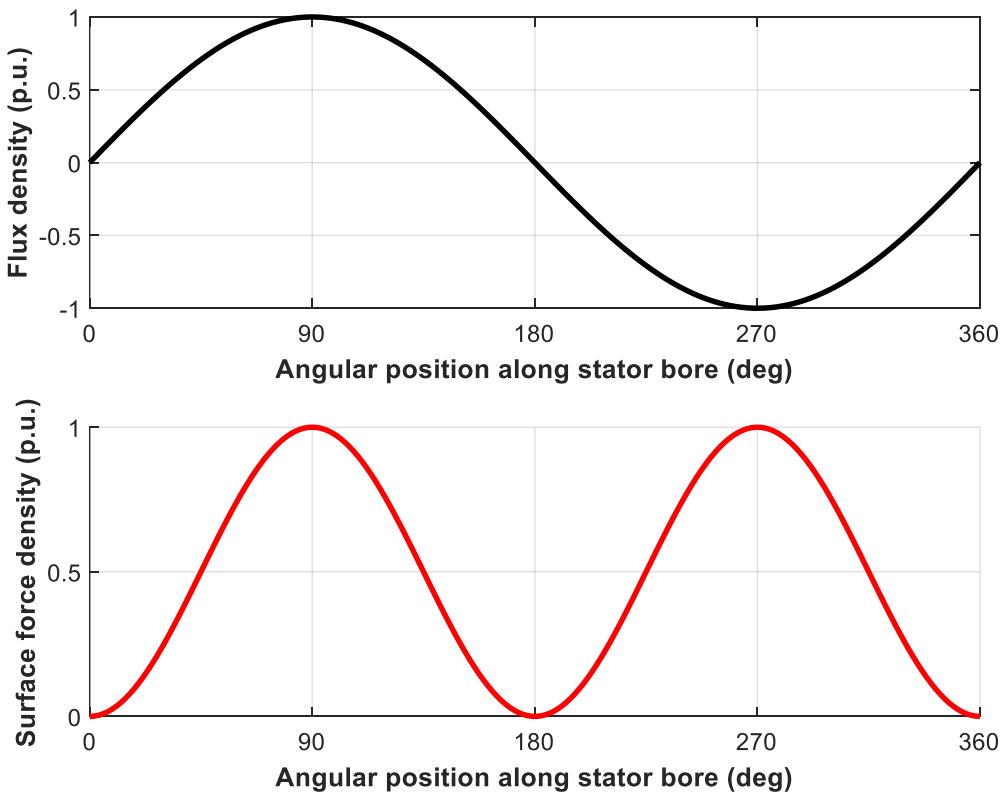
Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**

- Flux density square => two force maxima in each period (positive and negative half cycle of magnetizing current / flux density)

- Vibration fundamental => twice line frequency *2L*

- Coincidence / proximity of *2L* and *2X* for 2p = 2



Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**

- Interface of materials having different permeability (ferromagnetic material – air)

- Force acts in direction of lower permeability material

- Attractive force between rotor and stator

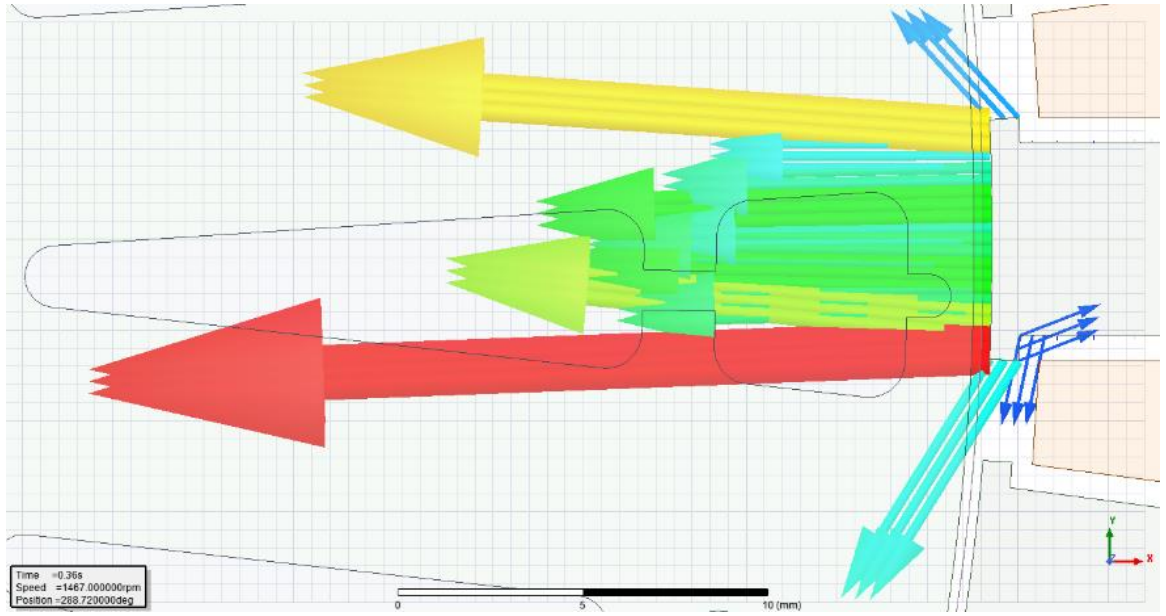
- Possibility of natural shapes excitation

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**

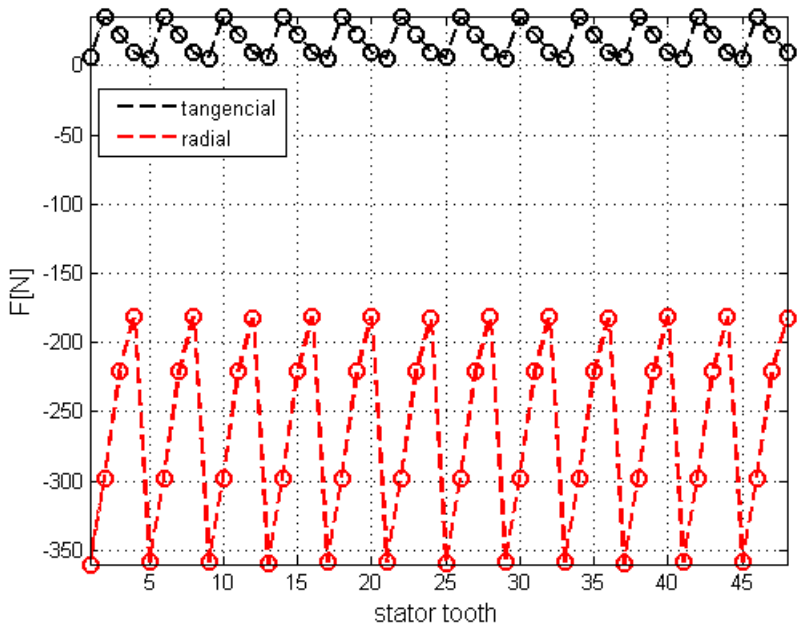
- Surface force density vectors concentrated on the tooth tip in an air gap direction

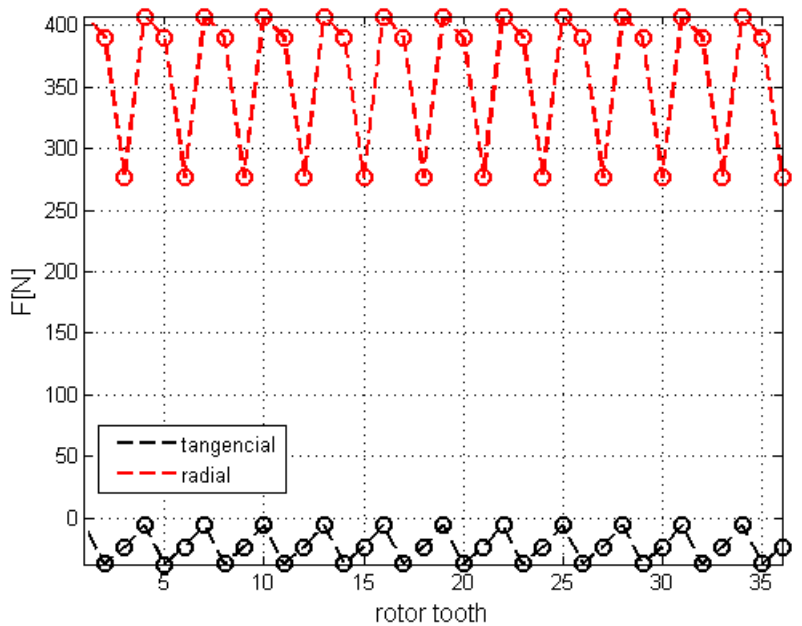
- Forces inside the slot can be neglected



Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**





Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Radial magnetic forces**

- Magnetic forces at 2L act also on endwindings
  - Binding and fastening to the supporting ring
  - Bar windings => insulation abrasion in the slot end area
    => insulation destruction





Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Unbalanced magnetic pull (UMP)**

- Magnetic field asymmetry
  - **Magnetic circuit** – rotor eccentricity, eliptical stator nebo rotor, bent shaft, uneven slot pitch around stator/rotor circumference, etc.
  - **Asymmetry of winding / power supply** – different number of turns, inter-turn short-circuit, broken rotor bar etc.
  - => magnetic force imbalance around air gap circumference => UMP acts in resultant force direction

- Excessive vibration, additional bearing load, bent shaft

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Unbalanced magnetic pull (UMP)**

- Eccentricity can be static, dynamic or mixed

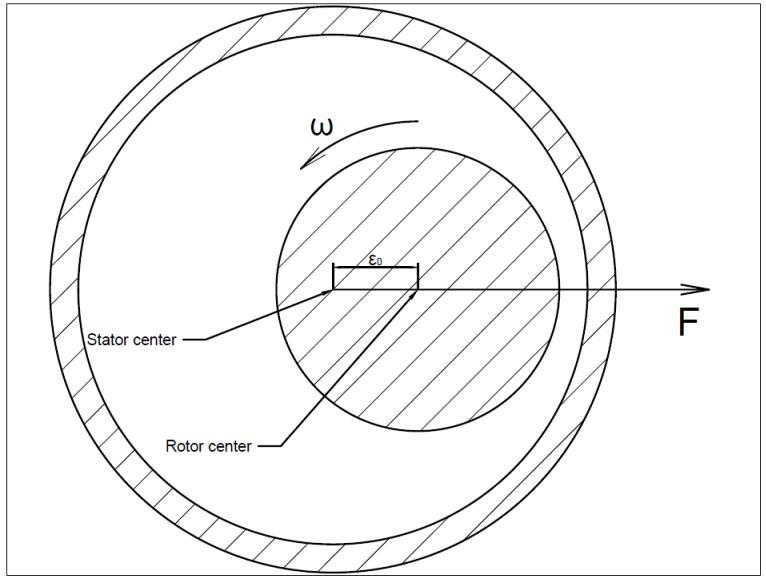
- Uneven air gap length around its circumference

- Shorter air gap legth => higher saturation => higher force in that direction => unbalanced magnetic pull

Noise and vibration in electrical machines

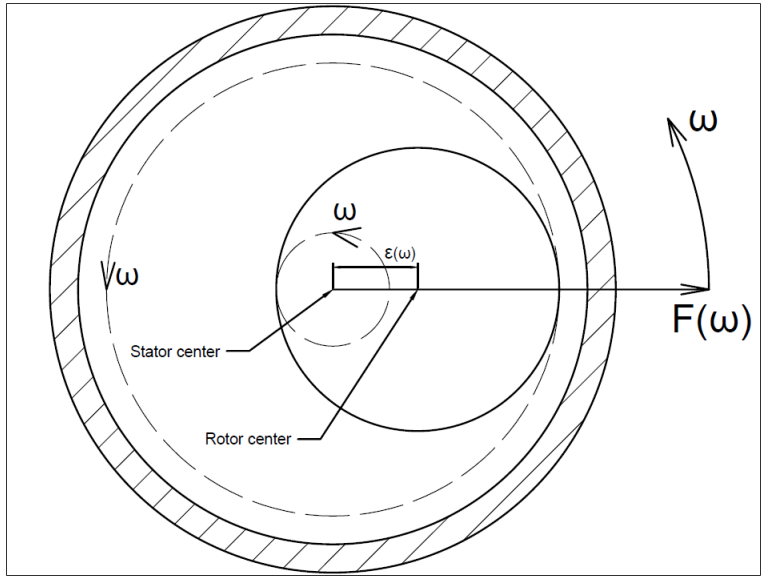
- **Electromagnetic noise and vibration sources**
- **Unbalanced magnetic pull (UMP)**

- Static eccentricity
  - Rigid shaft set into stator with a slight misalignment from stator axis
  - Rotor revolves around its own axis
  - Minimal air gap length position time invariant =>
    => UMP value and direction invariant
  - Can cause shaft deflection
  - Vibration at *2L*



Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Unbalanced magnetic pull (UMP)**



- Dynamic eccentricity
  - Shaft deflection due to manufacture fault or thermal imbalance
  - UMP direction changes with revolving rotor
  - Shaft and stator vibration at rotational frequency *1X*

$$f_{1X} = \frac{n}{60}$$

  - IMs have sidebands shifted of

$$f_p = 2pf_s$$

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Unbalanced magnetic pull (UMP)**

- High frequency noise due to eccentricity
  - ***c*** is any integer, k_e is zero for SE and low integer for DE, ***s*** is per unit slip and ***e*** is zero or even integer

$$f_{ecc} = \left[\left(cQ_r \pm k_e \right) \frac{1-s}{p} \pm e \right] f_L$$

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Slot harmonics**

- High frequency noise due to stator and / or rotor slotting

- Slot harmonics vibration caused by leakage magnetic fields around rotor conductors (bars) => force acting on stator teeth

- Frequencies often above 1 kHz => out of standard vibration diagnostics range

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Slot harmonics**

- Rotor bar (slot) passing frequency

$$f_{Qr} = \frac{nQ_r}{60}$$

- Sidebands shifted of + or – *2L, 4L, 6L, …*

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Magnetostriction**

- Change in shape and dimension (µm) due to AC magnetization of ferromagnetic material
  - Orientation of magnetic domains (and its wall motion) inside material along the magnetic field direction

- Vibration at odd multiples of *2L*

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Magnetostriction**

- Not important noise source in rotating machines

- Dominant noise source in transformers
  - Low frequency „humming“
  - Grows with the core saturation (B^2)
  - Influence of lamination pressing force

Noise and vibration in electrical machines

- **Electromagnetic noise and vibration sources**
- **Thermal imbalance**

- Rotor deflection due to uneven warming-up (e.g. shorted rotor lamination or different conductivity of rotor bars)

- Increased vibration at rotating frequency *1X*

- No symptoms in case of cold rotor => vibration grows with temperature

Noise and vibration in electrical machines

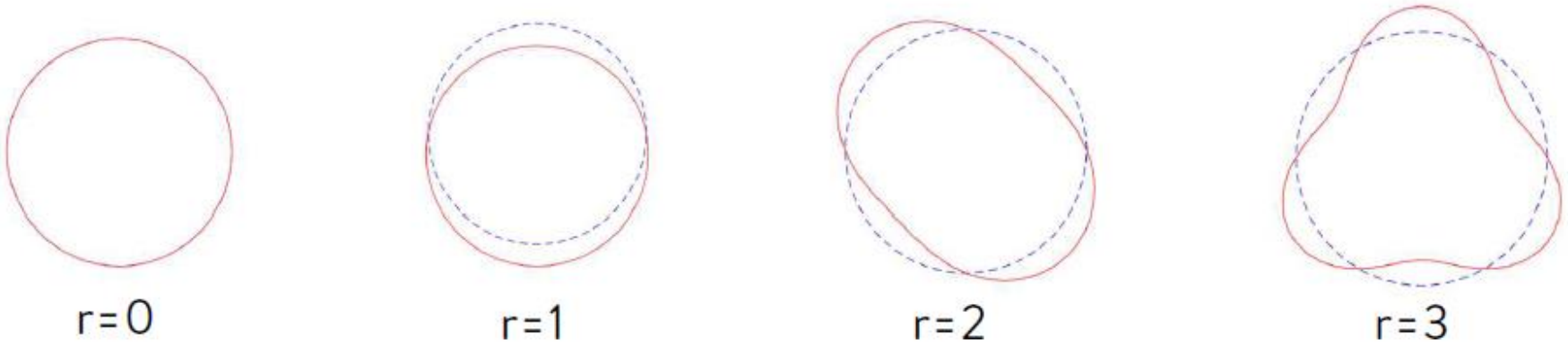
- **Mechanical sources of noise and vibration**
- **Natural shapes (modes)**

- Natural frequency = frequency of strong oscillations (resonance) of the system even in case of weak excitation

- Natural shape = shape (mode) of vibration waveform corresponding to the particular natural frequency

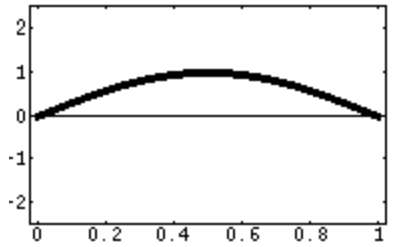
Noise and vibration in electrical machines

- **Mechanical sources of noise and vibration**
- **Order of magnetic force wave around stator bore**

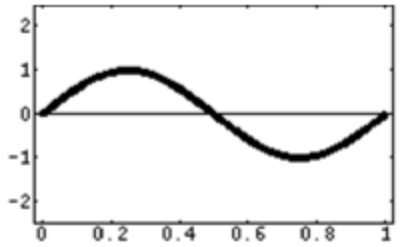


Noise and vibration in electrical machines

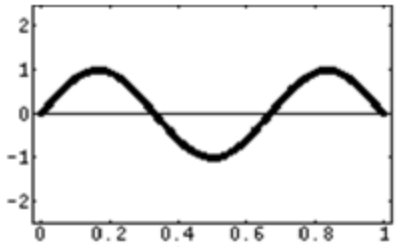
- **Mechanical sources of noise and vibration**
- **Natural shapes**



1st mode

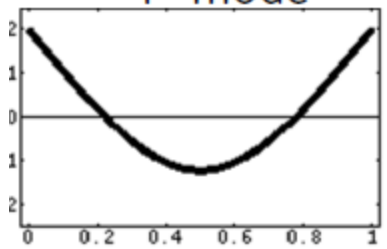


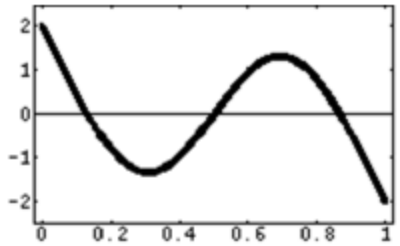
2nd mode

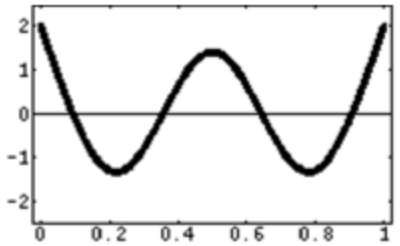


3rd mode

simply supported at both ends



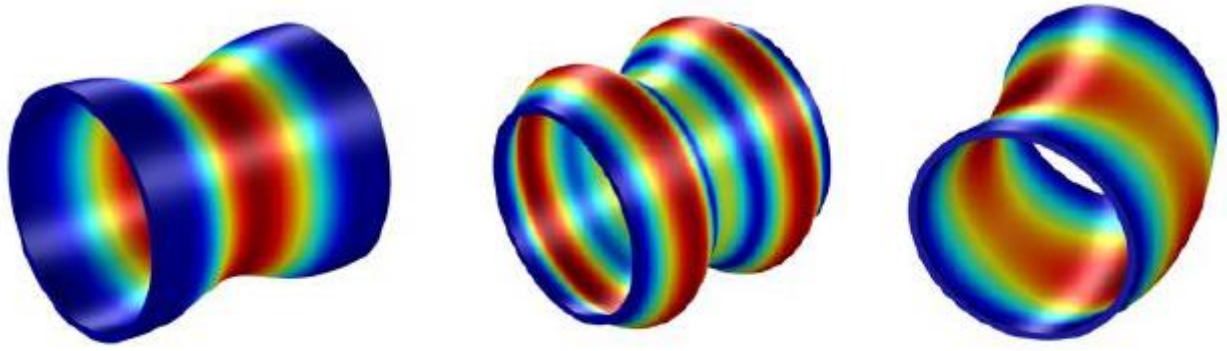




free-free

Noise and vibration in electrical machines

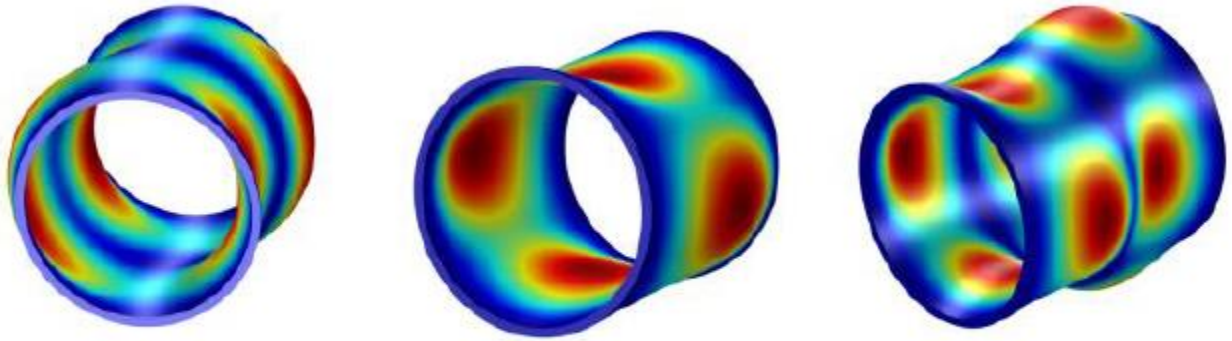
- **Mechanical sources of noise and vibration**
- **Natural shapes**



m = 0, n = 1 m = 0, n = 3 m = 1, n = 1

Noise and vibration in electrical machines

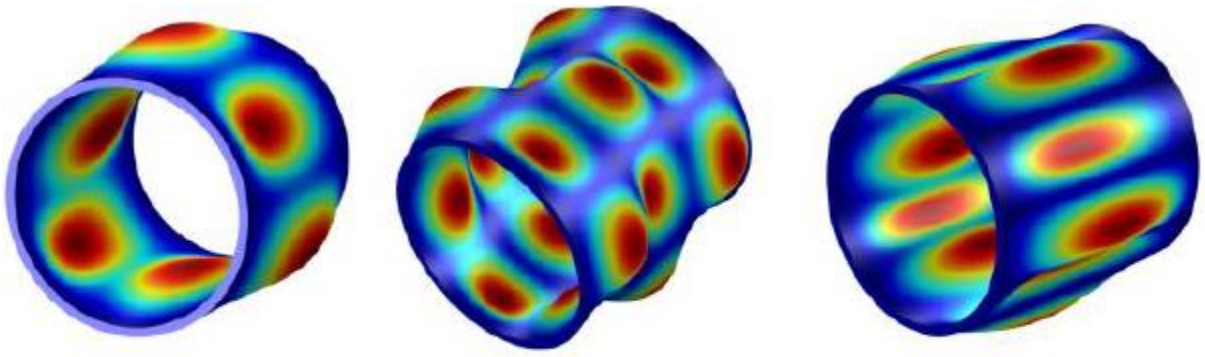
- **Mechanical sources of noise and vibration**
- **Natural shapes**



m = 1, n = 2 m = 2, n = 1 m = 2, n = 2

Noise and vibration in electrical machines

- **Mechanical sources of noise and vibration**
- **Natural shapes**



m = 3, n = 1 m = 3, n = 3 m = 6, n = 1

Thank you

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