New technologies of electric energy converters and actuators

Contents

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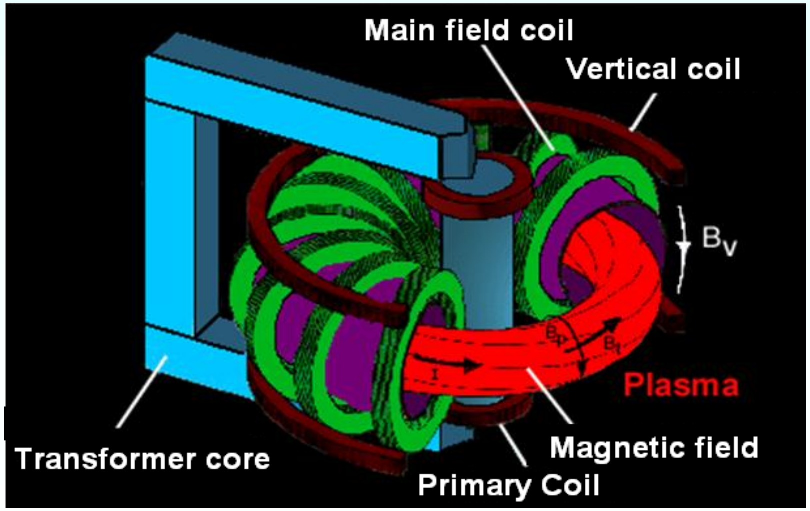

New technologies of electric energy converters and actuators

3. Magnetic bearings („magnetic levitation“)

Used literature

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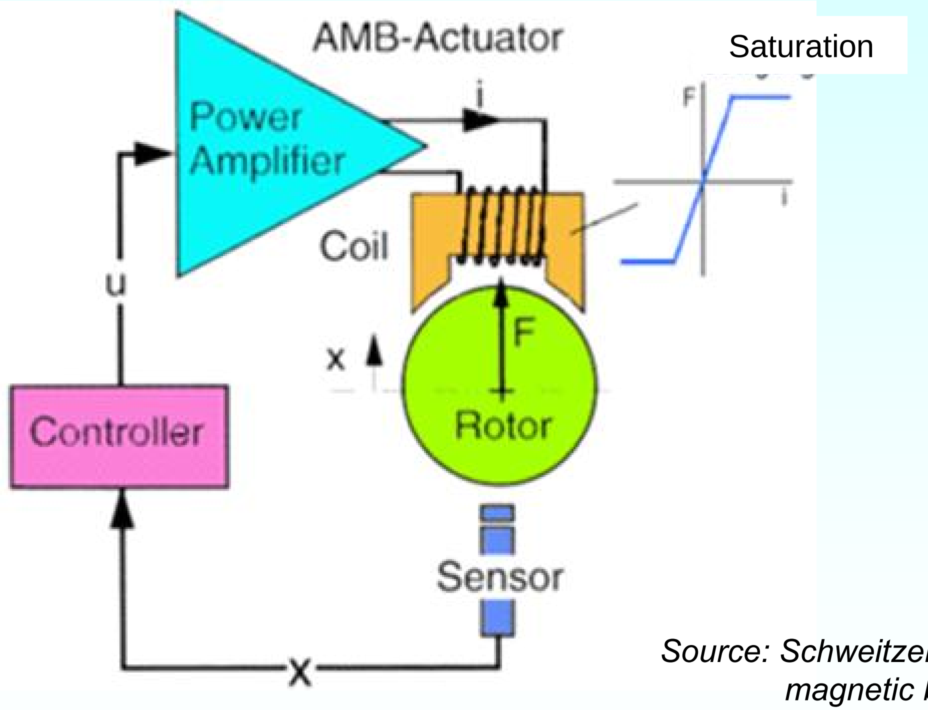
3. Magnetic bearings („magnetic levitation“)

3.1 Basics of magnetic levitation



Source: Schweitzer, G. et al.: Active magnetic bearings

3.1 Magnetic bearing principles

- Levitation force = Magnet force: a) with **reluctance forces**, b) with ***Lorentz*-forces**.
- **Passive (non-controlled, self-stable)** und **active (controlled) magnetic levitation**
- **Electro-magnetic levitation (EML):** ***Maxwell*´s stress on magnetized matter ($\mu > \mu_0$)**

Attractive magnetic force

active (controlled) levitation

Electro-dynamic levitation (EDL): Force through eddy currents used

Repulsive magnetic force

passive (self-stable) levitation

Diamagnetic levitation: Force on diamagnetic matter ($0 < \mu < \mu_0$)

Repulsive magnetic force

passive (self-stable) levitation

Earnshaw-Theorem

- ***Earnshaw*-Theorem: 1842:**

The position of electric or magnetic poles of opposite polarity is not stable, if the attractive force between them is proportional to the inverse square of the distance between the poles.

- This is valid for all materials with $\mu_r \geq 1$, therefore for EML-Systems. For that case the *Earnshaw* theorem will be proven later in this chapter.

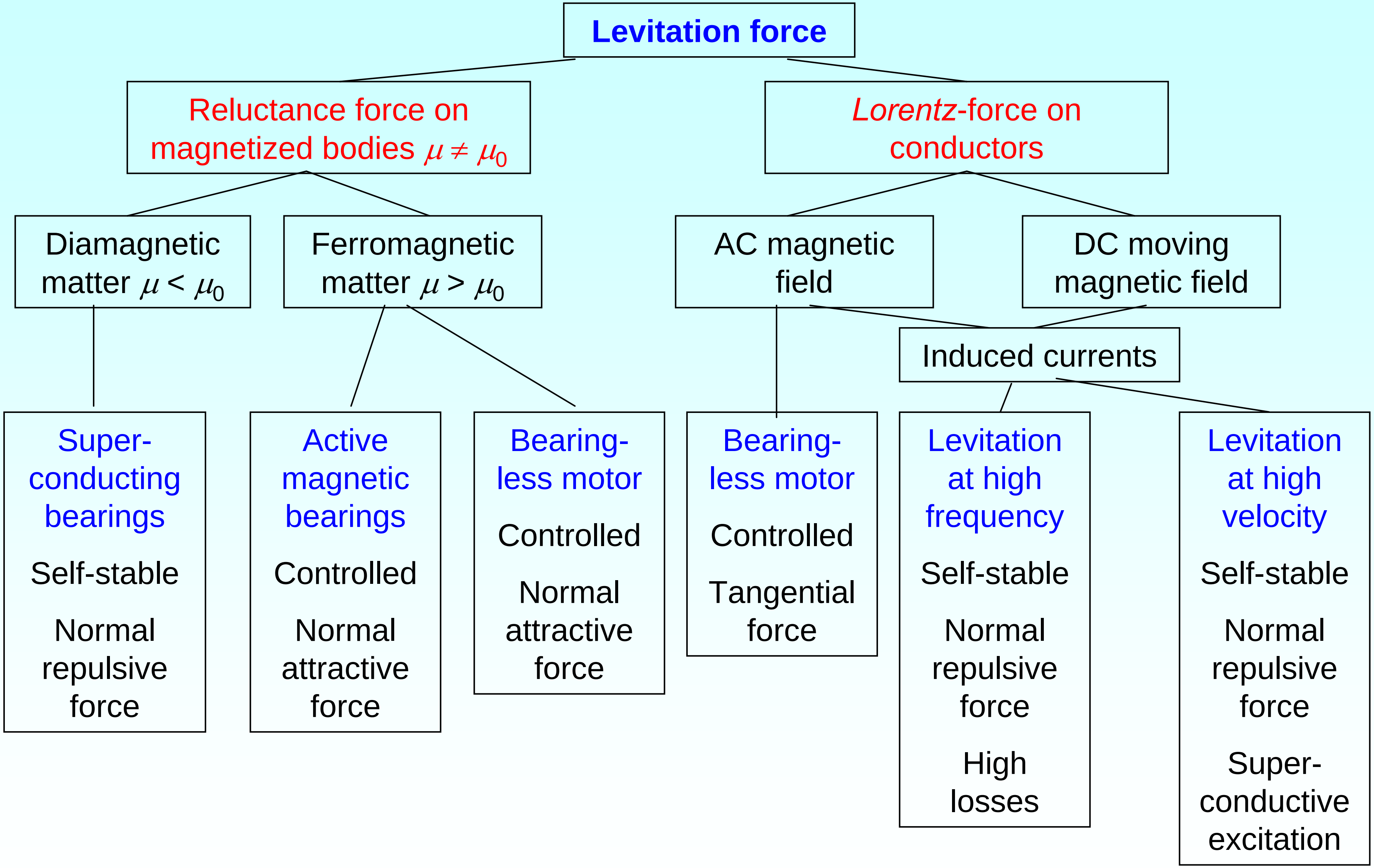
- For diamagnetic materials ($0 \leq \mu_r < 1$) the position is stable without control.

- As eddy currents excite fields, opposing the primary inducing field, the resulting field is smaller than the primary one. Hence the system acts like a diamagnetic system: $0 \leq \mu_r < 1$. It is stable without control.

- Self-stable levitation systems:
  - **electro-dynamic levitation (EDL)**
  - **superconducting bearings (e. g. *Meissner-Ochsenfeld* effect)**

Facit: *The electro-dynamic levitation principle works only well in structures without ferro-magnetic material, so that the repulsive force is not reduced by an attractive one.*

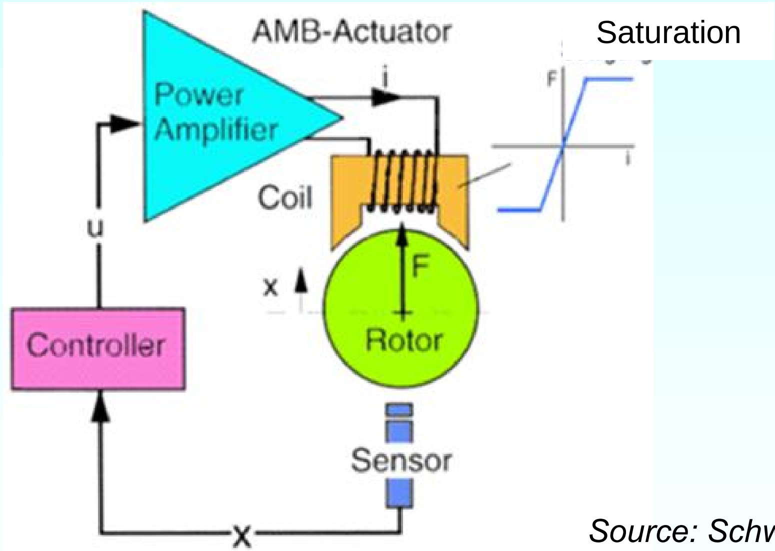
3.1 Basics of magnetic levitation



New technologies of electric energy converters and actuators

3. Magnetic bearings („magnetic levitation“)

3.2 Electromagnetic levitation

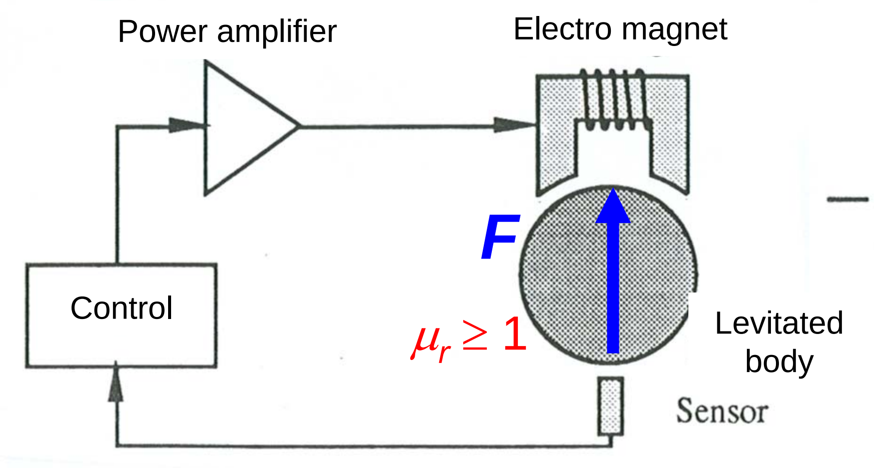


Source: Schweitzer, G. et al.: Active magnetic bearings

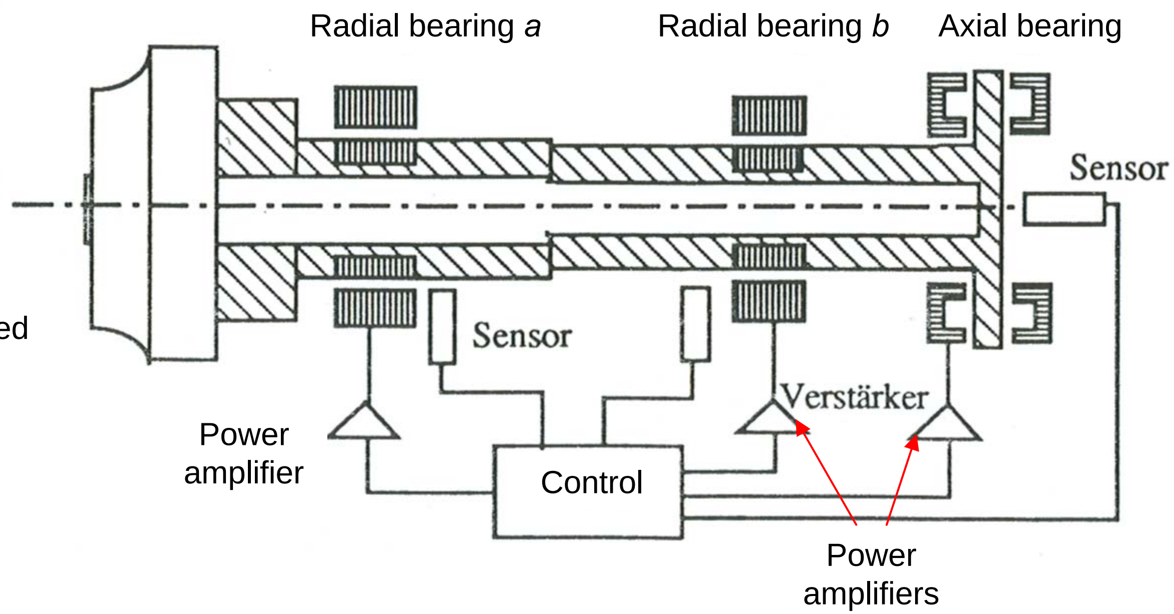
3.2 Electromagnetic levitation

Performance of active magnetic bearings

- **Magnetic force *F*** acts only in <u>one</u> direction and is only <u>attractive</u> ($\mu_r \geq 1$)



Source: Schweitzer, G. et al.: Active magnetic bearings

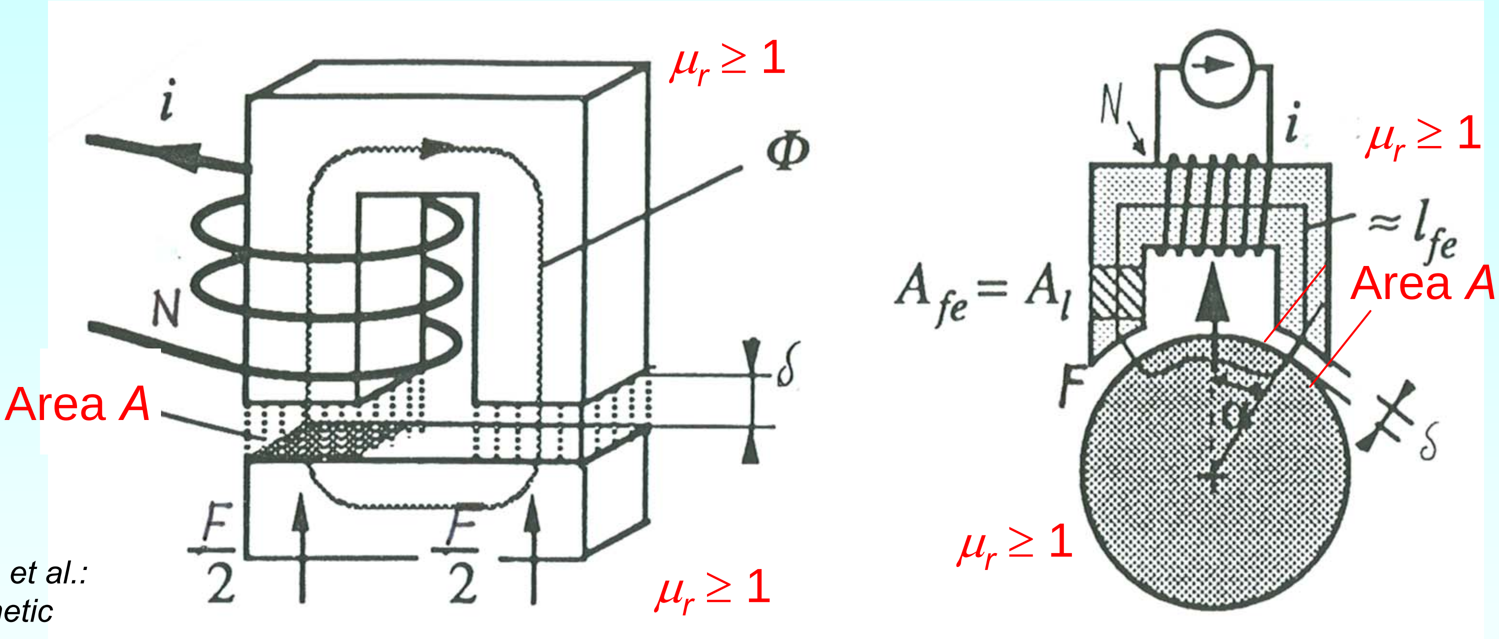


Example: Levitated compressor wheel

Principles of construction of Active Magnetic Bearings

Force of a magnet

(Radial-) bearing geometry



Source:

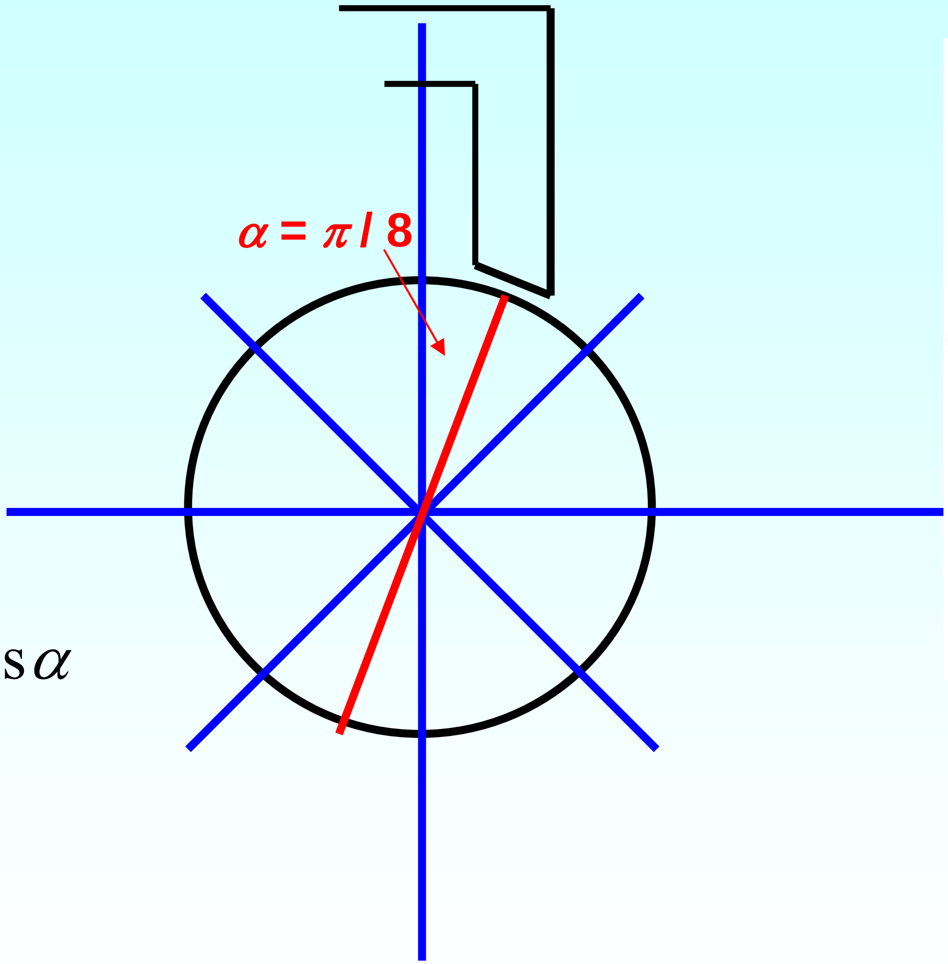
Schweitzer, G. et al.: Active magnetic bearings

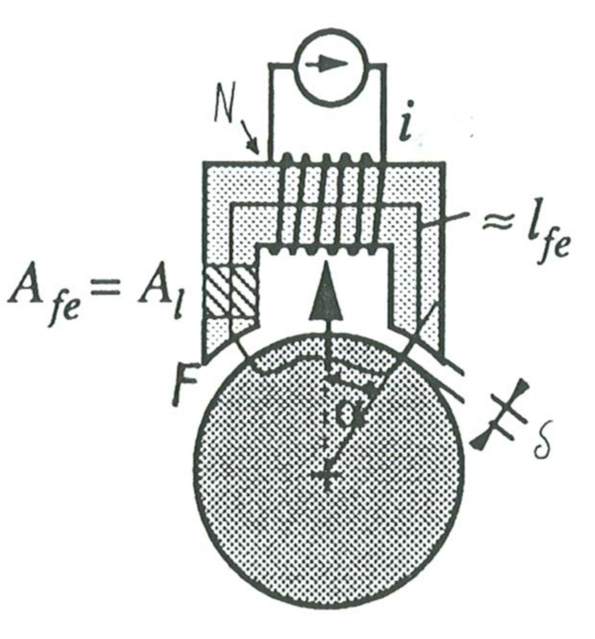
Maxwell-Stress: $p = \dfrac{B^2}{2\mu_0}$ $\Rightarrow$ Force: $F_m = 2 \cdot p \cdot A = \dfrac{B^2}{\mu_0} \cdot A$ or $F = F_m \cos\alpha$

Magnetic field ($\mu_{Fe} \to \infty$): $B = \mu_0 \dfrac{N \cdot i}{2\delta}$ $\Rightarrow$ **Force:**

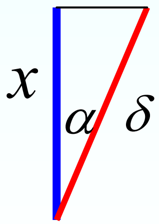
$$F = \mu_0 \cdot \frac{(N \cdot i)^2}{(2\delta)^2} \cdot A \cdot \cos\alpha$$

Magnet bearing attack angle α of force





$$x = \delta \cdot \cos\alpha$$



Source: Schweitzer, G. et al.: Active magnetic bearings

Inductance and force of active magnetic bearings

- **Inductance** *L* of excitation coil: $L = \Psi / i = N \cdot \Phi / i = N \cdot B \cdot A / i$

$L = \mu_0 \cdot \frac{N^2}{2\delta} \cdot A$ or with $x = \delta \cdot \cos\alpha$: $\boxed{L = \mu_0 \cdot \frac{N^2}{2x} \cdot A \cdot \cos\alpha}$

- ***Example:*** Air gap 1 mm, Area 1 cm², Coil current 12 A, *N* = 200, $\alpha = \pi/8$:

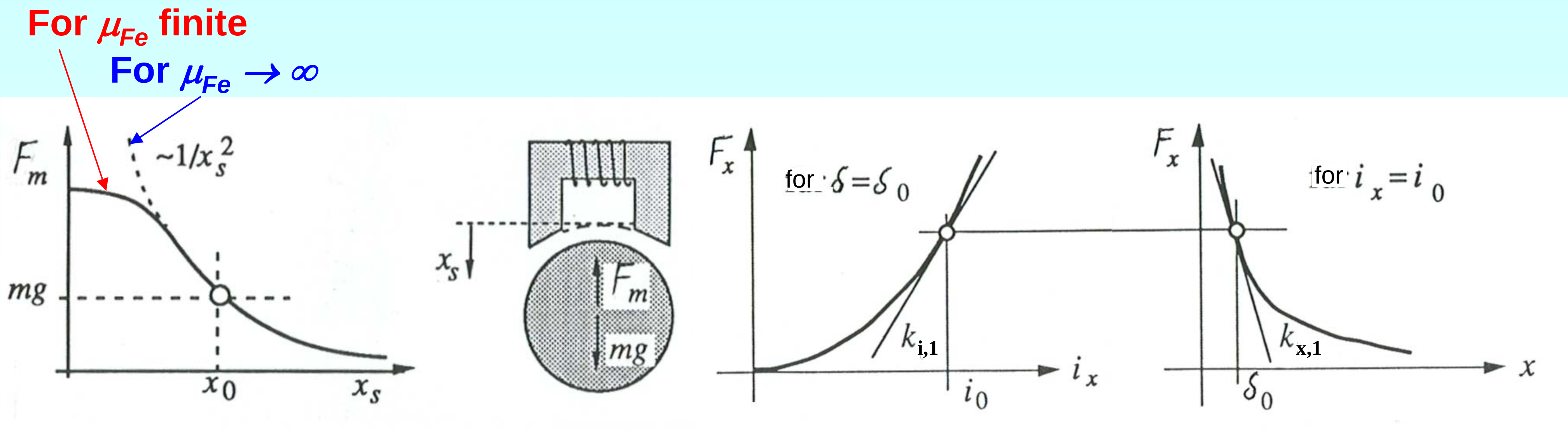
$$B = \mu_0 \frac{N \cdot i}{2\delta} = 4\pi \cdot 10^{-7} \cdot \frac{200 \cdot 12}{2 \cdot 10^{-3}} = 1.5T$$

$$L = \mu_0 \cdot \frac{N^2}{2\delta} \cdot A = 4\pi \cdot 10^{-7} \cdot \frac{200^2}{2 \cdot 10^{-3}} \cdot 10^{-4} = 2.5mH$$

$$F_m = \mu_0 \cdot \frac{(N \cdot i)^2}{(2\delta)^2} \cdot A = 181N \qquad \boxed{F = 181 \cdot \cos(\pi/8) = 167\mathrm{N}}$$

A body with a mass m = 17.0 kg at 1 mm distance from the electro magnet can be levitated (m·g = 17·9.81 = 167 N) against the gravity force.

Magnet bearing force: Effect of current and distance



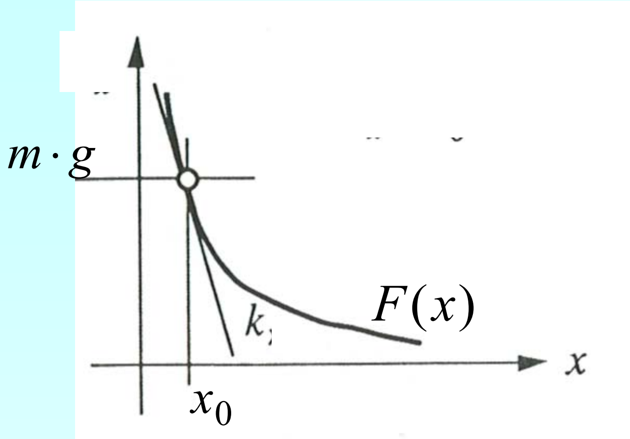
Force-current-factor $k_{i,1}$ of one electro-magnet

Force-distance-factor $k_{x,1}$ of one electro-magnet

Source: Schweitzer, G. et al.: Active magnetic bearings

The magneto-static force increases with the square of current (neglecting saturation) and decreases with the inverse square of the air gap distance.

Proof of *Earnshaw´s* theorem



- Magnetic force: $F(x) = \dfrac{F_M}{1+(x/\Delta)^2}$
- *Newton´s* law: $m\dfrac{d^2x}{dt^2} + F = m \cdot g$
- Equilibrium position: $F = m \cdot g \Rightarrow x_0 = \Delta \cdot \sqrt{\dfrac{F_M}{m \cdot g} - 1}$
- Force linearization in the equilibrium position: $F(x) = F(x_0) + dF/dx\big|_{x_0} \cdot (x - x_0)$

$$\left.\frac{dF}{dx}\right|_{x_0} = -\frac{F_M}{\left(1+\left(\frac{x_0}{\Delta}\right)^2\right)^2} \cdot \frac{2x_0}{\Delta^2} = -\frac{(m \cdot g)^2}{F_M} \cdot \frac{2}{\Delta} \cdot \sqrt{\frac{F_M}{m \cdot g} - 1} = -k < 0$$

- Linear differential equation: $x - x_0 = \xi : m \cdot \ddot{x} = m \cdot \ddot{\xi} = m \cdot g - F(x_0) + k \cdot (x - x_0)$

$\xi(t=0) = 0$

$$m \cdot \ddot{\xi} - k \cdot \xi = 0$$

- Solution for a small disturbance: $\xi(t) = \dfrac{\dot{\xi}_0}{2 \cdot \sqrt{k/m}} \cdot \left[\exp\left(\sqrt{k/m} \cdot t\right) - \exp\left(-\sqrt{k/m} \cdot t\right)\right]$

$\dot{\xi}(t=0) = \dot{\xi}_0 << 1$

Position deviation $\xi(t)$ rises to an infinitely big value = UNSTABLE equilibrium position

New technologies of electric energy converters and actuators

Summary:
Working principle of an active magnetic bearing

- Magnetic attractive force used for levitation, basically unstable
- Electrically excited coils for magnetic field generation
- Control of levitation gap via distance measurement and controlled coil current
- Stabilization by control of levitation gap via fast switching power electronics

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Mathematical linearization of the bearing force

- **Bearing as actuator; linearization around working point ("Gravity current" i_0, x_0)**
- **Deviation from working point Δx, Δi: small change around (i_0, x_0)**
- ***Example:*** Working point: current i_0 = 12 A, x_0 = 1 mm, Δx = 0. 1 mm, Δi = 1 A:

$\Delta x/x = 0.1$, $\Delta i/i_0 = 0.08$: $(\Delta x/x)(\Delta i/i_0) = 0.1\cdot 0.08 = 0.008 \ll 1$

- Counting sense: Δi is counted positive, if the current increases: $i = i_0 + \Delta i > i_0$

But Δx is taken positive, if the air-gap length decreases: $x = x_0 - \Delta x < x_0$

$$F = \mu_0 \cdot \frac{N^2 \cdot (i_0 + \Delta i)^2}{4(x_0 - \Delta x)^2} \cdot A \cdot \cos^3\alpha \approx \mu_0 \cdot \frac{N^2 \cdot i_0^{\ 2}}{4x_0^{\ 2}} \cdot A \cdot \cos^3\alpha \cdot \left(1 + \frac{2\Delta i}{i_0} + \frac{2\Delta x}{x_0}\right)$$

$$F \approx \mu_0 \cdot \frac{N^2 \cdot i_0^{\ 2}}{4\delta_0^{\ 2}} \cdot A \cdot \cos\alpha \cdot \left(1 + \frac{2\Delta i}{i_0} + \frac{2\Delta x}{x_0}\right) = F_0 + k_{i,1} \cdot \Delta i + k_{x,1} \cdot \Delta x$$

- F_0: Force in working point (e.g. = Gravity force)

$k_{i,1}$: **"Force-current-factor"** (N/A), $k_{x,1}$: **„Force-distance-factor“** (N/mm)

Force linearization for a single-sided AMB

$$F = \frac{\mu_0 N^2 A}{4} \cdot \cos^3 \alpha \cdot \frac{(i_0 + \Delta i)^2}{(x_0 - \Delta x)^2}$$

$$\Delta i / i_0 << 1,\ \Delta x / x_0 << 1 :$$

$$\frac{i_0^2 \cdot (1 + \Delta i / i_0)^2}{x_0^2 \cdot (1 - \Delta x / x_0)^2} \approx \frac{i_0^2}{x_0^2} \cdot \frac{1 + 2\Delta i / i_0}{1 - 2\Delta x / x_0} \approx \frac{i_0^2}{x_0^2} \cdot (1 + 2\Delta i / i_0) \cdot (1 + 2\Delta x / x_0) \cong \frac{i_0^2}{x_0^2} \cdot (1 + 2\Delta i / i_0 + 2\Delta x / x_0)$$

$$F \approx \frac{\mu_0 N^2 \cdot i_0^2}{4 x_0^2} \cdot A \cdot \cos^3 \alpha \cdot \left(1 + \frac{\Delta i}{i_0} + \frac{\Delta x}{x_0}\right)$$

$$\Rightarrow \underline{\underline{F \approx F_0 + k_{i,1} \Delta i + k_{x,1} \Delta x}}$$

Technical limit for linearization: $\Delta i / i_0 < 0.5,\ \Delta x / x_0 < 0.5$

Error less than: $(\Delta i / i_0)^2 < 0.25,\ (\Delta x / x_0)^2 < 0.25$

Example: Bearing force after linearization

- Air gap δ_0 = 1 mm, Area 1 cm², Coil current i_0 = 12 A, N = 200, $\alpha = \pi/8$:

$$F_0 = \mu_0 \cdot \frac{N^2 \cdot i_0^{\,2}}{4\delta_0^{\,2}} \cdot A \cdot \cos\alpha = 167\,N$$

$$k_{i,1} = \mu_0 \cdot \frac{N^2 \cdot i_0}{2\delta_0^{\,2}} \cdot A \cdot \cos\alpha = \underline{\underline{27.8\,\mathrm{N/A}}} \qquad k_{x,1} = \mu_0 \cdot \frac{N^2 \cdot i_0^{\,2}}{2\delta_0^{\,3}} \cdot A = \underline{\underline{362\,\mathrm{N/mm}}}$$

- **Force-distance-factor: independent of number of coil turns, if $\Theta = N \cdot i$ used**
  Force-current-factor: depends on number of coil turns

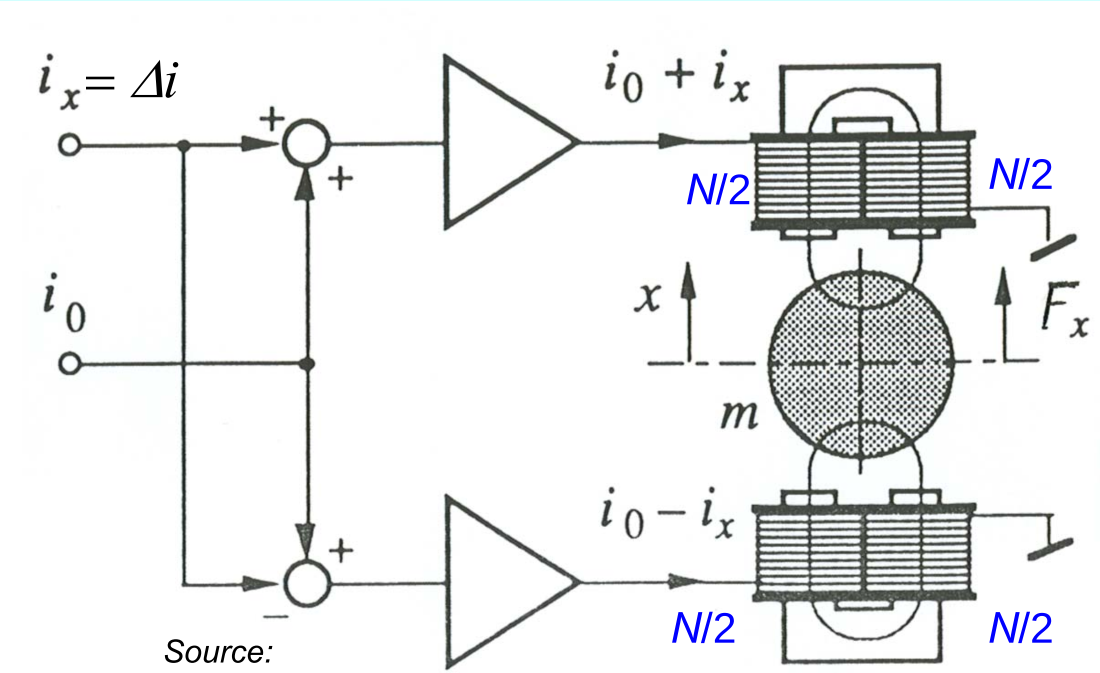
Conclusion:

- ***Small air gap at the working point provides in electromagnetic bearings a higher bearing force with a smaller necessary bearing excitation.***

- ***The parameters $k_{i,1}$ und $k_{x,1}$ and the "offset force" F_0 strongly depend on the working point parameters (i_0, δ_0).***

Linearization of the bearing characteristic

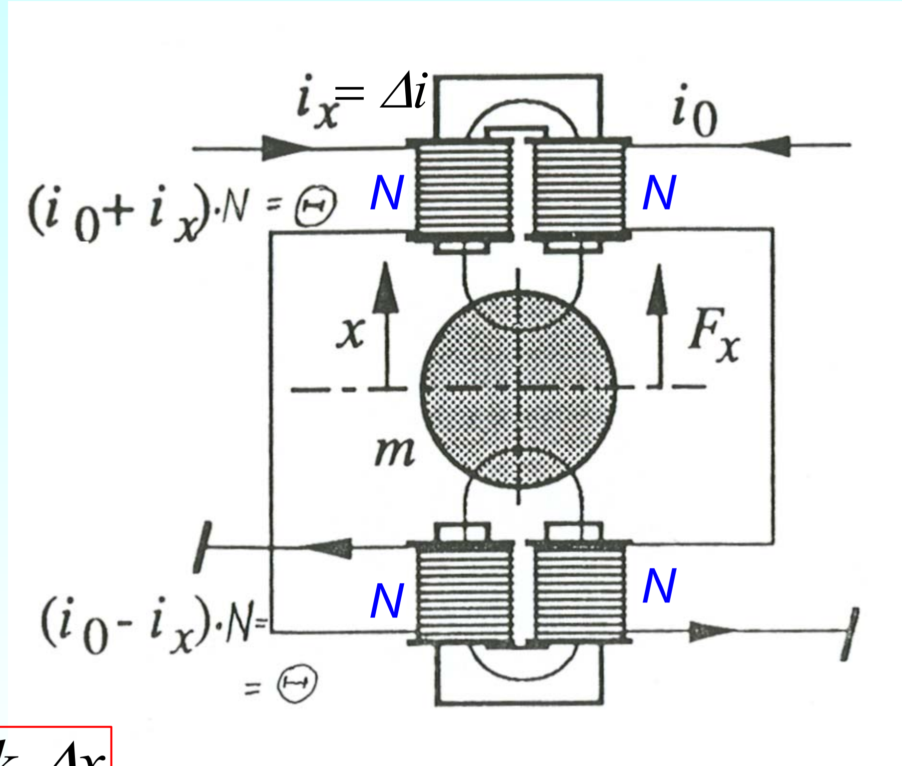
a) by differential feeding



Source:

Schweitzer, G. et al.: Active magnetic bearings

b) by differential windings



$$F \approx k_i \Delta i + k_x \Delta x$$

The cost increases: Two electro magnets instead of one, <u>but</u> the force changes ***linear*** *with the bearing control current - until iron saturation starts.*

Bearing characteristics with "differential feeding / windings"

- Two bearings: Two forces: **Linear characteristics, "offset force" F_0 eliminated!**

$$F = F^{+} - F^{-} = \frac{\mu_0 N^2 A}{4} \cdot \cos^3 \alpha \cdot \left(\frac{(i_0 + \Delta i)^2}{(x_0 - \Delta x)^2} - \frac{(i_0 - \Delta i)^2}{(x_0 + \Delta x)^2} \right)$$

$$F \approx \frac{\mu_0 N^2 \cdot {i_0}^2}{{x_0}^2} \cdot A \cdot \cos^3 \alpha \cdot \left(\frac{\Delta i}{i_0} + \frac{\Delta x}{x_0} \right) \qquad \Rightarrow \qquad F \approx k_i \Delta i + k_x \Delta x$$

- $k_i = 2k_{i,1}$, $k_x = 2k_{x,1}$: "Force-current-factor" and „force-distance-factor" increase two times with a double-sided bearing. Inductance L increases also two times (series circuits !) for differential windings (case b)).

$$k_i = \frac{\mu_0 N^2 i_0 A}{\delta_0^2} \cdot \cos \alpha \qquad\qquad k_x = \frac{\mu_0 N^2 i_0^2 A}{\delta_0^3}$$

- ***Example:*** δ_0 = 1 mm, A = 1 cm², i_0 = 12 A, N = 200, $\alpha = \pi/8$:

$$k_i = 55.6 N/A \qquad\qquad k_x = 724 N/mm$$

Force linearization of a double-sided AMB

$$F = F^{+} - F^{-} = \frac{\mu_0 N^2 A}{4} \cdot \cos^3\alpha \cdot \left(\frac{(i_0 + \Delta i)^2}{(x_0 - \Delta x)^2} - \frac{(i_0 - \Delta i)^2}{(x_0 + \Delta x)^2} \right)$$

$\Delta i / i_0 << 1, \Delta x / x_0 << 1:$

$$F^{+} \approx F_0 + k_{i,1}\Delta i + k_{x,1}\Delta x \qquad F^{-} \approx F_0 - k_{i,1}\Delta i - k_{x,1}\Delta x$$

$$F = F^{+} - F^{-} = F_0 + k_{i,1}\Delta i + k_{x,1}\Delta x - (F_0 - k_{i,1}\Delta i - k_{x,1}\Delta x) = 2k_{i,1}\Delta i + 2k_{x,1}\Delta x$$

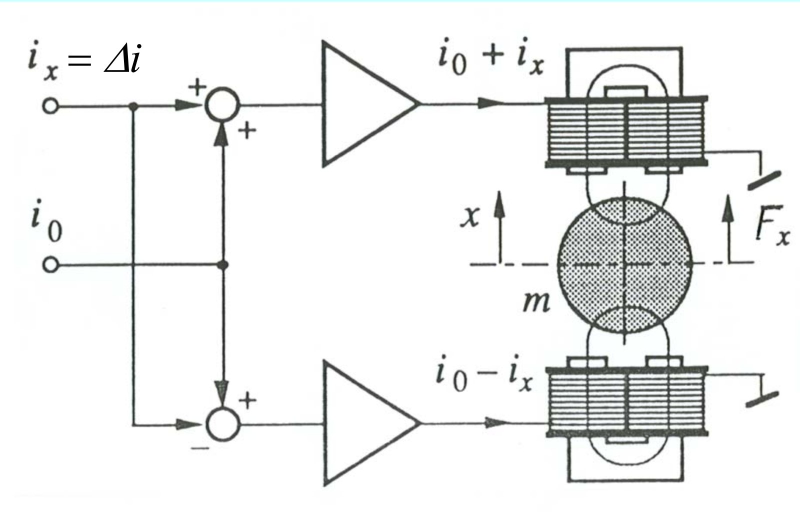
$$k_i = 2k_{i,1} \qquad k_x = 2k_{x,1} \qquad \Rightarrow \qquad \underline{\underline{F \approx k_i \Delta i + k_x \Delta x}}$$

$$F \approx \frac{\mu_0 N^2 \cdot i_0^{\,2}}{x_0^{\,2}} \cdot A \cdot \cos^3\alpha \cdot \left(\frac{\Delta i}{i_0} + \frac{\Delta x}{x_0} \right)$$

Technical limit for linearization: $\Delta i / i_0 < 0.5, \Delta x / x_0 < 0.5$

Error less than: $(\Delta i / i_0)^2 < 0.25, (\Delta x / x_0)^2 < 0.25$

Gravity force balance in a double-sided AMB



Source:

Schweitzer, G. et al.: Active magnetic bearings

$$F \approx k_i \Delta i + k_x \Delta x$$

The mass m shall be held at $\Delta x = 0$:

$$F = k_i \Delta i + k_x \Delta x = k_i \Delta i = m \cdot g$$

A controlled current of $\Delta i = m \cdot g / k_i$ *is necessary!*

The upper winding is fed with: $i_0 + m \cdot g / k_i$

The lower winding is fed with: $i_0 - m \cdot g / k_i$

The maximum levitated mass m_{max} is determined by: $i_0 - m_{\max} \cdot g / k_i = 0$

Then the force of the lower magnet is zero and the resulting force is maximum!

$$m_{\max} = i_0 k_i / g$$

Coil resistance and losses per axis

	a) Differential feeding	b) Differential windings
Number of coils	2	4
Turns/coil	$N/2 + N/2 = N$	N
Coil wire cross section (for $\Delta i_{max} = i_0$)	q	$q/2$
Max. current density J	$= (\Delta i_{max} + i_0)/q = 2i_0/q$	$\Delta i_{max}/(q/2) = i_0/(q/2) = 2i_0/q$
Turn length	l_w	l_w
Resistance/coil	$R = \dfrac{N \cdot l_w}{\kappa \cdot q}$	$R^* = \dfrac{N \cdot l_w}{\kappa \cdot (q/2)} = 2R$
Total losses with $\Delta i_{max} = i_0$	$R \cdot (2i_0)^2 = 4Ri_0^2$ $(i_0 - \Delta i = 0,\ i_0 + \Delta i = 2i_0)$	$4R^* i_0^2 = 8Ri_0^2$

Two times losses at full current

Comparison: Differential feeding vs. differential windings for an *x*- and a *y*-axis AMB

	Differential feeding	Differential windings
Number of DC-excitations	4	2
Constant current source	0	1
Losses at maximum current	100 %	200 %

At max. current: Magnet force is maximum ⇒ Force of lower magnet is zero ⇒ $i_0 = \Delta i$

- Differential feeding: *Lower magnet has no losses*!

$$\Theta = N(i_0 - \Delta i) = Ni = 0,\ i = 0,\ P = R \cdot i^2 = 0$$

Upper magnet has maximum losses!

$$\Theta = N(i_0 + \Delta i) = N2\Delta i,\ i = 2\Delta i,\ P = R \cdot i^2 = 4R\Delta i^2 \qquad P_{res} = P$$

- Differential windings:

Losses P in lower magnet = Losses P in upper magnet: Factor 2: $P_{res} = 2P$

Per magnet: $\Theta = N(i_0 - \Delta i) = Ni_0 - N\Delta i = 0,\ i_0 = \Delta i,\ P = 2R^* \cdot \Delta i^2 = 4R\Delta i^2$

Measured Current-Force-Characteristic of a radial magnetic bearing with differential feeding

Dimensions:

Bearing bore diameter d = 90 mm, bearing length b = 70 mm, nominal air gap δ_0 = 0.4 mm

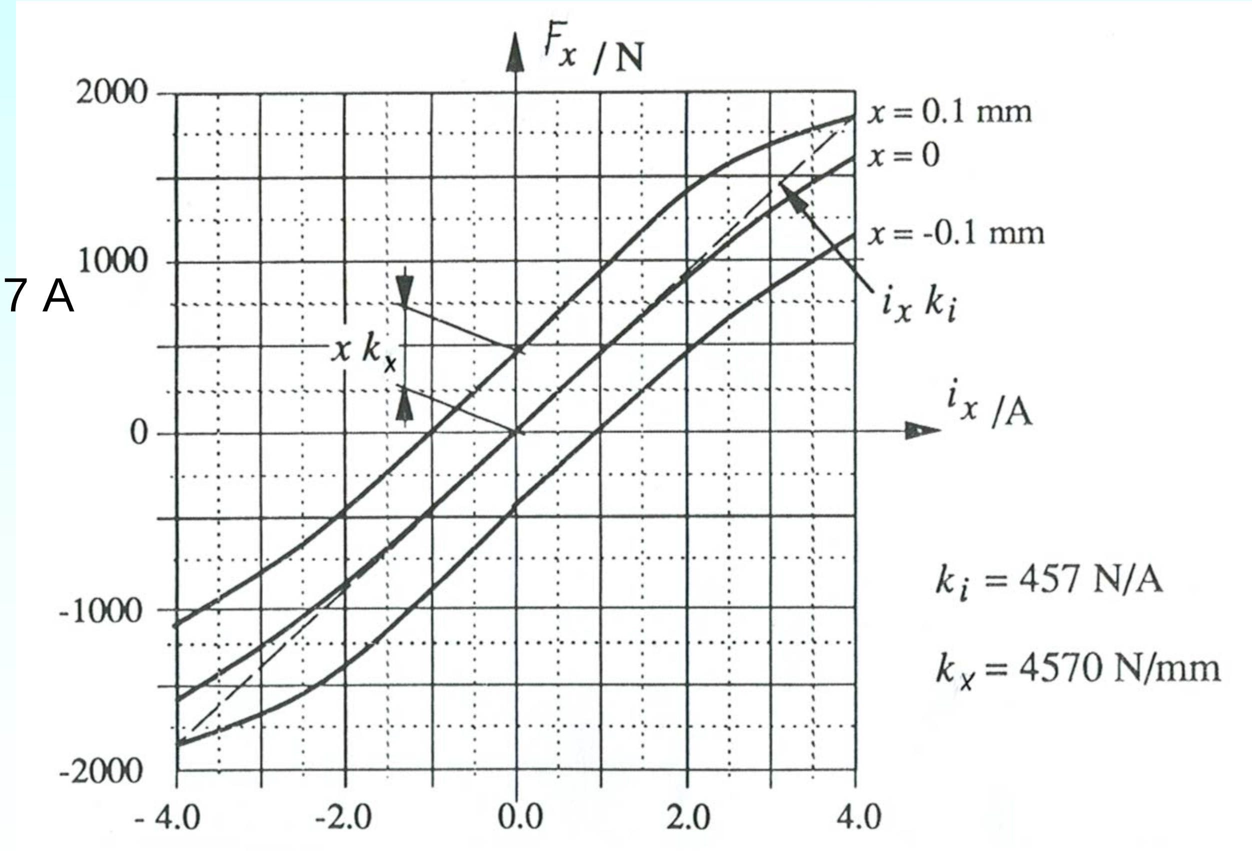
Number of turns N = 117

Base excitation current i_0 = 3.7 A

Pole area A = 1237 mm^2

Source:

Schweitzer, G. et al.: Active magnetic bearings



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Summary:
Linearization of the bearing force

- Magnetic attractive force depends on square of current vs. gap
- Linearized force depends linear on control current
- Linearization done by opposing magnet coils either by differential windings or differential current feeding
- Linearization allows a linear PID-control of the gap

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Design of magnetic radial bearings

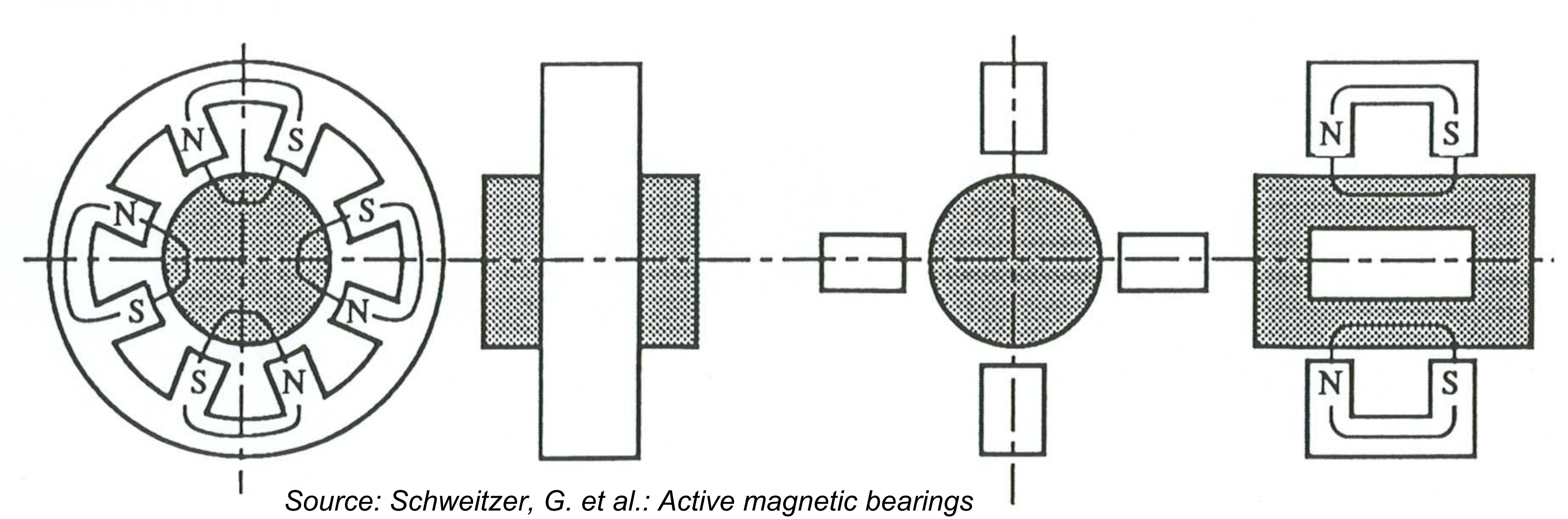
- Double-sided AMB: Two opposing magnets work along one coordinate axis
- Two coordinate axes are controlled per radial bearing

a) Hetero-polar bearing

Field lines perpendicular to rotor axis
Change of field polarity during rotation
Frequency: $f = 2 \cdot n$:
Eddy current & hysteresis losses in the rotor

b) Homo-polar bearing

Field lines along to rotor axis
No change of field polarity during rotation
Frequency: $f = 0$:
Nearly no rotor losses



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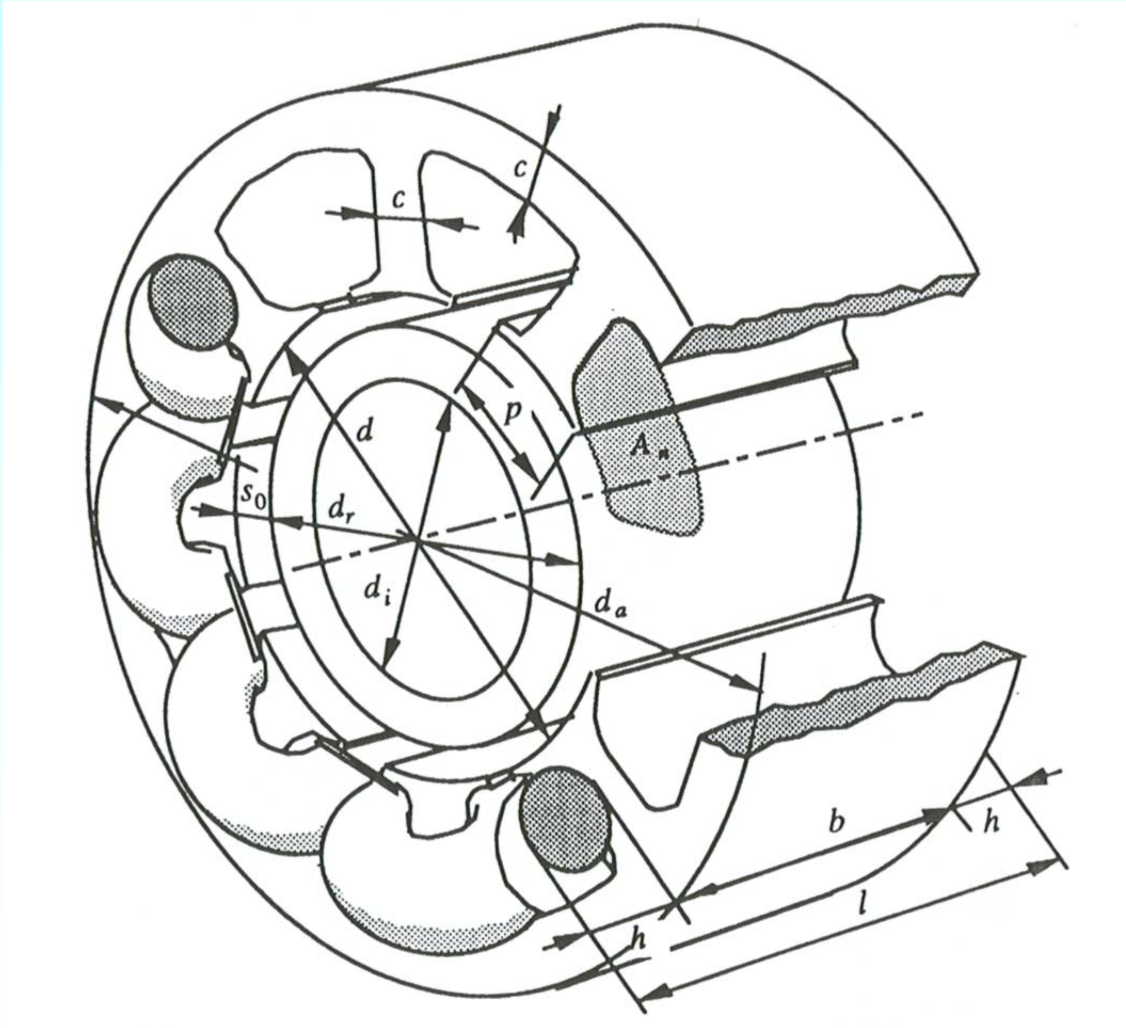
Magnetic radial bearing



Source:

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Specific load force *f* of radial magnetic bearings

- $f = F/(d \cdot b)$: on projected area $d \cdot b$ related load force
- ***Example:*** Iron yoke saturation limit *B* = 1.5 T , $\alpha = \pi/8$:

With pole shoe width *p* = Slot width of the winding: For the pole follows:

$$A = p \cdot b = \frac{d\pi}{2 \cdot 8} \cdot b \quad \Rightarrow \quad f = \frac{F}{d \cdot b} = \frac{B^2}{\mu_0} \cdot \left(\frac{d\pi \cdot b}{2 \cdot 8} \right) \cdot \cos\alpha \cdot \frac{1}{d \cdot b} = \frac{B^2}{\mu_0} \cdot \frac{\pi}{16} \cdot \cos\frac{\pi}{8} = 32 \mathrm{N/cm}^2$$

- Cobalt alloys: Saturation flux density increases to ca. 2 T: *f* = 60 N/cm²

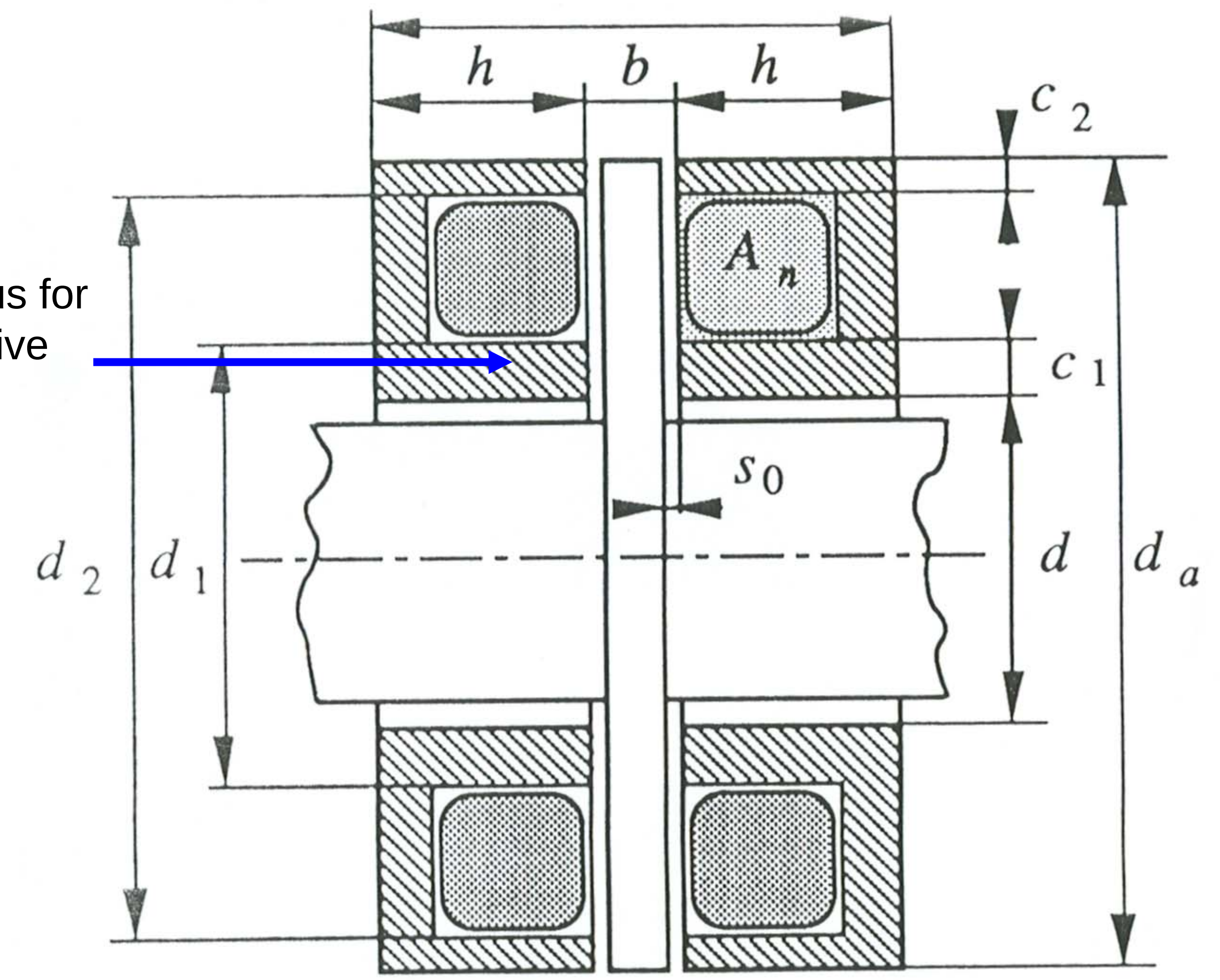
- ***Centrifugal force limit of the bearing rotor:***
  - Tangential stress due to radial centrifugal force: $\sigma = \rho \cdot v^2$ (ρ: mass density)
  - Rotors made of steel laminations: Yield strength $\sigma = R_{p0.2}$ = 300 ... 500 N/mm² $\Rightarrow$ v_{max} = ca. 200 m/s

    (lamination thickness 0.1 mm, 0.35 mm, 0.5 mm)
  - **Amorphous metals:** Thin sheets 0.035 mm thickness, temperature limit ca. 450 °C

    Yield strength ca. 1500 ... 2000 N/mm²: v_{max} = ca. 400 m/s = four times centrifugal forces

Magnetic axial bearing

Bigger width due to smaller radius for identical areas for the flux to give identical flux densities



Source:

Schweitzer, G. et al.: Active magnetic bearings

New technologies of electric energy converters and actuators

Summary:
Design of magnetic bearings

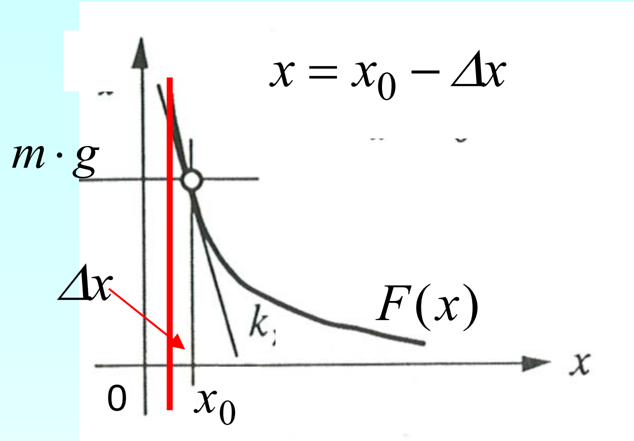
- Heteropolar vs. homopolar magnetic coil arrangements
- Heteropolar structure widely used (cheaper), but causes more eddy current losses
- Two coil pairs control two perpendicular axes in radial bearings
- One ring coil pair controls axial position in axial AMB

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Instability of magnetic bearings in uncontrolled operation

- Force equation for levitated rotor: $m\frac{d^2x}{dt^2}+F=m\cdot g$



- Small deflection Δx from working point x_0:

$$d^2x/dt^2 = -d^2\Delta x/dt^2 = -\Delta\ddot{x}$$

$$-m\Delta\ddot{x}+F_0+k_{i,1}\cdot\Delta i+k_{x,1}\cdot\Delta x=m\cdot g \qquad (F_0 = m\cdot g)$$

$$\Delta\ddot{x}-(k_{x,1}/m)\cdot\Delta x=(k_{i,1}/m)\cdot\Delta i$$

- **Homogeneous differential equation:** $\Delta\ddot{x}-(k_{x,1}/m)\cdot\Delta x=0$

Homogeneous solution: $\Delta x(t)=C_1\cdot\exp\left(\sqrt{k_{x,1}/m}\cdot t\right)+C_2\cdot\exp\left(-\sqrt{k_{x,1}/m}\cdot t\right)$

$$\text{e.g.}: \Delta x(0)=\Delta x_0, \Delta\dot{x}(0)=0: \Delta x(t)=\Delta x_0/2\cdot\left[\exp\left(\sqrt{k_{x,1}/m}\cdot t\right)+\exp\left(-\sqrt{k_{x,1}/m}\cdot t\right)\right]$$

Position deviation increases with exponentially with time; the rotor does not return back to its starting operation point. The working point is unstable.

Static stabilization with a P-Controller

- **Proportional controller:** Increase of Δx must be met with a current decrease $-\Delta i$!

$$\Delta i = -K_p \cdot \Delta x$$

Assumption: Voltage source impresses enough current. The time constant $T = L/R$ of the coil is neglected, the actual current follows the current demand immediately (**current source operation**).

$$\Delta \ddot{x} - (k_{x,1}/m) \cdot \Delta x = -(k_{i,1}/m) \cdot K_p \cdot \Delta x \quad \Rightarrow \quad \Delta \ddot{x} - \left(\frac{k_{x,1} - k_{i,1} K_p}{m} \right) \cdot \Delta x = 0$$

- **Solution of the differential equation:**

If $k = k_{i,1} K_p - k_{x,1} > 0$: Solution is an **un-damped sinus function**.

$$\Delta x(t) = C_1 \cdot \sin(\omega_e t) + C_2 \cdot \cos(\omega_e t)$$

Natural frequency: $\omega_e = \sqrt{\frac{K_p k_{i,1} - k_{x,1}}{m}} = \sqrt{\frac{k}{m}}$

$$\text{e.g.}: \Delta x(0) = \Delta x_0, \Delta \dot{x}(0) = 0 : \Delta x(t) = \Delta x_0 \cdot \cos(\omega_e t)$$

*Working point is **stable**, but at any disturbance the levitated rotor oscillates without damping around x_0. Bigger current-force-factor k_i or $k_{i,1}$ allows smaller K_p. If the distance-force-factor k_x or $k_{x,1}$ is bigger, K_p must be bigger.*

Mechanical analogy of P-control: Spring-mass-system

Spring force $F_s = c \cdot (x - x_{s0})$

Equilibrium at x_0 $m \cdot g = c \cdot (x_0 - x_{s0})$

***Newton´s* law** $m \cdot \ddot{x} = m \cdot g - F_s$

$$m \cdot \ddot{x} = m \cdot g - c \cdot (x - x_{s0}) =$$
$$= m \cdot g - c \cdot (x_0 - x_{s0}) - c \cdot (x - x_0) =$$
$$= -c \cdot (x - x_0)$$

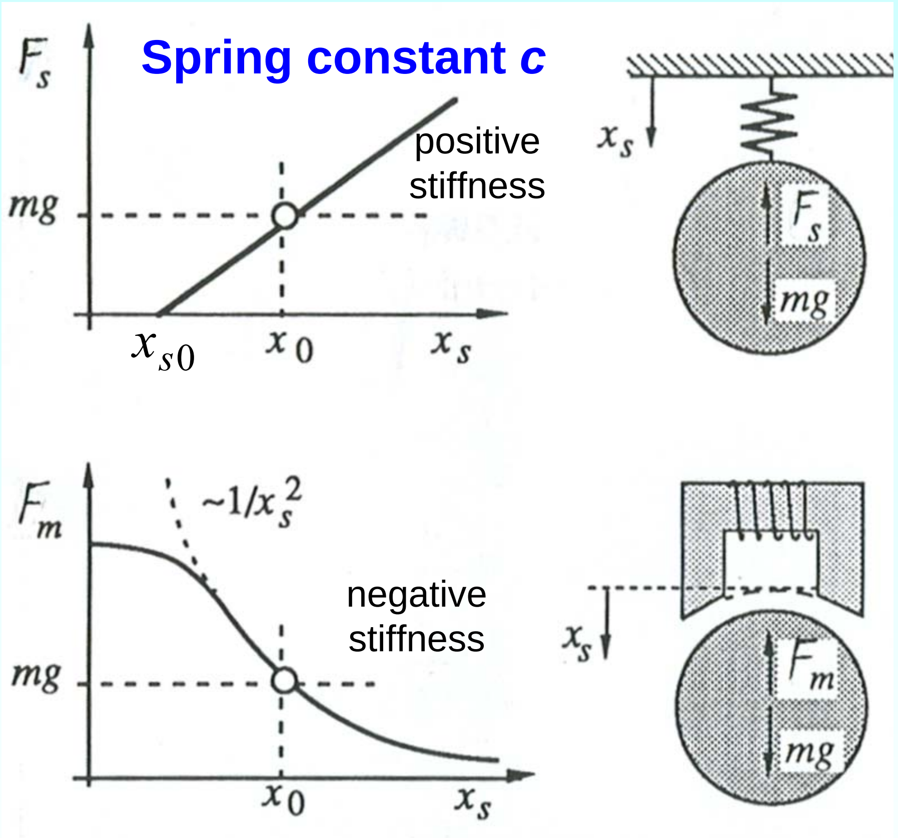
Linear differential equation:

$$m \cdot d^2(x - x_0)/dt^2 + c \cdot (x - x_0) = 0$$

$$\xi = x - x_0 : \ddot{\xi} = \ddot{x} \qquad m \cdot \ddot{\xi} + c \cdot \xi = 0$$

Solution:

(Undamped) Oscillation of the mass around x_0



Source: Schweitzer, G. et al.: Active magnetic bearings

$$\xi(t) = A \cdot \sin(\omega \cdot t) + B \cdot \cos(\omega \cdot t)$$ $$\omega = \sqrt{c/m}$$ $$\text{e.g.}: \xi(0) = \Delta x_0, \dot{\xi}(0) = 0 : \xi(t) = \Delta x_0 \cdot \cos(\omega_e t)$$

Dynamic stabilization with a PD-controller

- $\Delta i = -K_p \cdot \Delta x - K_d \cdot d\Delta x / dt$

D-component in controller damps the stationary oscillations $\Rightarrow$ working point is then dynamically stable.

- System differential equation for a double-sided bearing (k_i, k_x instead of $k_{i,1}$, $k_{x,1}$):

$$\Delta\ddot{x} + \frac{K_d k_i}{m} \cdot \Delta\dot{x} - \left(\frac{k_x - k_i K_p}{m} \right) \cdot \Delta x = 0 \quad \Rightarrow \quad \Delta\ddot{x} + 2\alpha_d \cdot \Delta\dot{x} + \omega_e^2 \cdot \Delta x = 0$$

$$\Delta\ddot{x} + (d/m) \cdot \Delta\dot{x} + (k/m) \cdot \Delta x = 0$$

- Solution: **Damped sinus oscillations:**

$$\Delta x(t) = C_1 \cdot \exp(-\alpha_d t) \cdot \sin(\omega t) + C_2 \cdot \exp(-\alpha_d t) \cdot \cos(\omega t) \qquad \text{e.g.: } \Delta x(t) = \Delta x_0 \cdot e^{-\alpha_d t} \cdot \cos(\omega \cdot t)$$

Angular frequency ω slightly **smaller** than in non-damped case: $\omega = \sqrt{\omega_e^2 - \alpha_d^2}$

- $k = K_p k_i - k_x$: Bearing-**stiffness** is limited by the maximum controller output.

  $d = K_d k_i$: **Damping coefficient,** which has to be adjusted

Roughly: $d \approx \sqrt{m \cdot k} \Rightarrow \alpha_d / \omega = 1/\sqrt{3}$: **Compromise:** $\alpha_d/\omega \approx 0.1 \ldots 1$

Adjusting of K_p und K_d of the PD-Controller

Angular frequency: $\omega = \sqrt{\omega_e^2 - \alpha_d^2}$

- $k = K_p k_i - k_x$: **Bearing-stiffness**

  $d = K_d k_i$: **Damping**

Roughly: $d \approx \sqrt{m \cdot k} \Rightarrow \alpha_d / \omega = 1/\sqrt{3} = 0.58$

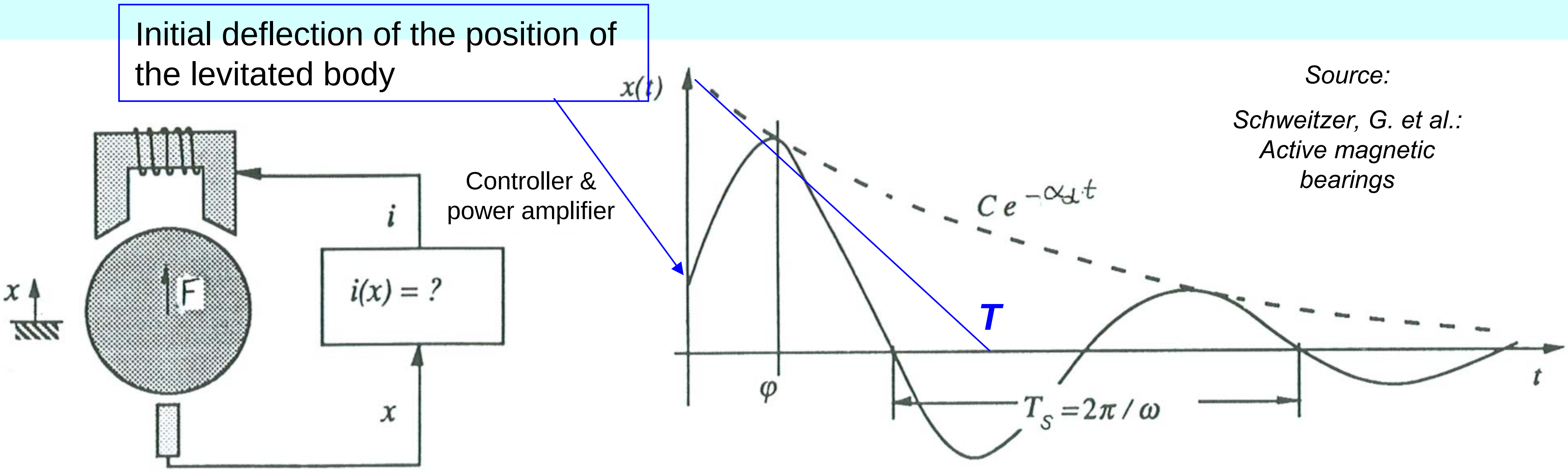
$$\frac{\alpha_d}{\omega} = \frac{\alpha_d}{\sqrt{\omega_e^2 - \alpha_d^2}} = \frac{1}{\sqrt{\dfrac{\omega_e^2}{\alpha_d^2} - 1}} = \frac{1}{\sqrt{\dfrac{k/m}{(d/(2m))^2} - 1}} = \frac{1}{\sqrt{\dfrac{4 \cdot k \cdot m}{d^2} - 1}} = \frac{1}{\sqrt{\dfrac{4 \cdot k \cdot m}{m \cdot k} - 1}} = 1/\sqrt{3}$$

Typical adjustment for not too long oscillations:

$\alpha_d/\omega \approx 0.1 \ldots 1$: $T_s/T = 2\pi \cdot (\alpha_d/\omega) \approx 0.6 \ldots 6$

Damping of the transients oscillation of levitated bodies

- **Frequency $f = \omega/(2\pi)$, Decay time constant $T = 1/\alpha_d$**

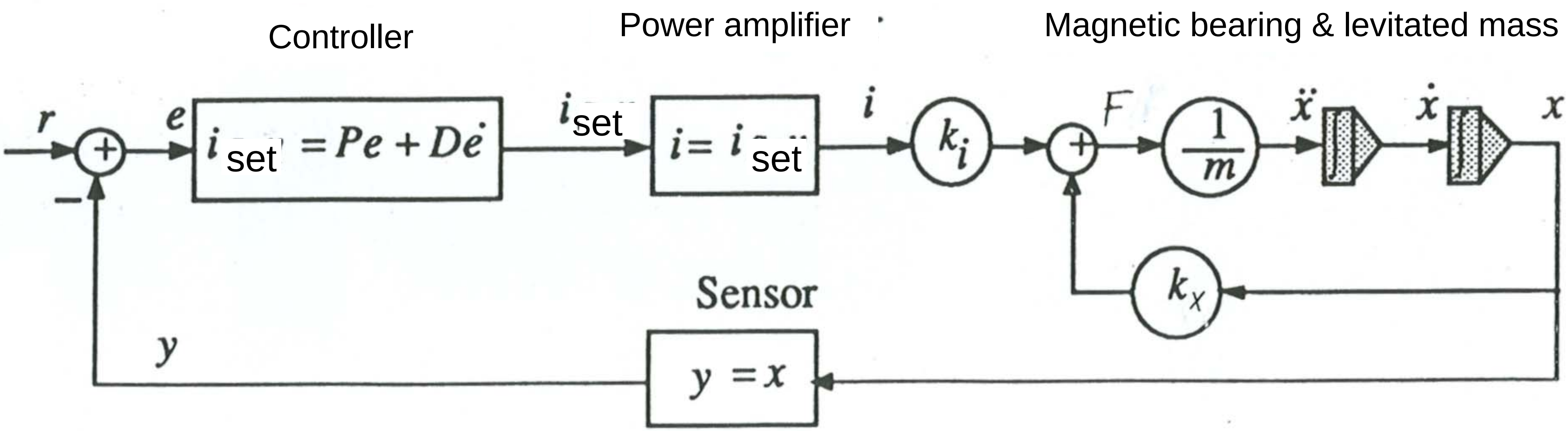


$$\frac{\alpha_d}{\omega} = 1/\sqrt{3} \Rightarrow \frac{T_s}{T} = \frac{\alpha_d}{f} = \frac{\alpha_d}{\omega} \cdot 2\pi = \frac{2\pi}{\sqrt{3}} = 3.6$$

After $T = T_s/3.6$, hence ca. ¼ of the oscillation period, the oscillation has decayed to 1/*e* of the initial value.

Current-controlled magnetic bearing with PD control

- **Linearized magnetic bearing characteristic**



Source:

Schweitzer, G. et al.: Active magnetic bearings

i_{set}: Set-point value

PD-controlled bearing – Transfer function in the *Laplace*-domain

- **PD-controller: Initial conditions:** $\Delta x(0) = 0$

$$L(\Delta i) = I(s) = -K_p \cdot L(\Delta x) - K_d \cdot L(d\Delta x / dt) = -K_p \cdot X(s) - K_d \cdot s \cdot X(s)$$

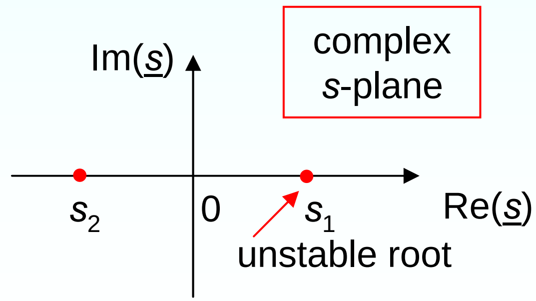
Transfer function ***$F_{PD}(s)$*****:** $I(s) = F_{PD}(s) \cdot X(s) \quad F_{PD}(s) = -K_p - s \cdot K_d$

- **Magnetic bearing: (PT_2-behavior):** $s^2 X(s) - \frac{k_x}{m} X(s) = \frac{k_i}{m} I(s)$

Transfer function ***G(s)*****:** $X(s) = G(s) \cdot I(s) \quad G(s) = \frac{k_i}{m \cdot s^2 - k_x}$

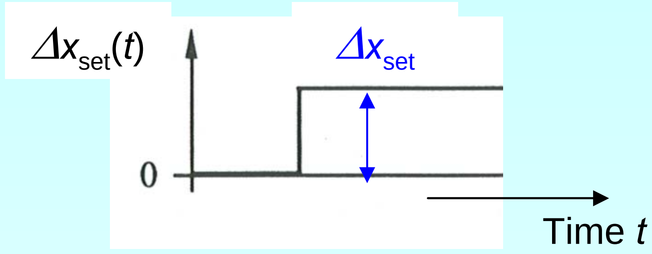
Two roots of „characteristic“ polynomial:

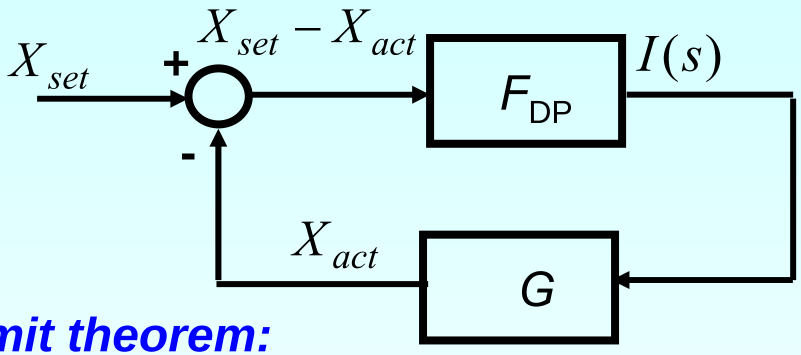
$$p(s) = s^2 - k_x / m = (s - s_1) \cdot (s - s_2) \quad s_{1,2} = \pm\sqrt{k_x / m}$$



PD-controlled bearing in the *Laplace*-domain

- **Closed-loop controller action: step excitation:**





$$X_{set}(s) = \frac{\Delta x_{set}}{s}$$

$$I = F_{PD} \cdot (X_{set} - X_{act})$$

$$X_{act} = G \cdot I$$

$$\frac{X_{act}(s)}{X_{set}(s)} = \frac{F_{PD}(s) \cdot G(s)}{F_{PD}(s) \cdot G(s) + 1}$$

Laplace time-limit theorem:

$$\lim_{t \to \infty} f(t) = \lim_{s \to 0} (s \cdot F(s))$$

$$\frac{X_{act}(s)}{\Delta x_{set}} = \frac{F_{PD}(s) G(s)}{F_{PD}(s) G(s) + 1} \cdot \frac{1}{s}$$

$$\frac{\Delta x_{act}(t \to \infty)}{\Delta x_{set}} \underset{s \to 0+}{=} \frac{s \cdot X_{act}(s)}{\Delta x_{set}} = \frac{K_p \cdot (k_i / k_x)}{K_p \cdot (k_i / k_x) + 1} < 1$$

PD-controller: Rotor is levitated stable, but it remains a permanent deviation between actual and set-point value of the position of the levitated body. A bigger proportional gain K_p yields a smaller steady-state deviation.

PID-controlled bearing in the *Laplace*-domain

- **PID-controller: avoids a steady-state deviation between actual and set-point value of the position of the levitated body**

Time domain: $\Delta i = -K_p \cdot \Delta x - K_d \cdot d\Delta x / dt - \frac{1}{T_I} \int \Delta x \cdot dt$

Transfer function: $F_{PID}(s) = -K_p - K_d \cdot s - \frac{1}{s \cdot T_I}$

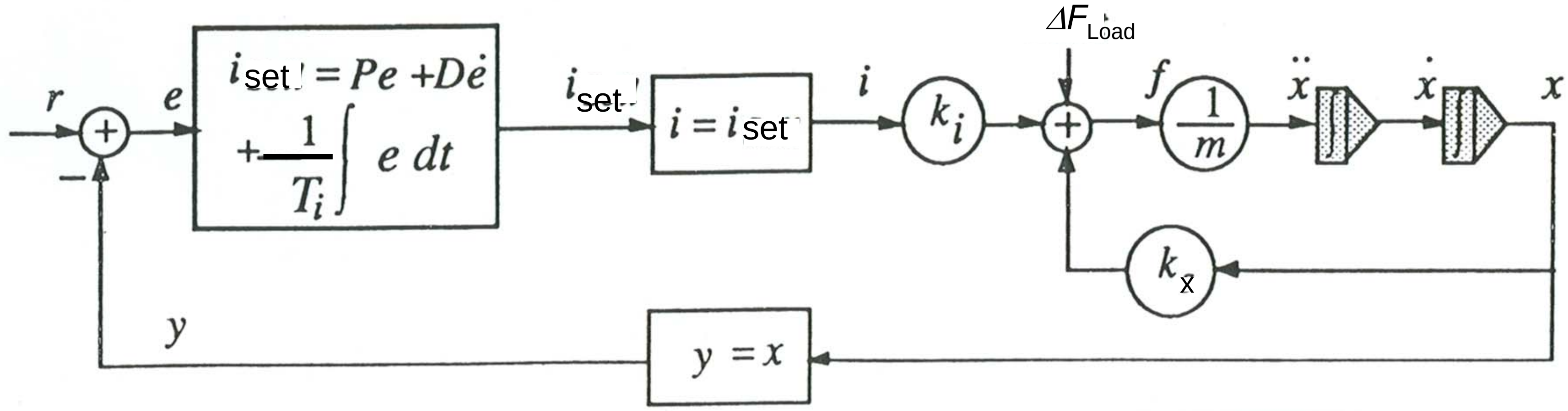
- **„End value“:** $\frac{\Delta x_{act}(t \to \infty)}{\Delta x_{set}} \underset{s \to 0+}{=} \frac{s \cdot X_{act}(s)}{\Delta x_{set}} = \frac{F_{PID}(0) \cdot G(0)}{F_{PID}(0) \cdot G(0) + 1} = \frac{-\frac{k_i}{T_I}}{-\frac{k_i}{T_I}} = 1$

- a) Final deviation $\Delta x = 0$: Hence the AMB has a stationary infinite stiffness, since despite the load ΔF_{Last} no deviation Δx of the set-point position occurs.

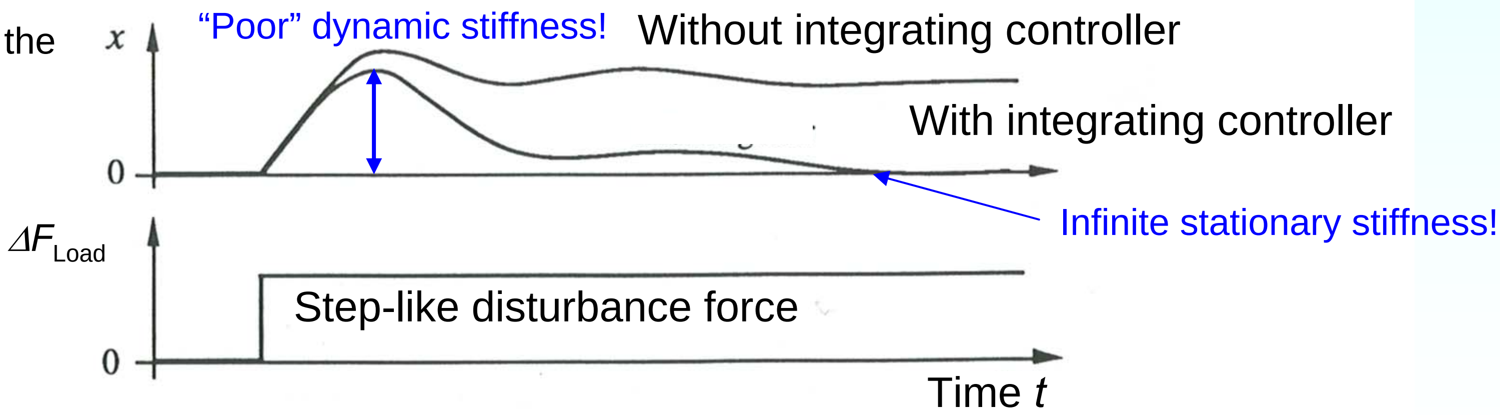
  b) Dynamic deviation $\Delta x \neq 0$ occurs during the control operation: Hence the AMB has a finite dynamic stiffness, which is considerably smaller than the mechanical bearing stiffness.

Current controlled magnetic bearing with PID-controller

- Linearized magnetic bearing characteristic, feed forward control of disturbance ΔF_{Load}



Deflection of position of the levitated body



Source:

Schweitzer, G. et al.: Active magnetic bearings

New technologies of electric energy converters and actuators

Summary:
Control of active magnetic bearings

- Magnetic bearing inherently instable (EARNSHAW´s theorem)
- Levitation gap is measured and controlled via the coil current
- Current P-control stabilizes, but is prone to oscillations
- PD-control damps the bearing oscillations
- PID-control puts steady state deviation of controlled levitation gap to zero

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Voltage controlled AMB

- At high controller output signal: The DC chopper operates with a high voltage level. Maximum voltage is the DC voltage U_d. Current builds up with time constant $T = L/R$.

$$u = R \cdot i + \frac{d\psi}{dt} = R \cdot i + \frac{d(L(x) \cdot i)}{dt} = R \cdot i + \frac{dL}{dx} \cdot \frac{dx}{dt} \cdot i + L \cdot \frac{di}{dt} \qquad x = x_0 - \Delta x$$

$$u_0 + \Delta u = R \cdot i_0 + R \cdot \Delta i - \frac{dL}{dx} \cdot \frac{d\Delta x}{dt} \cdot (i_0 + \Delta i) + L \cdot \frac{d\Delta i}{dt}$$

$$\boxed{\Delta\dot{x} \cdot \Delta i << 1:} \quad u_0 + \Delta u \cong R \cdot i_0 + R \cdot \Delta i - \frac{dL}{dx} \cdot \frac{d\Delta x}{dt} \cdot i_0 + L \cdot \frac{d\Delta i}{dt} \qquad u_0 = R \cdot i_0$$

Voltage equation: $\Delta u \cong R \cdot \Delta i - \frac{dL}{dx} \cdot i_0 \cdot \Delta\dot{x} + L \cdot \Delta\dot{i} = R \cdot \Delta i + \underline{\underline{k_u}} \cdot \Delta\dot{x} + L \cdot \Delta\dot{i}$

- **Voltage factor** $k_u = -i_0 \cdot dL/dx$: By induction of motion due to the moving lev. body a voltage is induced in the bearing coil, from which the position of the body may be calculated. This is used with **sensorless AMB.**

- **Note:** $k_i = -\frac{dL}{dx} \cdot i_0 = k_u$ Hence: **Voltage-factor = Force-current-factor**

Voltage factor k_u

Voltage factor: $k_u = -\frac{dL}{dx} \cdot i_0 = \mu_0 \cdot \frac{N^2}{2\delta^2} \cdot A \cdot i_0$ $\quad L = \mu_0 \cdot \frac{N^2}{2\delta} \cdot A \quad -dL/d\delta = \mu_0 \cdot \frac{N^2}{2\delta^2} \cdot A$

Force-current factor: $k_i = \left.\frac{dF}{di}\right|_{i=i_0} = \frac{d}{di}\left(\mu_0 \cdot \frac{(N \cdot i)^2}{4\delta^2} \cdot A\right) = \mu_0 \cdot \frac{N^2}{2\delta^2} \cdot A \cdot i_0 = k_u$

The "voltage-factor" is identical with the Force-current-factor !

System equations of voltage-controlled magnetic bearings (1)

- **Force in *x*-direction:** **mechanical equation:** $\Delta\ddot{x} - (k_x/m)\cdot\Delta x = (k_i/m)\cdot\Delta i$

  electrical equation: $\Delta u = R\cdot\Delta i + k_i\cdot\Delta\dot{x} + L\cdot\Delta\dot{i}$

3rd order diff. equation (PT_3): $\Delta\dddot{x} + \frac{R}{L}\Delta\ddot{x} - \left(\frac{k_x}{m} - \frac{k_i^2}{m\cdot L}\right)\cdot\Delta\dot{x} - \frac{R}{L}\cdot\frac{k_x}{m}\cdot\Delta x = \frac{k_i}{m\cdot L}\Delta u$

($T = L/R$)

- **Transfer function of distance:** $X(s) = G_u(s)\cdot U(s)$

$$\left(s^3 + \frac{s^2}{T} - \left(\frac{k_x}{m} - \frac{k_i^2}{m\cdot L}\right)\cdot s - \frac{k_x}{T\cdot m}\right)\cdot\Delta X(s) = \frac{k_i}{m\cdot L}\cdot\Delta U(s)$$

$$G_u(s) = \frac{\frac{k_i}{m\cdot L}}{s^3 + \frac{s^2}{T} - \left(\frac{k_x}{m} - \frac{k_i^2}{m\cdot L}\right)\cdot s - \frac{k_x}{T\cdot m}}$$

System equations of voltage-controlled magnetic bearings (2)

Due to $k_i = k_x \cdot (x_0 / i_0)$ **,** $k_i / L = \mu_0 \cdot \frac{N^2 \cdot i_0}{\delta_0^{\ 2}} \cdot A \cdot \cos\alpha / \left(2\mu_0 \cdot \frac{N^2}{2\delta_0} \cdot A \right) = i_0 / x_0$

and $x_0 = \delta_0 \cdot \cos\alpha$ **we get:** $k_x - k_i^2 / L = k_x - k_i \cdot (i_0 / x_0) = 0$

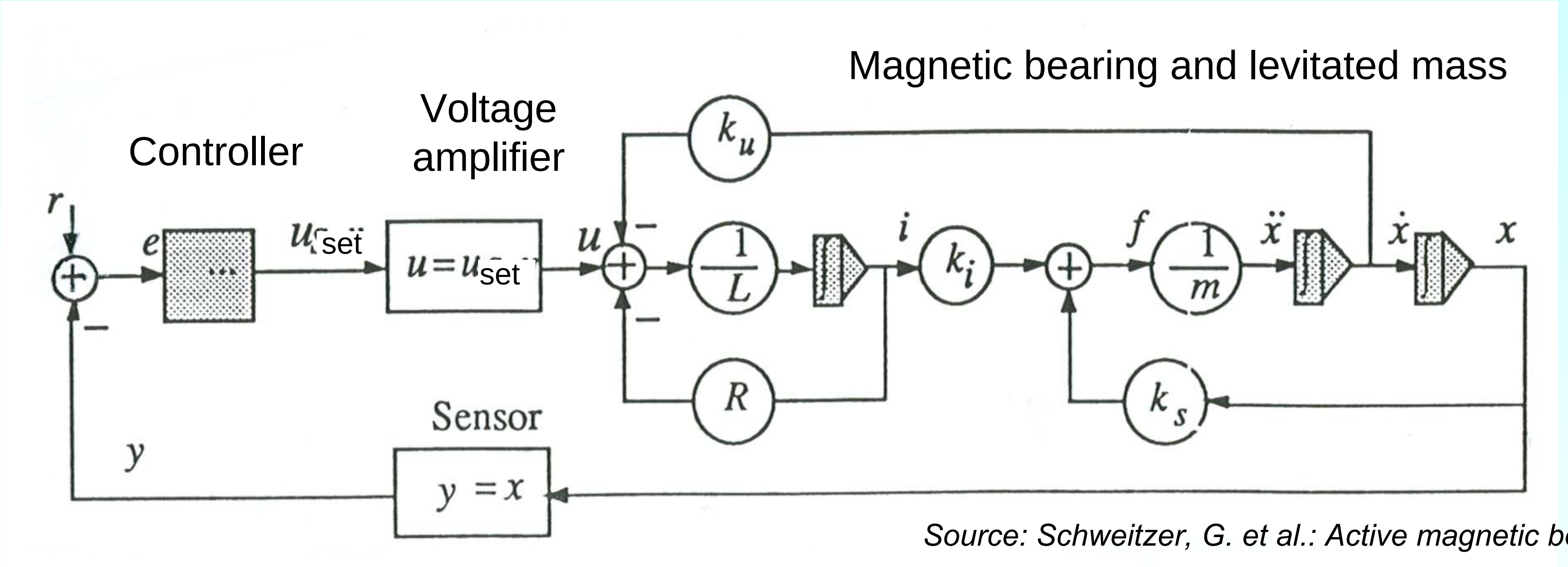
$$G_u(s) = \frac{\frac{k_i}{m \cdot L}}{s^3 + \frac{s^2}{T} - \frac{k_x}{T \cdot m}} \quad \Rightarrow R \to 0 \text{: } T \to \infty \Rightarrow \quad G_u(s, R = 0) = \frac{\frac{k_i}{m \cdot L}}{s^3}$$

⇒Triple pole at $s = 0$: The un-controlled voltage-fed AMB is at the stability limit !
(BUT: The un-controlled current-fed AMB is completely unstable!)

⇒ For stabilization of the voltage-fed AMB a higher order controller than PD is necessary!

Voltage controlled magnetic bearing systems

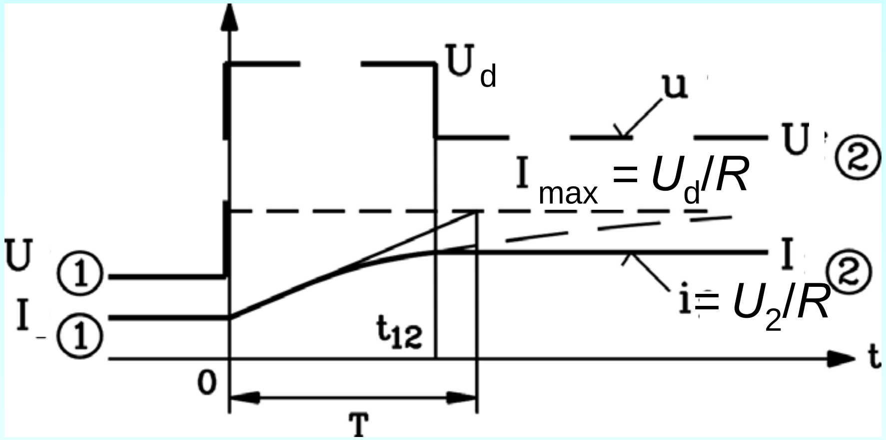
- Coil with electrical time constant *L/R*



Source: Schweitzer, G. et al.: Active magnetic bearings

- ***The voltage-controlled bearing has a weaker instability than the current-controlled bearing.***
- ***A “sensorless" bearing is feasible.***
- ***The power amplifier is mostly a simple voltage chopper with PWM.***
- ***The power limit of the system is fully utilized, when the maximum voltage is applied.***

"High-speed" current build-up



- Quick current **build-up**: Applying of a big "ceiling voltage" U_d : Current rises in minimum time t_{12} from a starting value I_1 (set-point 1) to a new set-point value I_{f2} (set-point 2).
- The time t_{12} is <u>shorter</u> than the electrical **time constant $T = L/R$.**
- **A faster current build-up needs a higher ratio "U_d/U_2". This means a higher rating of the power amplifier.**

New technologies of electric energy converters and actuators

Summary:
Voltage controlled active magnetic bearings

- At very fast movements the induced voltage in the coils cannot be neglected
- Instead of „impressed“ current the impressed voltage has to be considered
- Control circuit becomes more complicated
- Usually one tries to avoid voltage control by a sufficient high inverter DC voltage
- The induced voltage effects may be neglected

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Power amplifier (PA)

- PA converts the controller output signal into the signal for the bearing coil current!

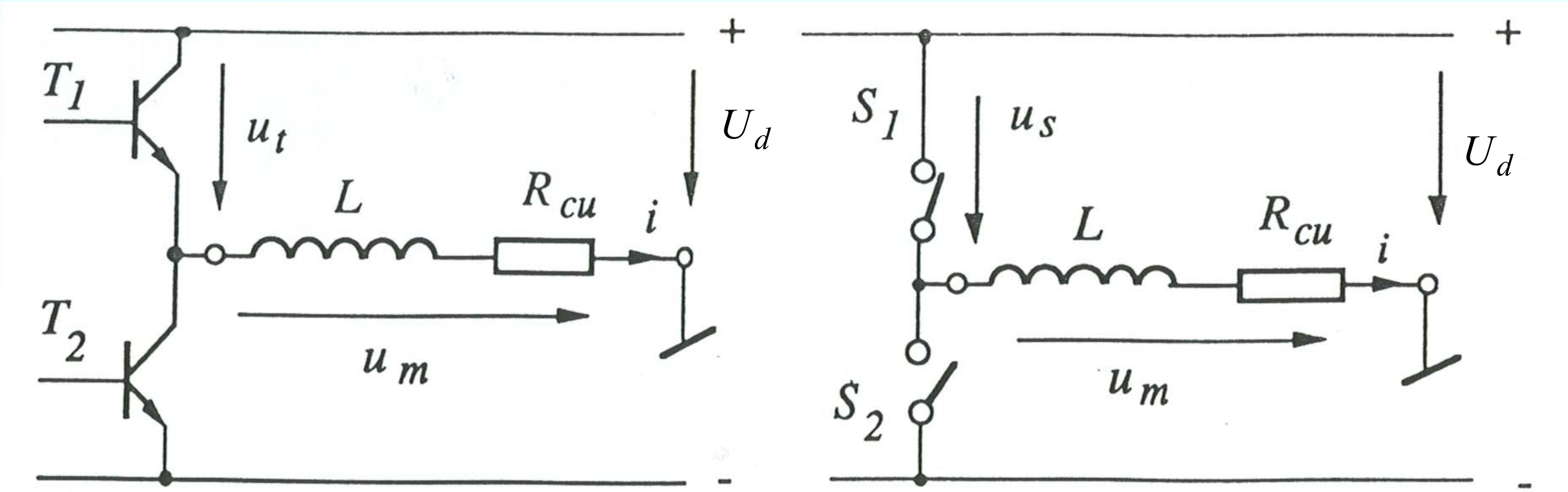
  - Analogue amplifier: Only small power rating up to 0.5...0.6 kVA because of the high losses.

  - Switching amplifier (Chopper): for bigger power ratings (due to lower losses!)

Analogue amplifier
Transistors in amplifier mode

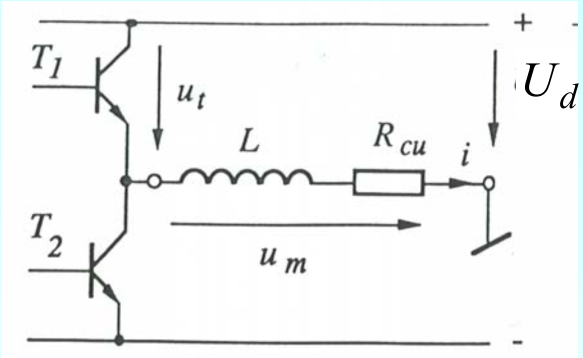
Switching amplifier
Transistors in switching mode

Source: Schweitzer, G. et al.: Active magnetic bearings



Analogue amplifier

- **Analog amplifier:** Continuously operated transistors as variable resistances, giving a "voltage divider"



$$u_t = U_d - u_m$$

At DC current operation: $L \cdot di/dt = 0$: $u_t = U_d - R_{Cu} \cdot i$

Example: $\pm U_d = \pm 150$ V, Coil resistance $R_{Cu} = 2\ \Omega$, max. coil current $i = 6$ A:

$$u_t = U_d - R_{Cu} \cdot i = 150 - 2 \cdot 6 = 138\text{V}$$

Transistor-power losses: $P = u_t \cdot i = 138 \cdot 6 = \underline{\underline{828W}}$

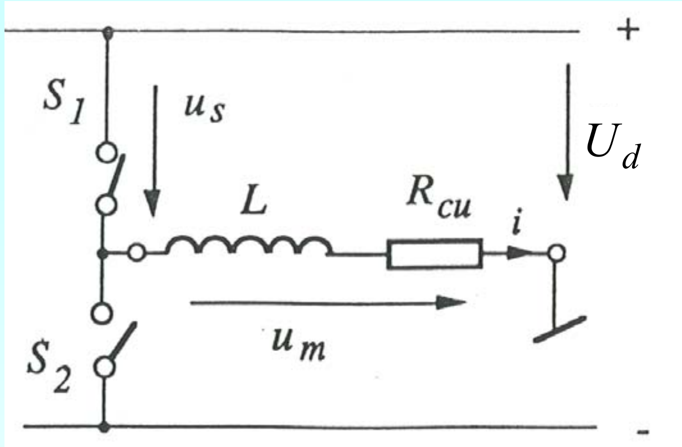
Source: Schweitzer, G. et al.: Active magnetic bearings

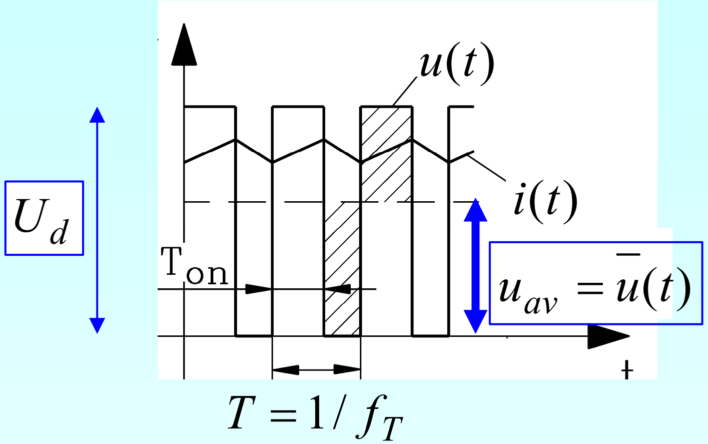
Facit:

The analogue amplifier has very high losses, so it is used only at low power levels.

Source: Schweitzer, G. et al.: Active magnetic bearings

Switching amplifier





- Voltage chopped between $\pm U_d$ and 0 with a fixed high switching frequency f_T (e. g. 50 kHz)

- **Pulse width modulation PWM** or **Hysteresis-Control are applied**.

- Transistors, operated a power switches, have a small threshold voltage u_S in the conducting state. Often MOS-FET technology is used, which allows high f_T.

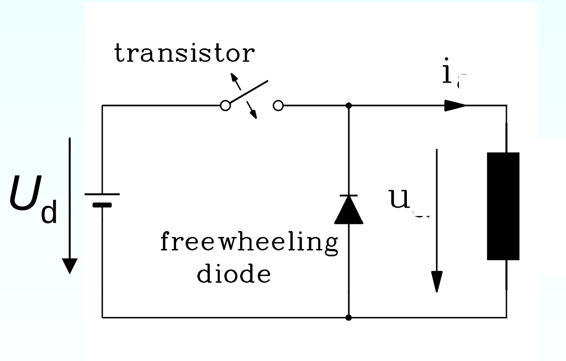
- Higher f_T decreases current **ripple amplitude**, but may cause EMI through capacitive and inductive coupling into the position measurement system !

Facit: ***Switching amplifiers (Choppers) have lower losses, but cause a current switching ripple and often EMI problems !***

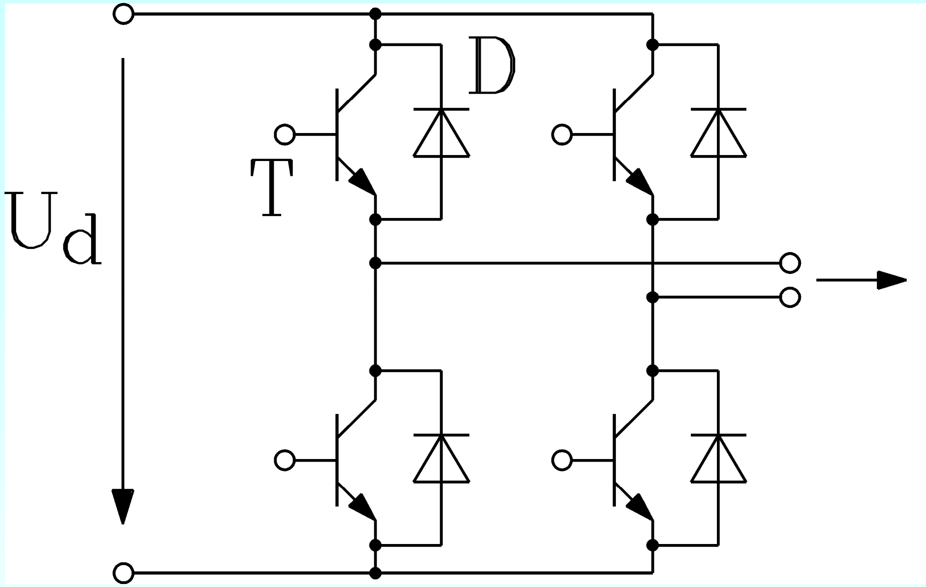
Losses with switching amplifiers

- Transistor conduction losses: e. g. u_S = 2 V, i = 6 A: P_D = 12 W;
- Transistor-switching losses, which are small in MOS-FETs.
- Eddy current losses in the AMB due to the current ripple with frequency $2f_T$.
  - a) Eddy current losses in the coil conductors
  - b) Increased iron core losses in the laminated stator iron
  - c) Additional eddy current and hysteresis losses in ferromagnetic levitated body

A free-wheeling diode is needed anti-parallel to the switching transistor to avoid an over-voltage, when the coil is switched off, and the stored magnetic energy $L \cdot i^2/2$ has to be dissipated.



Inverter topology (H-bridge)



Feeding the R-L-coil system of the AMB

- Per phase a full H-bridge is needed for four-quadrant operation = positive and negative current flow and voltage polarity in the AMB coil !
- DC link U_d feed all H-bridges of the used axial and radial AMBs for the TFM
- Per radial bearing = *x*- and *y*-coil:
  2 H-bridges = 8 Transistors T, 8 free-wheeling diodes D

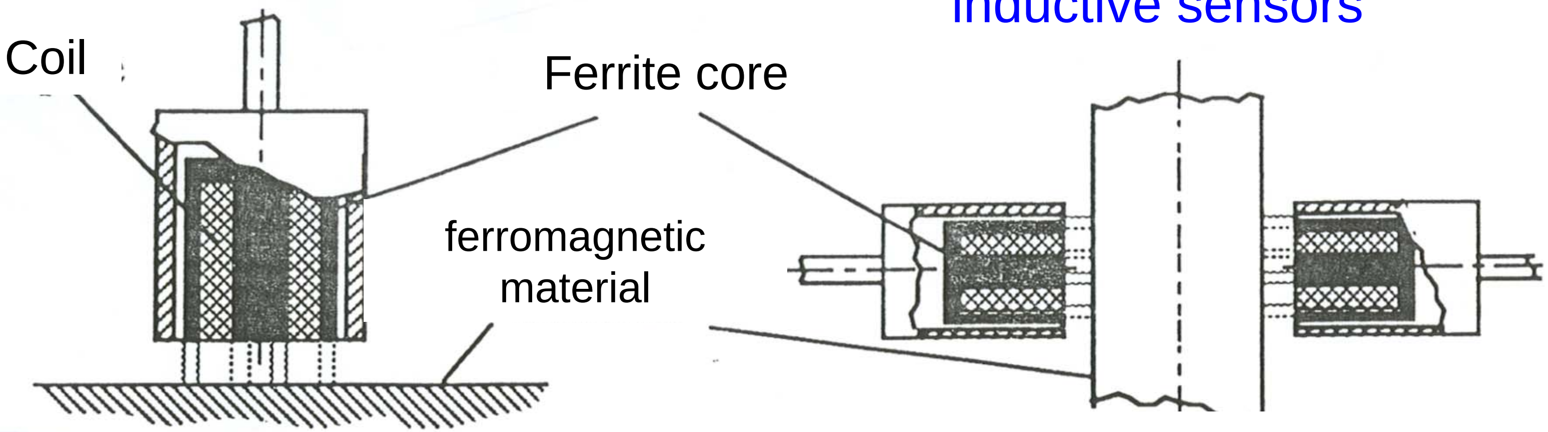
Bearing Position Measurement Sensors

- Non-contact position measurement of the (moving) levitated body
- **Inductive measurement:** Coil with ferrite core is part of a resonant circuit 5 kHz ... 100 kHz. The ferromagnetic levitated body changes with Δx the coil inductance $\Rightarrow$ oscillator detuning $\Rightarrow$ Voltage amplitude U changes $\Rightarrow$ Demodulation $\Rightarrow$ U-Signal (after linearization) proportional to Δx
- **Eddy current sensors:** HF AC current (1 ... 2 MHz) in a air-cored coil excites an air gap magnetic field $\Rightarrow$ It causes eddy currents I_{Ft} in the conducting levitated body $\Rightarrow$ I_{Ft} increase with $1/\Delta x$. Their self-field reduces the coil inductance $\Rightarrow$ Voltage amplitude U changes proportional with Δx. Aluminum body better suited as measuring surface than steel.
- **Capacitive measurement:** Sensor electrode and levitated conductive body form a capacitor $\Rightarrow$ capacitance increases with $1/\Delta x$ $\Rightarrow$ HF AC current (50 kHz .. 5 MHz) causes a capacitive voltage drop proportional to Δx. High resolution: e. g. 0.02 μm for 0.5 mm measuring range
- **Magnetic measurement:** The magnetic field B of a DC excited coil or PM penetrates the ferromagnetic levitated body $\Rightarrow$ B increases with $1/\Delta x$: B measured via *Hall*-probes etc.; Often probes arranged in a differential circuits for linearization of the B-signal
- **Optical measurement :** a) " Light barrier “, b) “Variable angle of reflection“. Sensitive to dirt!

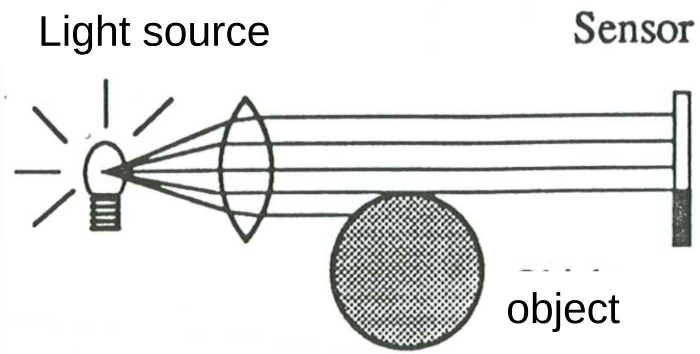
Inductive & optical position measurement sensors

Inductive measurement

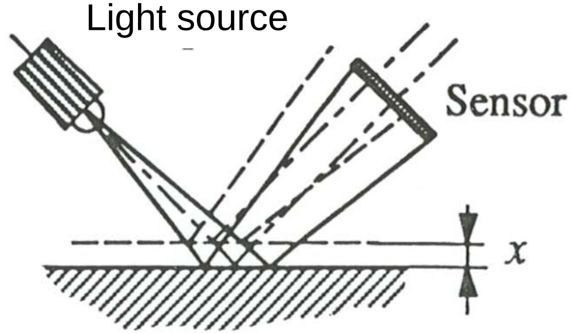
Differential arrangement of two inductive sensors



Measurement via light barrier



Optical measurement with vary reflection angle



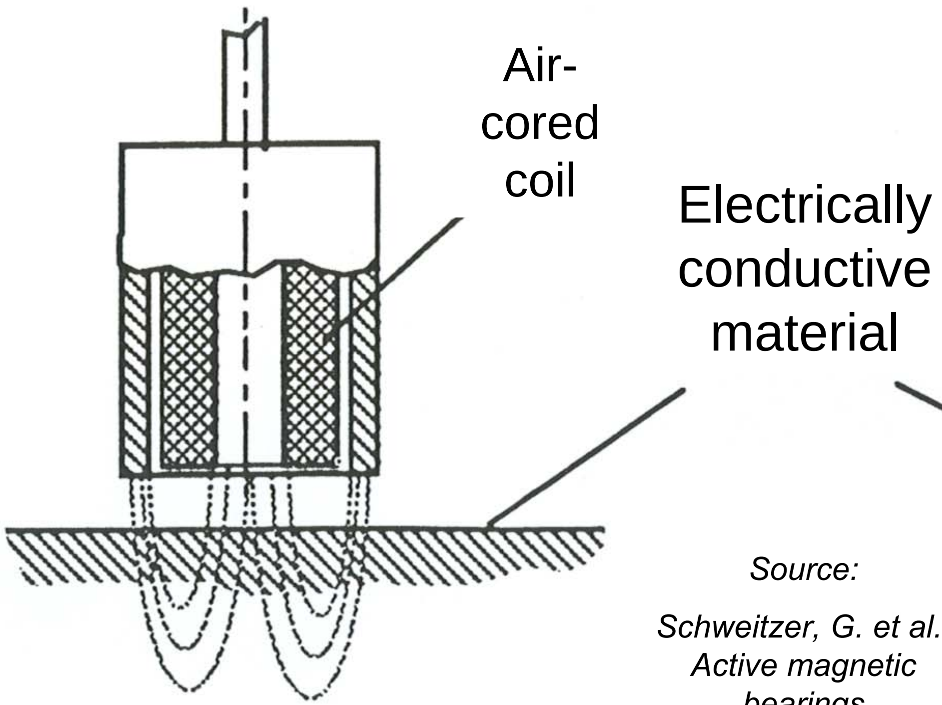
Source:

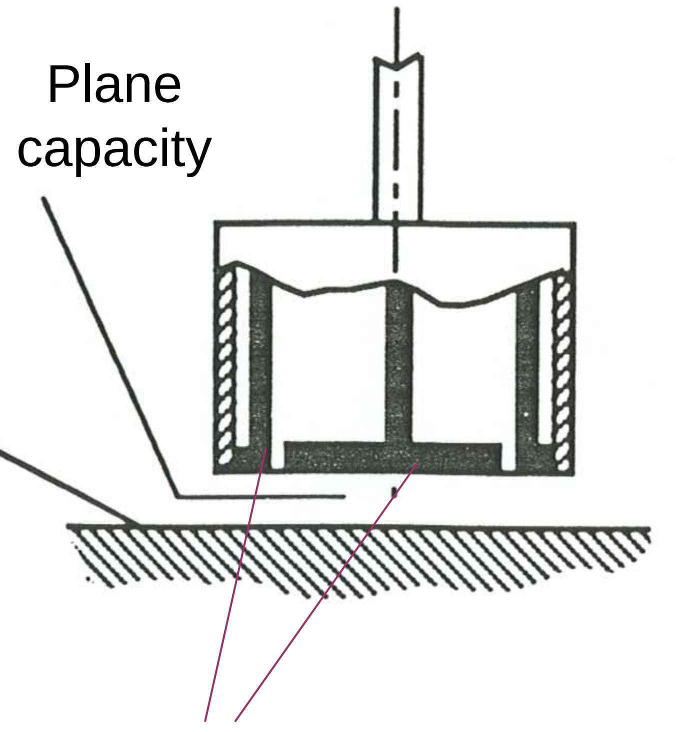
Schweitzer, G. et al.: Active magnetic bearings

Eddy current & capacitive position measurement sensors

Eddy currents sensor

Capacitive sensor



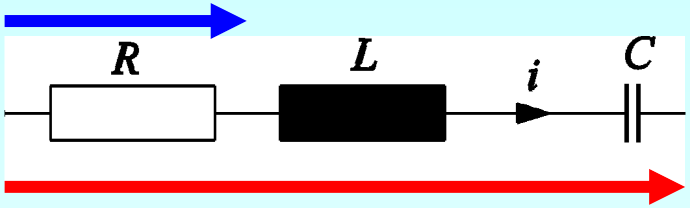


Source:

Schweitzer, G. et al.: Active magnetic bearings

Series oscillation circuit

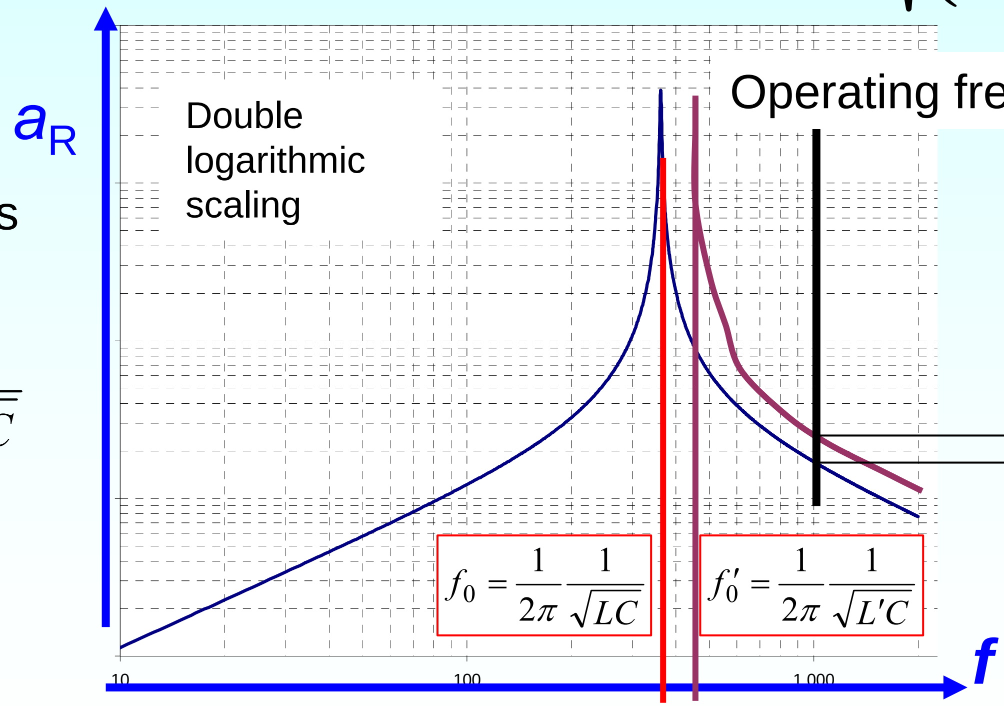
Output AC voltage $\underline{U}_R$



Input AC voltage $\underline{U}$

$$a_R = \frac{U_R}{U} = \frac{R \cdot I(\omega)}{U} = \frac{R}{\sqrt{\left(\omega L - \frac{1}{\omega C}\right)^2 + R^2}}$$

- A change of L leads to a change of resonance frequency: $\omega_0 = \frac{1}{\sqrt{LC}}$



$$\Delta U_R \propto \frac{1}{\sqrt{L(x)}} \propto \Delta x$$

$$\omega = 2\pi \cdot f$$

Amplifier power rating $\hat{U}_{max} \cdot \hat{I}_{max}$

- An unwanted oscillation of the levitated body induces a voltage u_i in the magnet coil, which increases with oscillation frequency f. The feeding voltage u must overcome u_i to impress the necessary levitation current i.

$$u_i = -\frac{d\psi}{dt} = -N \cdot A \cdot \frac{dB}{dt} = -\mu_0 N^2 A \frac{1}{2} \frac{d}{dt}\left(\frac{i}{\delta_0 - x}\right)$$

- **Voltage limit:** Feeding voltage u is equal to u_i:

Voltage limit (at $R \cong 0$): $u + u_i = 0 \quad \Rightarrow \quad u = -u_i$

Bearing force: $F = \mu_0 A \frac{N^2}{4} \cdot \left(\frac{i}{\delta_0 - x}\right)^2 \qquad \frac{dF}{dt} = \mu_0 A \frac{N^2}{4} \cdot 2 \cdot \left(\frac{i}{\delta_0 - x}\right) \cdot \frac{d}{dt}\left(\frac{i}{\delta_0 - x}\right) = u \cdot \left(\frac{i}{\delta_0 - x}\right)$

- **Design rule** for maximum necessary amplifier power rating $u \cdot i$:

$\frac{dF}{dt} = u \cdot \left(\frac{i}{\delta_0 - x}\right)$ At zero position deviation $x = 0$: $\boxed{\frac{dF}{dt} = \frac{u \cdot i}{\delta_0}}$

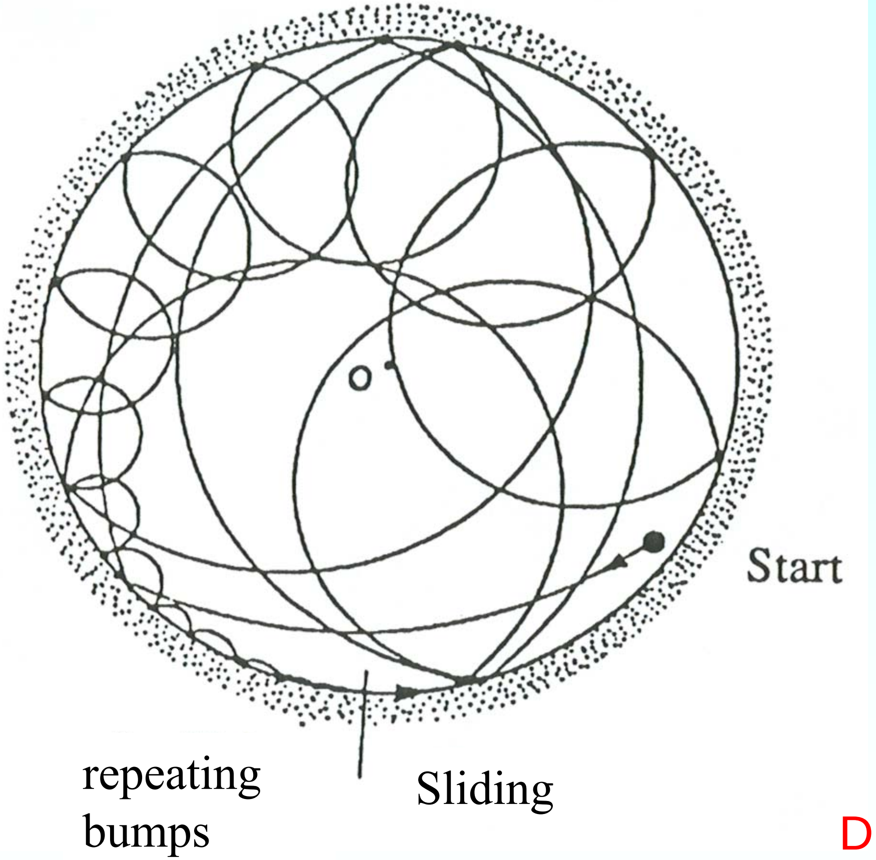
For sinusoidal movement ω: $\boxed{\omega_{max} \hat{F}_{max} = \hat{U}_{max} \cdot \hat{I}_{max} / \delta_0}$

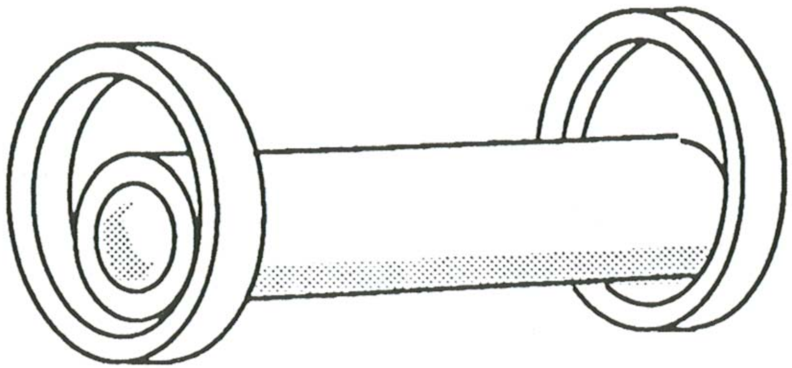
Auxiliary bearings as back-up

Source:

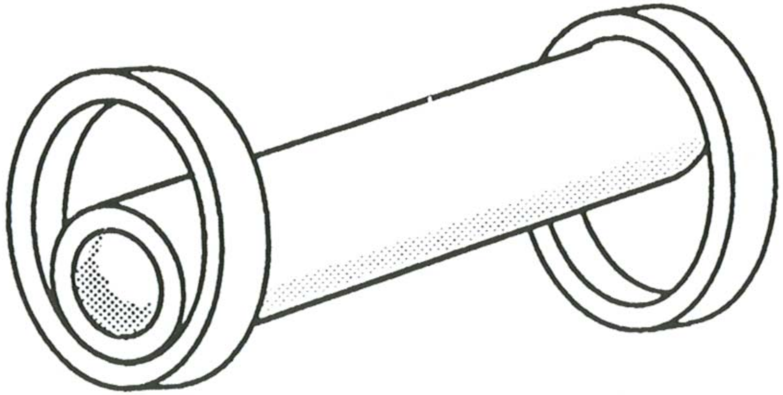
Schweitzer, G. et al.: Active magnetic bearings

Falling of the levitated rotating body into the auxiliary bearing sleeve





Common-mode movement in the aux. bearings



Differential-mode movement in the aux. bearings

Falling into the auxiliary bearings

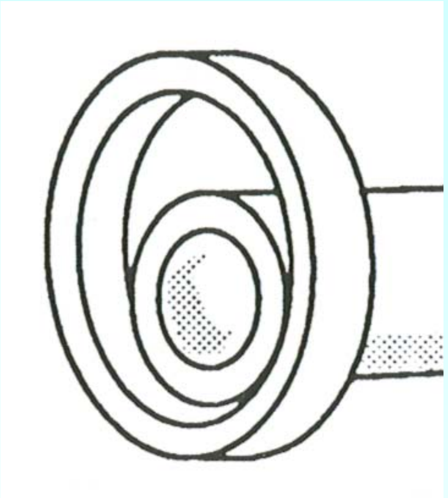
- **Interruption of voltage supply:** Levitated body falls into the aux. bearings. Air gap of the aux. bearings must be smaller than the sensor air gap and the AMB air gap to avoid damage there.

- **Rotating levitated body:** Stored kinetic energy of the falling body is dissipated via friction into heat and deformation of the aux. bearings. So inverter-fed E-drives shall dissipate a part of the kinetic energy via the DC link into the resistive braking chopper. Hence the residual kinetic energy, which is dissipated in the aux. bearing, is reduced.

- **Further improvement:** Coupling of DC links of the E-drive and the AMB. Braking energy of the decelerated (generator operating) drive supports the voltage of the DC link capacitor. So the AMB may work longer, while the drive speed falls. Hence the dissipated residual kinetic energy in the aux. bearings is minimized.

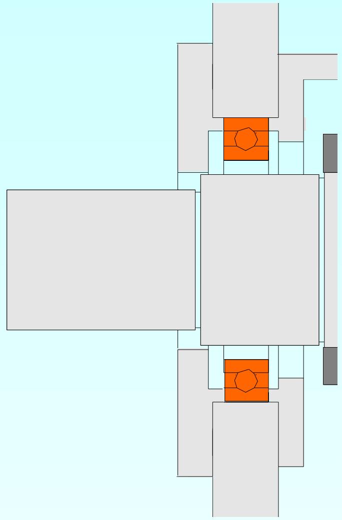
- Sometimes: UPS is use for AMB.

Examples for auxiliary bearings



Source:

Schweitzer, G. et al.: Active magnetic bearings



Bronze rings as non-lubricated sleeve bearings:

The softer bronze material is deformed in case of a "crash" and not the harder rotating steel shaft. The bronze rings can be exchanged more easily than the rotor shaft.

Ball bearings with loose inner ring:

Shaft falls into the loose inner rings and may rotate further via the balls of the aux. bearings.

Losses in the AMB

- No bearing friction losses !
- **Rotor iron losses $P_{Fe,r}$:** Braking torque due to **iron losses** in the ferromagnetic parts e.g. the rotor laminations (Hysteresis und eddy current losses).

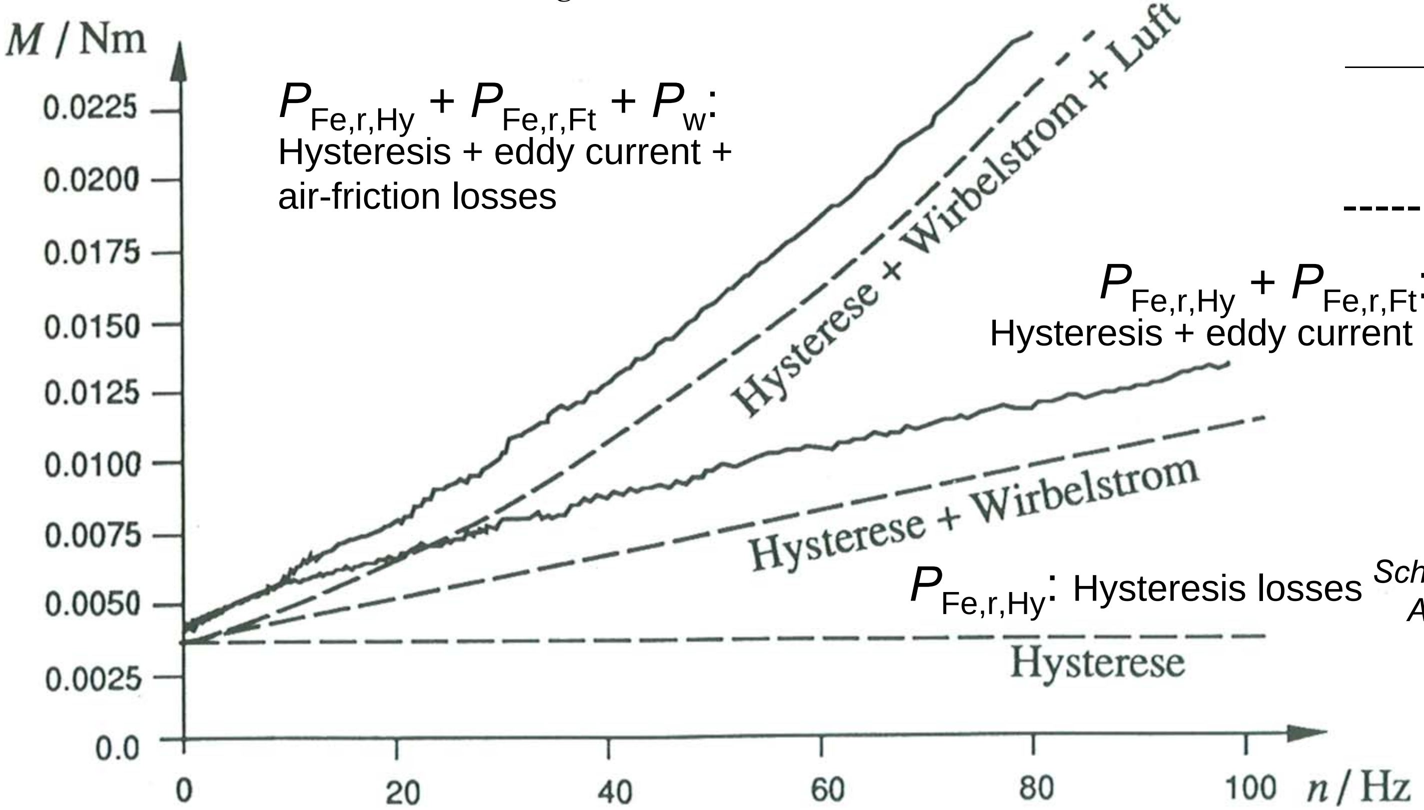
$M = P_{Fe,r}/(2\pi n)$ $P_{Fe,r} = P_{Fe,r,Hy} + P_{Fe,r,Ft}$ $f \sim n$, $P_{Fe,r,Hy} \sim f$ and $P_{Fe,r,Ft} \sim f^2$: $M \propto a + b \cdot f$

- **Air friction losses P_w** act also as a brake.
- In the bearing stator coils: ***Joule* losses** $P_{Cu,s} = I^2R$, (also **eddy currents losses** in the coil conductors due to the PWM current ripple)
- **Iron core losses $P_{Fe,s}$** in the stator iron yokes due to the PWM current ripple
- **Losses in the power electronics P_{Inv}:**
  a) Inverter: PWM-operation: Conducting and switching losses
  b) Rectifier losses: for producing a DC voltage from the AC grid
  c) Power supply losses for the electronic devices: for the sensor system and the controller
- ***Benchmark for total AMB losses $P = P_{Cu,s} + P_{Fe,s} + P_{inv}$*: Rotor (Mass *m*) levitated without rotation: *P/m* = 1 W/kg.**

Braking torque of the magnetic bearing system

- Bearing force: Radial: 1000 N & 2000 N measured force, axial: 1000 N,

"Friction coefficient" $\mu = \frac{M/(d/2)}{F_{ges}} = \frac{0.031/(0.08/2)}{4000} = 1.9 \cdot 10^{-4}$



$P_{Fe,r,Hy} + P_{Fe,r,Ft} + P_w$: Hysteresis + eddy current + air-friction losses

$P_{Fe,r,Hy} + P_{Fe,r,Ft}$: Hysteresis + eddy current losses

$P_{Fe,r,Hy}$: Hysteresis losses

——— measured

------------ calculated

Source:

Schweitzer, G. et al.: Active magnetic bearings

Rigid body oscillation of controlled systems

- Radial bearing with controller and oscillating rigid body form the oscillatory system.

- "Rigid" body: No elastic deformation of the body occurs during the vibration!

Example: P-controller: un-damped oscillations e. g.: in the *x*-axis

Intrinsic angular frequency: $\omega_{e,x} = \sqrt{(K_{p,x}k_i - k_x)/m}$

- Oscillation in *x*- and *y*-direction is possible.
  General: Superposition of *x*- und *y*-oscillation: "Staggering" of the rotor

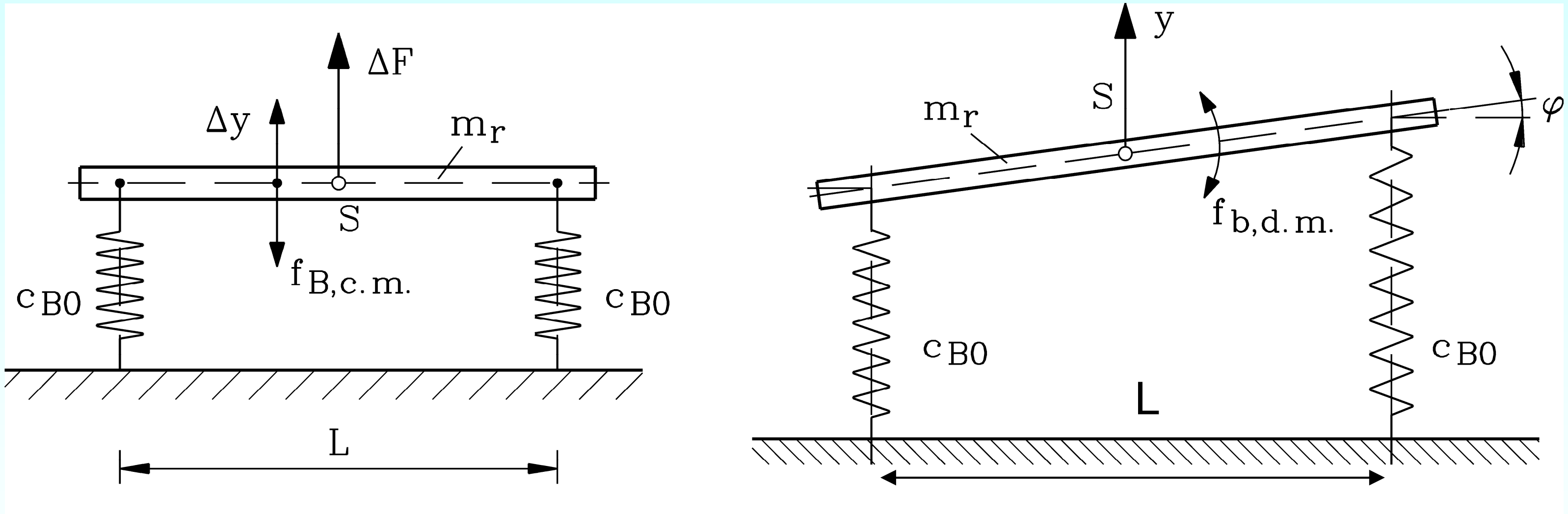
- **Two radial bearings:** Oscillation at the two radial bearings has two base modes:

  - In-phase oscillation in both bearings = **Common mode oscillation**
  - Opposite-phase oscillation in both bearings = **Differential mode oscillation**
  - In general: Superposition of **common & differential mode oscillations**

- Often the natural frequency of the diff. mode oscillation is higher than of the common mode oscillation ! $f_{B,d.m.} > f_{B,c.m.}$

Rigid rotor vibration in elastic bearings

- **Magnetic bearings** have a rather low dynamic stiffness due to the control delay.
- So the bearing oscillation frequency is lower than the rotor natural elastic bending frequency.
- So rotor is considered RIGID in the vibrating bearings ! Rigid body oscillations occur !



a) Common mode vibration

b) Differential mode vibration

$$f_{B,c.m.} = \frac{1}{2\pi} \cdot \sqrt{\frac{2c_{B0}}{m_r}}$$

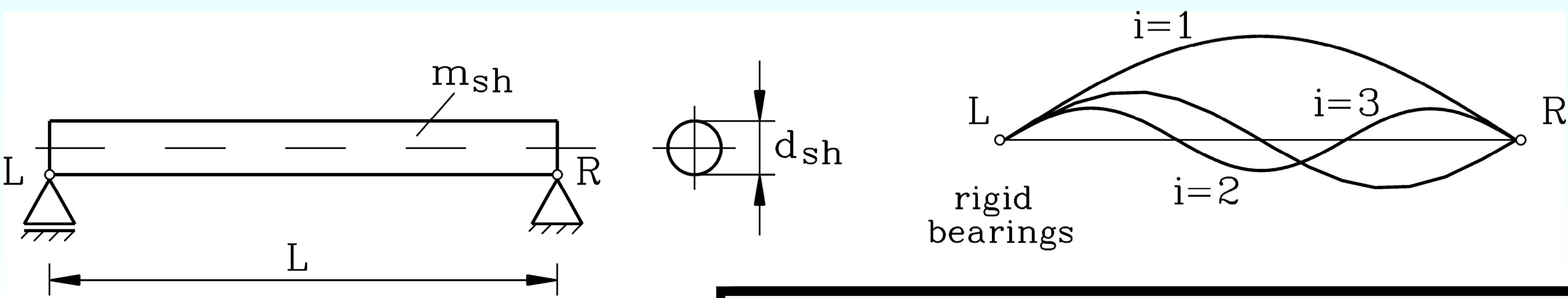
$$f_{B,d.m.} = \frac{1}{2\pi} \cdot \frac{L}{2} \cdot \sqrt{\frac{c_{B0}}{J_\varphi}} \neq f_{B,c.m.}$$

Bending vibrations of the elastic rotor

- **Rotor elasticity**: Bending vibrations of the elastic flexible rotor
  Fundamental vibration mode (1. elastic mode): has two nodes, vibrates at the 1st natural frequency (= 1st eigen-frequency),
  Other vibration modes: 2. mode = 3 nodes, 3. mode = 4 nodes etc. at higher natural frequencies

Example: Rotor is considered as cylindrical beam (diameter d_{sh}, length L) with DISTRIBUTED mass along the beam. An infinite number of natural vibration modes exists.

Ordinal number of bending modes *i*



Example:

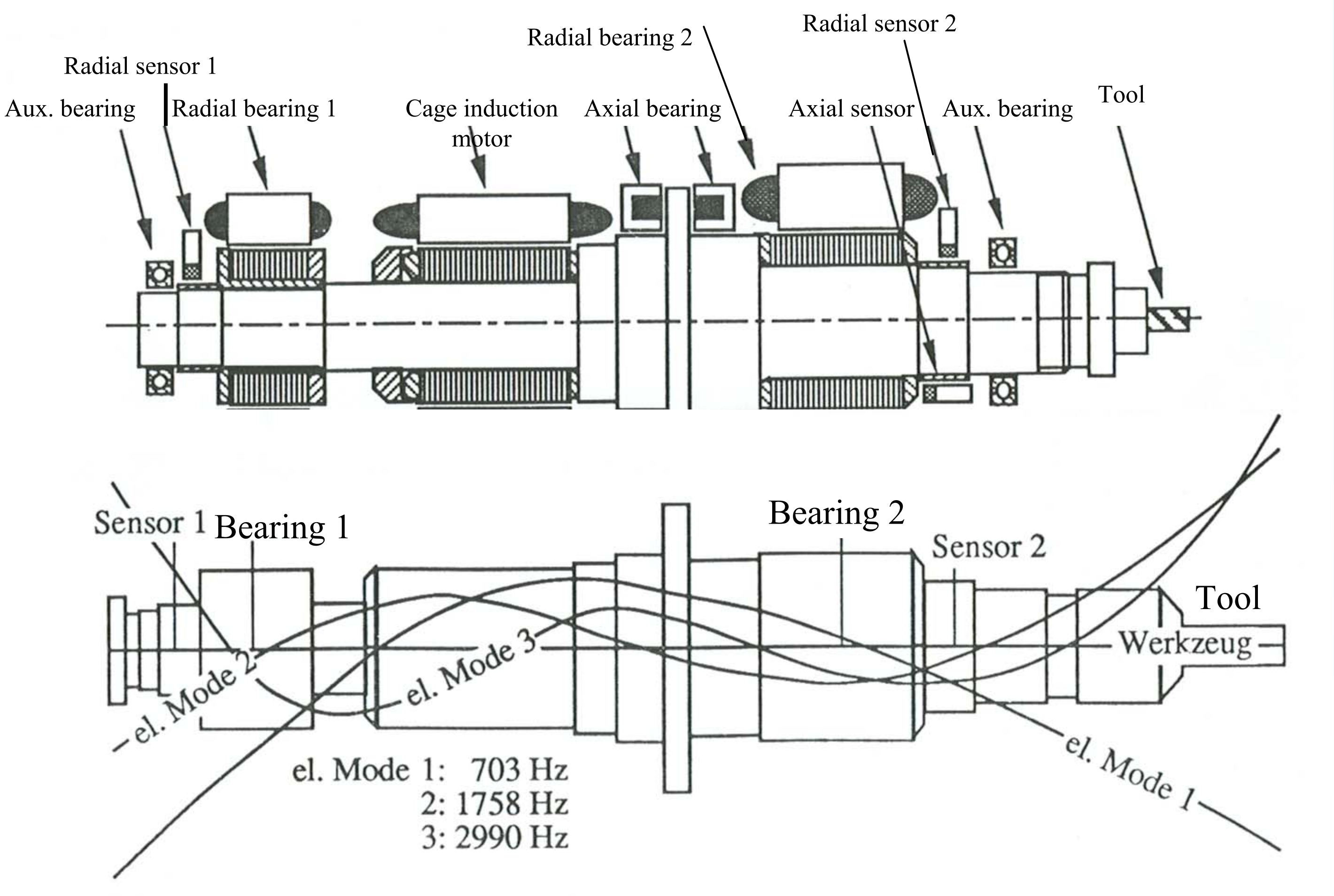
i	1	2	3
$f_{b,i}$ / Hz	703	1758	2990

Influence of rotor elasticity on the control system

- **Does the sensor system observe the rotor vibration modes?** If the **radial position sensors are placed exactly at the vibration nodes**, no Δx is measurable (**"Collocation" of sensor and vibration node**).
- By bearing design it MUST be ensured, that the rotor vibrations are detected. So the **controllability of the vibration modes** is possible.
- **By knowledge** of the vibration modes one can distinguish, if the sensors are positioned left or right of a vibration node:
  So: Δx-signal is in opposite phase / in phase with the rotor deflection: Hence the controller is programmed with / without change of the sign of the signal for the feedback. By that way the bearing force may damp the elastic rotor vibrations.
- **The maximum output frequency of the controller** must be above the natural frequency of the vibration mode, which shall be damped. Usually the first three rotor vibration modes should be damped in big drives (MW-range). In small drives often the eigen-frequencies are high enough to consider the rotor to be "rigid".

Natural bending vibration modes of a milling spindle rotor

- **High-Speed-Alu-squirrel cage rotor, 2 radial & 1 axial bearing, 40 000 /min, 35 kW**



Source:

Schweitzer, G. et al.: Active magnetic bearings

New technologies of electric energy converters and actuators

Summary:
Components of an active magnetic bearing

- Fast switching power electronics, distance measurement, auxiliary bearings are needed
- Eddy current or capacitive distance sensors most widely used
- Rotor and AMB are an oscillating system with rigid and elastic vibration modes
- For smaller rotating machines usually the first bending frequency is high enough to consider a stiff rotor

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

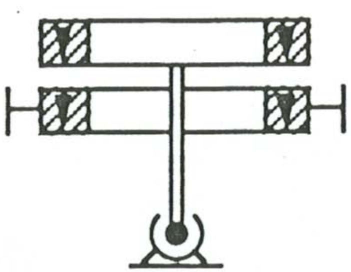
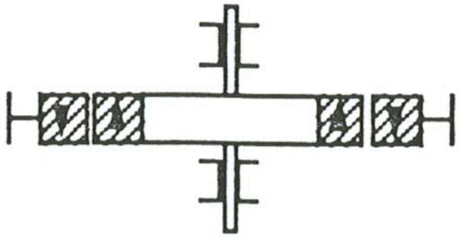
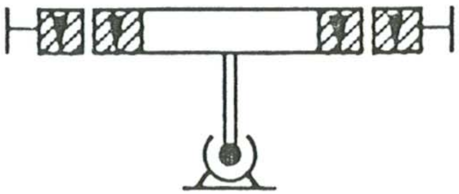
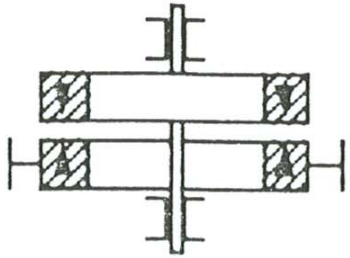
Passive permanent magnet bearings

Rare earth permanent magnet arrangement: Due to *Earnshaw´s* theorem it is only in combination with a controlled bearing part stable

Source:

Schweitzer, G. et al.: Active magnetic bearings

Reduced energy consumption, but lower dynamic bearing stiffness

	Radial bearing	Axial bearing
Attractive force		
Repulsive force		

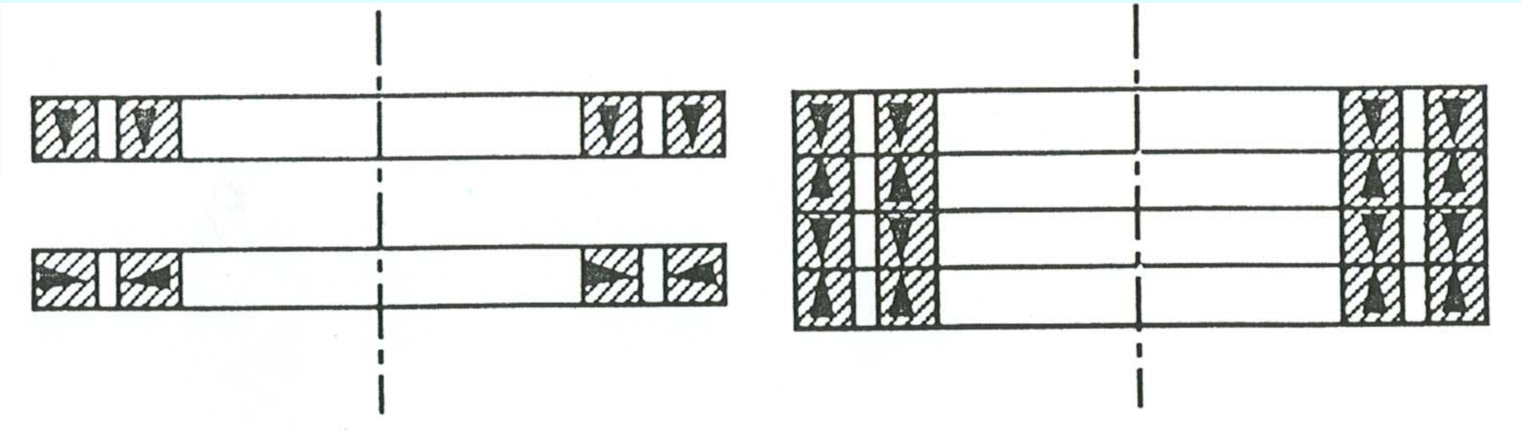
Passive radial magnetic bearing

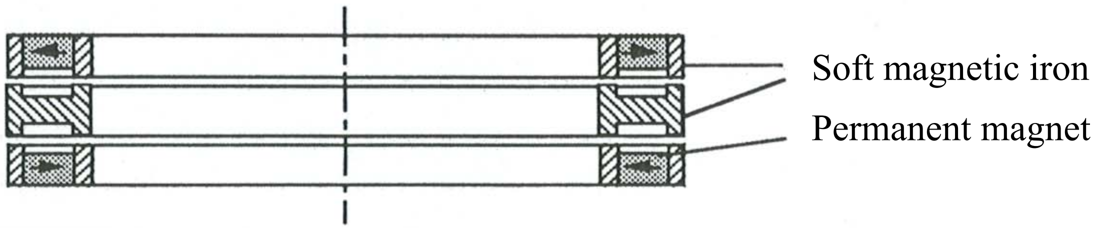
- ***Example:*** **SmCo magnet ring pairs with 28 mm diameter gives a stiffness per ring pair of only 16 N/mm.**

- **Stable** levitation is possible in radial direction.
- Axial direction is **unstable** and needs an AMB
- A higher number of ring pairs increases the bearing stiffness

Source:

Schweitzer, G. et al.: Active magnetic bearings





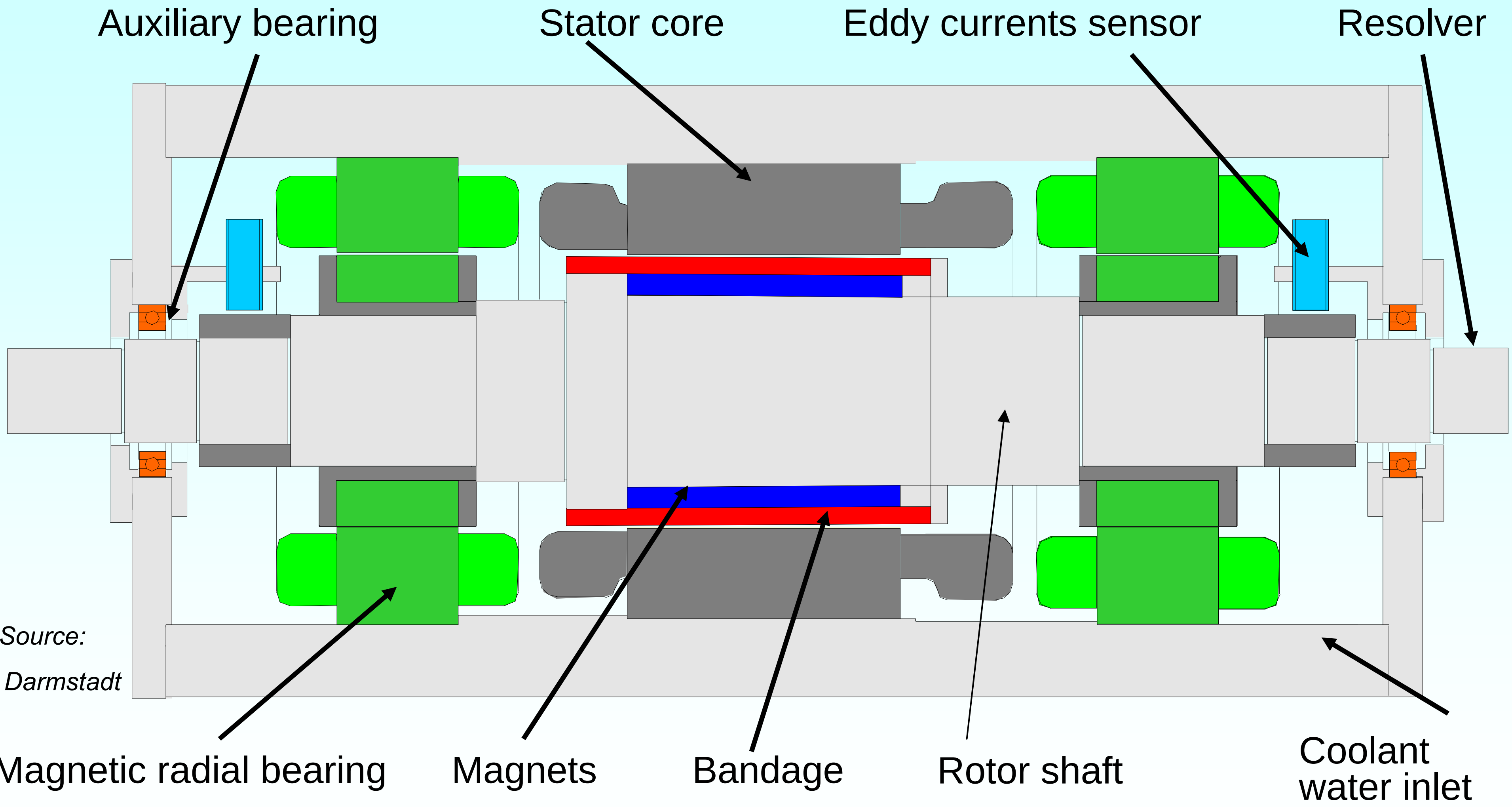
Summary:
Passive magnetic bearings

- Basically unstable, but cannot be controlled
- Only in combination with a controlled bearing axis the other bearing axes may be equipped with passive bearings
- Less dynamical and static stiffness than controlled bearings, but cheaper

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

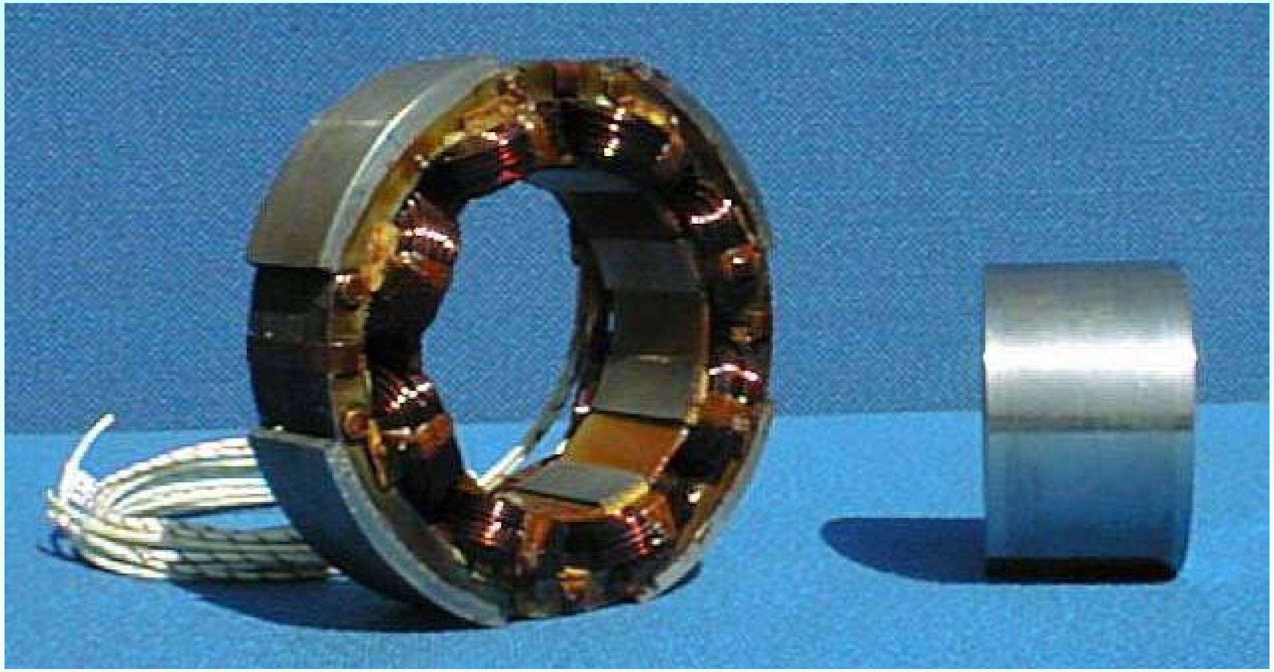
Magnetic bearing PM synchronous motor 40 kW, 40 000/min



Source:

TU Darmstadt

Technical data of a radial magnetic bearing



F_{Bearing} = 600 N
8-pole structure

Rotor weight force 100 N

Difference winding:
Base excitation:
N_0 = 45, I_0 = 6 A
Control excitation:
N_1 = 18, I_1 = 15 A

Rotor lamination:
d_a = 154 mm
d_i = 90 mm
l_{Fe} = 40 mm

δ_{bearing} = 0.4 mm
$\delta_{\text{aux. bearing}}$ = 0.2 mm

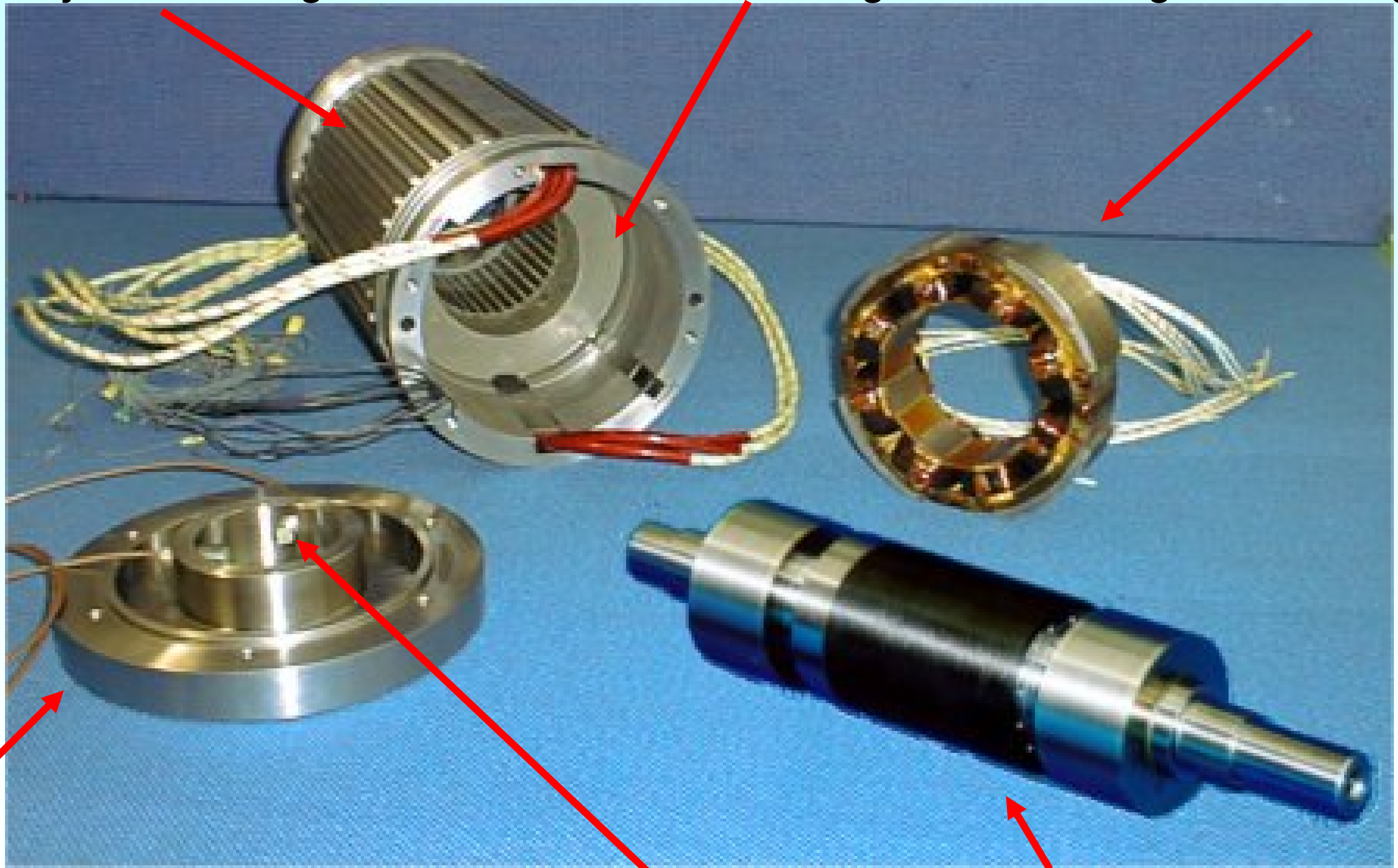
Steady-state specific load force: $$f = \frac{F}{d \cdot b} = \frac{600\text{N}}{9\text{cm} \cdot 4\text{cm}} = 16\frac{\text{N}}{\text{cm}^2}$$

Short-time overload: $$f = 32\frac{\text{N}}{\text{cm}^2}$$

Source: EAAT Chemnitz

PSM motor components $n_N = 40000\ \text{min}^{-1}$, $P_N = 40\ \text{kW}$

Stator with water jacket cooling & insulation cast end windings **Magnetic bearing stators**



Source:

TU Darmstadt

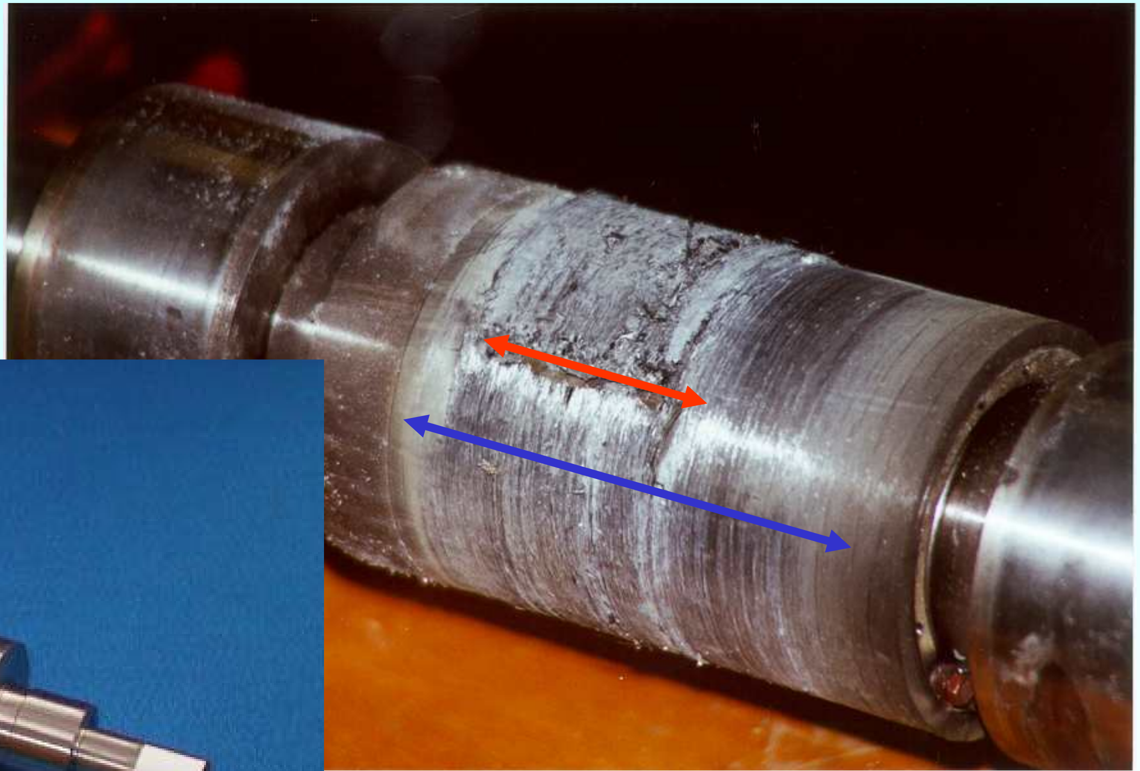
Bearing end shield with distance eddy current sensors **PM Rotor**

Crashed Rotor M1 and redesigned Rotor M2

Crashed Rotor M1:

PM Bandage Crash at 35000/min

- Breaking length
- PM active length



Redesigned Rotor M2

Source: TU Darmstadt

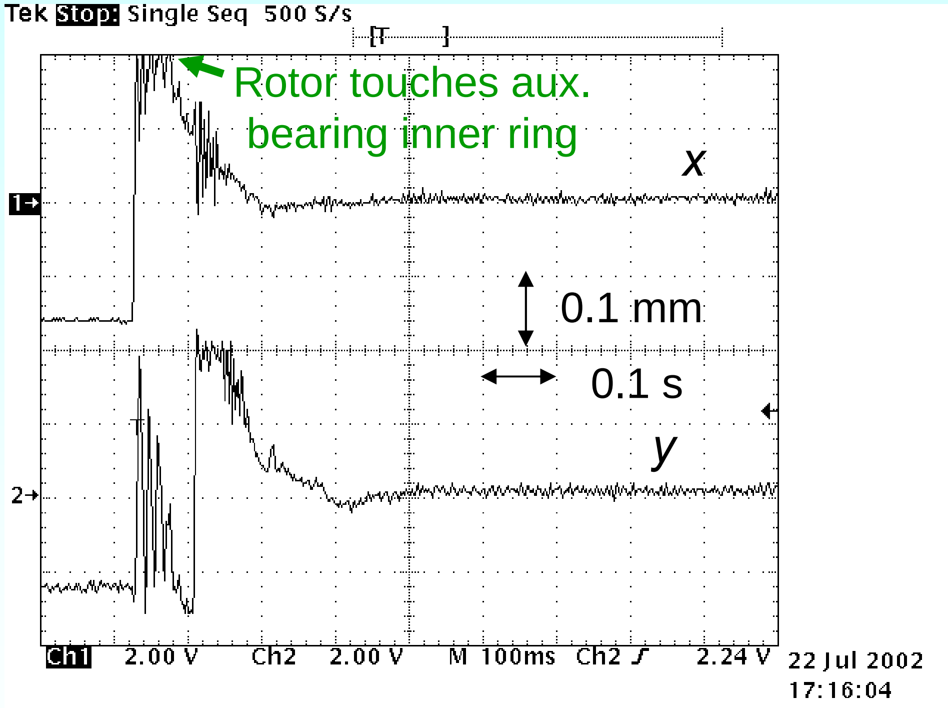
Performance of PID-controlled radial magnetic bearing

Measured position $x(t)$, $y(t)$ of shaft center at $n = 0$:

Source: TU Darmstadt

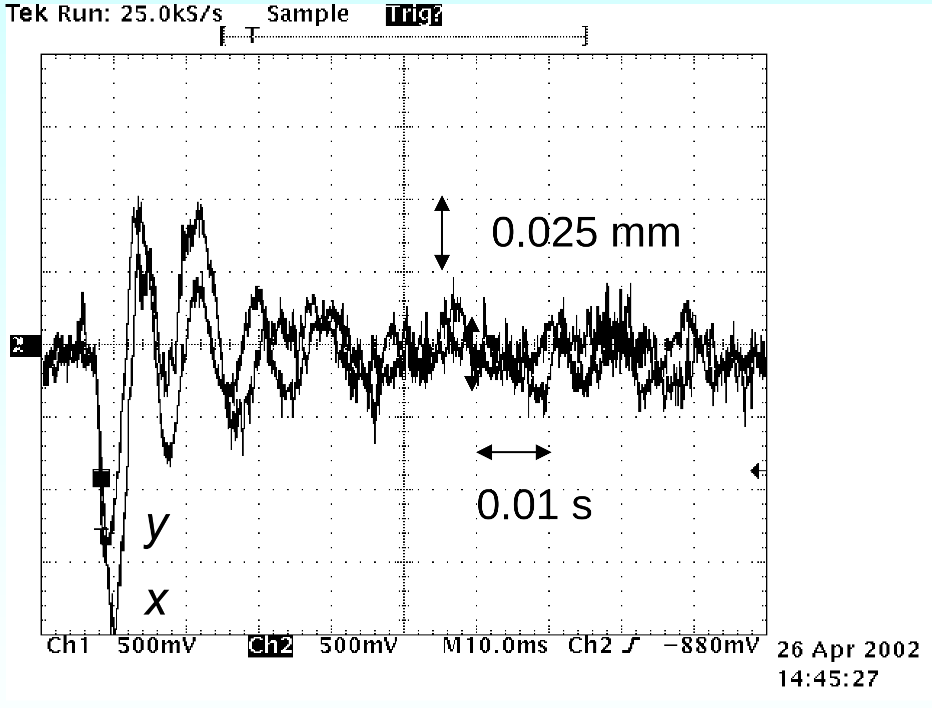
A) "Take off" levitation

(Bearing „on")



B) Impulse response

(Hammer blow on the shaft end)

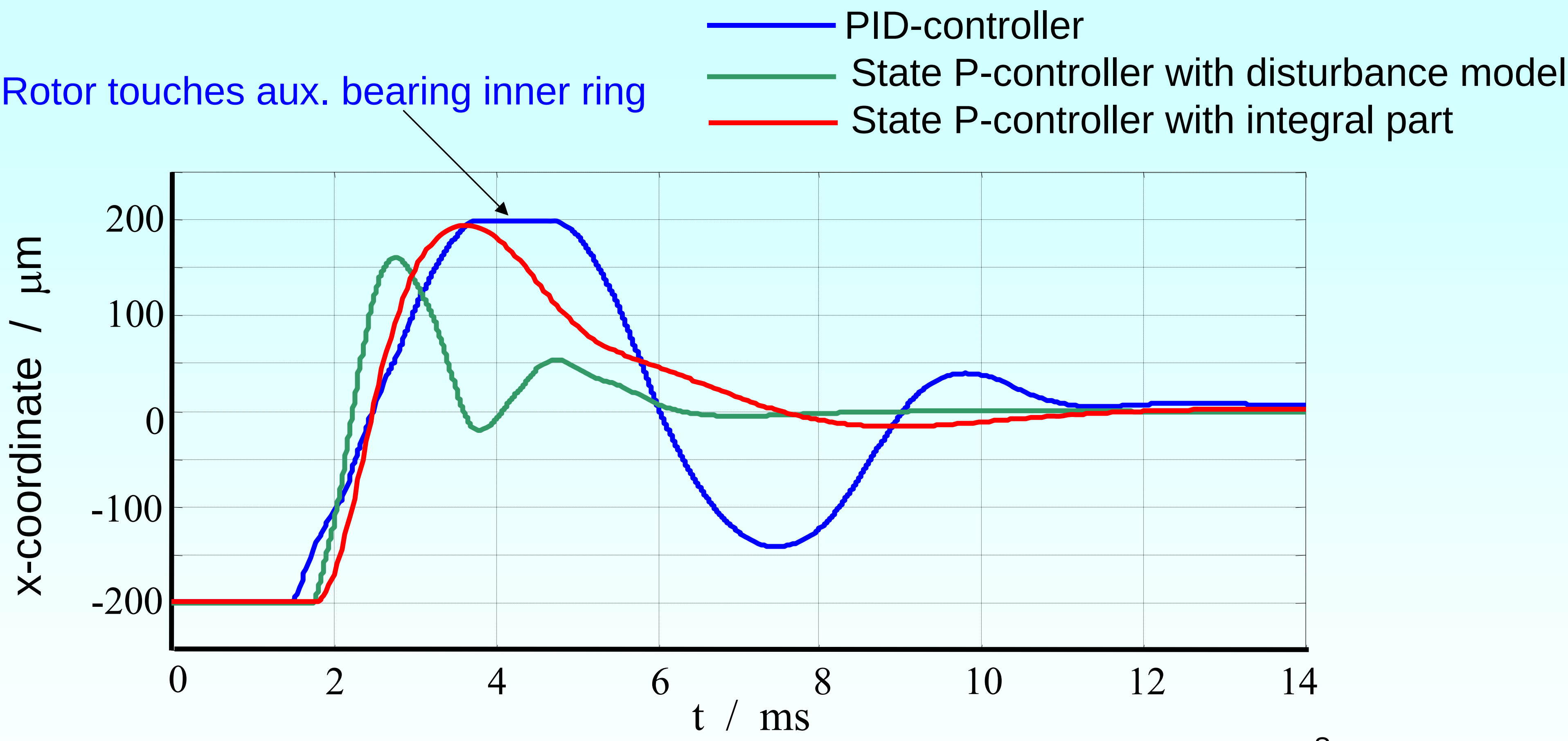


A) 2 V/Div. 100 ms/Div.

B) 500 mV/Div. 10 ms/Div.

Position scale: $c_{x,y}$ = 20V/mm, $\delta_{\text{aux.bearing}}$ = 0.2 mm

Calculated comparison of different control methods

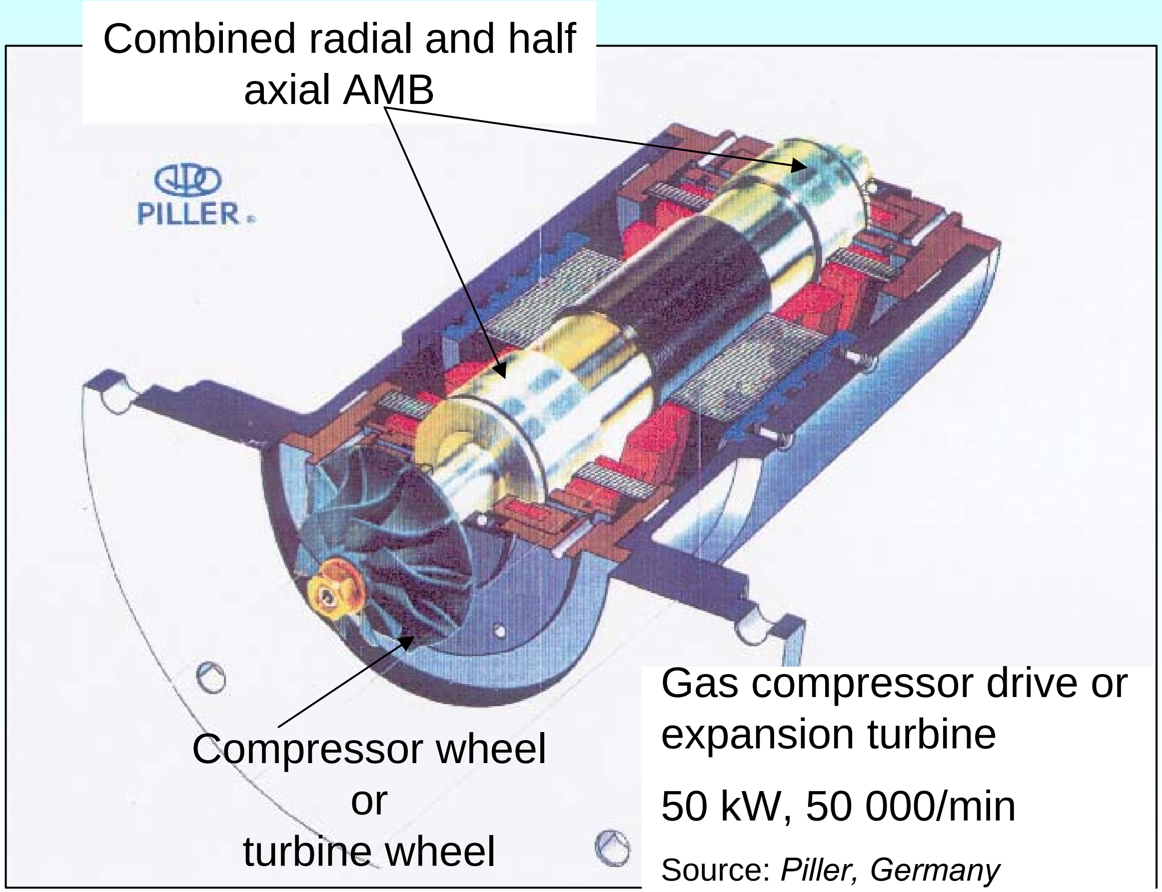


Source: TU Darmstadt

Set point: x_{set} = 0 at t = 0 at standstill state of rotor (n = 0):

Rotor take-off: Calculated vertical position $x(t)$

PSM High Speed drives with AMB (1)



Gas compressor drive or expansion turbine

50 kW, 50 000/min

Source: *Piller, Germany*

LEVITEC

Turbo radial compressor
1.2 kW, 70 000 /min

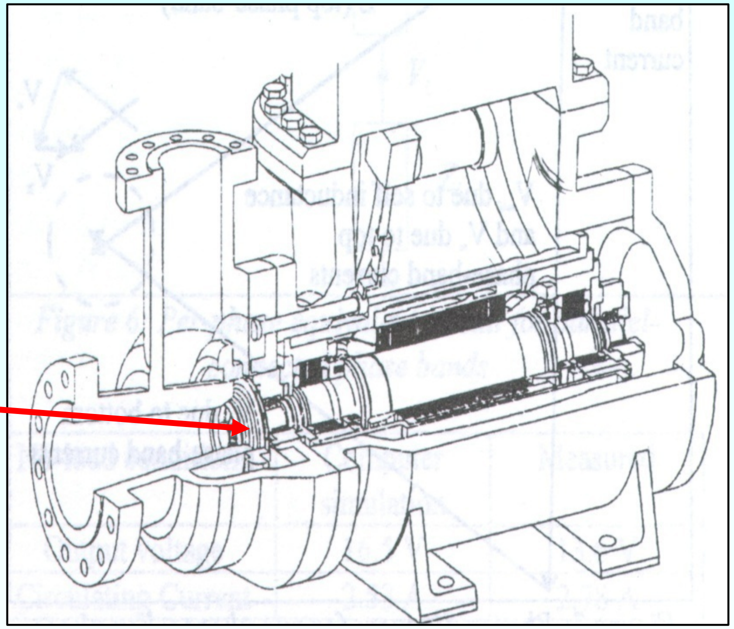
Source: Levitec,Lahnau, Germany

PSM High Speed drives with AMB (2)

- High-Speed drive allows
  - *smaller volume* with higher power („power comes from speed")
  - *less mass* = higher power density
  - *gearless direct drive*
  - *Low maintenance*

-*Example:* Smaller compressor runner for 400 kW due to high speed 50 000 /min!

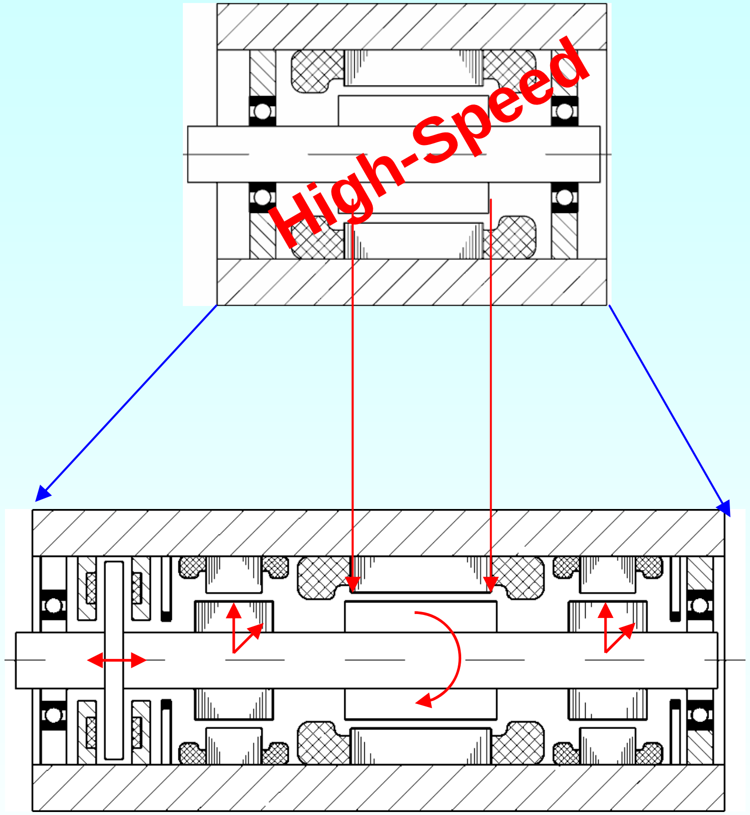
In trend: Due to higher speed increasing ***no contact magnetic bearing*** for using = WEAR FREE !



High-Speed compressor

Source: Piller, Germany

Active magnetic bearings enlarge motor length



- AMB causes bigger axial length
- Hence lower bending frequencies
- Less dynamical stiffness

A) Mechanical bearing for High-Speed:

- Spindle bearing (= small balls = small centrifugal forces)
- Low friction: only oil lubricant, no grease
- Hybrid bearing (Ceramic balls)

Bearing "ball speed": $v = d_m \cdot n \cdot \pi$

$d_m \cdot n$: 1 … 2 Mio. mm/min

d_m: bearing average diameter n: speed

B) Magnetic bearing for High-Speed:

Benefit: maintenance free, lubrication free, wear free, active rotor influencing

Requirement:
- DC-excitation,
- DC-controller,
- distance measuring,
- mechanical bearing
- Special laminations

Large 2-pole 3-phase synchronous motor with AMB

2-pole 3-phase synchronous motor (Massive turbo rotor with electric excitation), with AMB, used as oil-free natural gas compressor drive

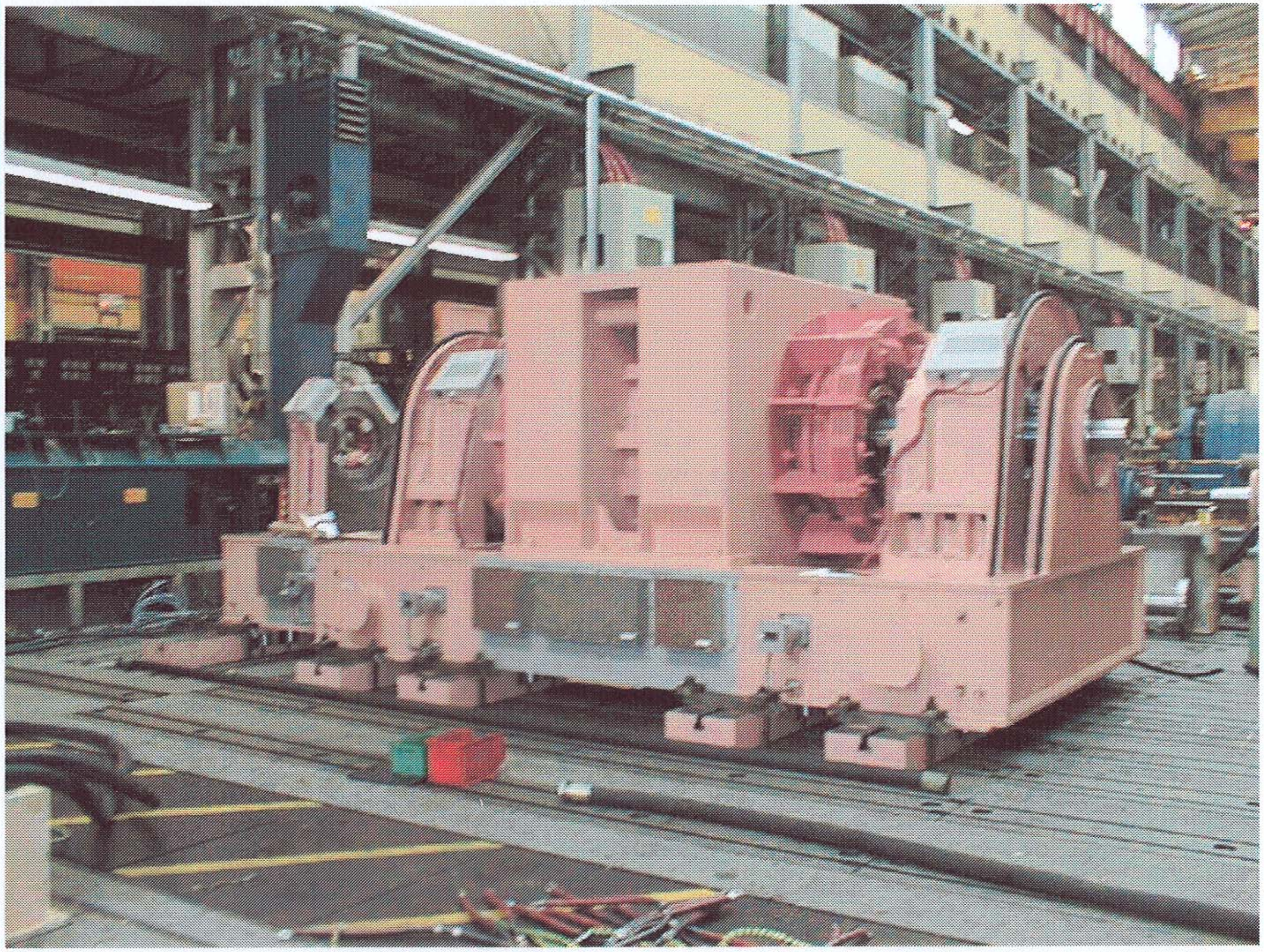
Data:

23 MW, 2x3.6 kV, 2x2.03 kA, 90 Hz

n_N = 5400/min

n_{max} = 7000/min

Motor mass: 61.5 t, Rotor mass 9.2 t



Source: Siemens AG

Radial magnetic bearing for the 23 MW motor

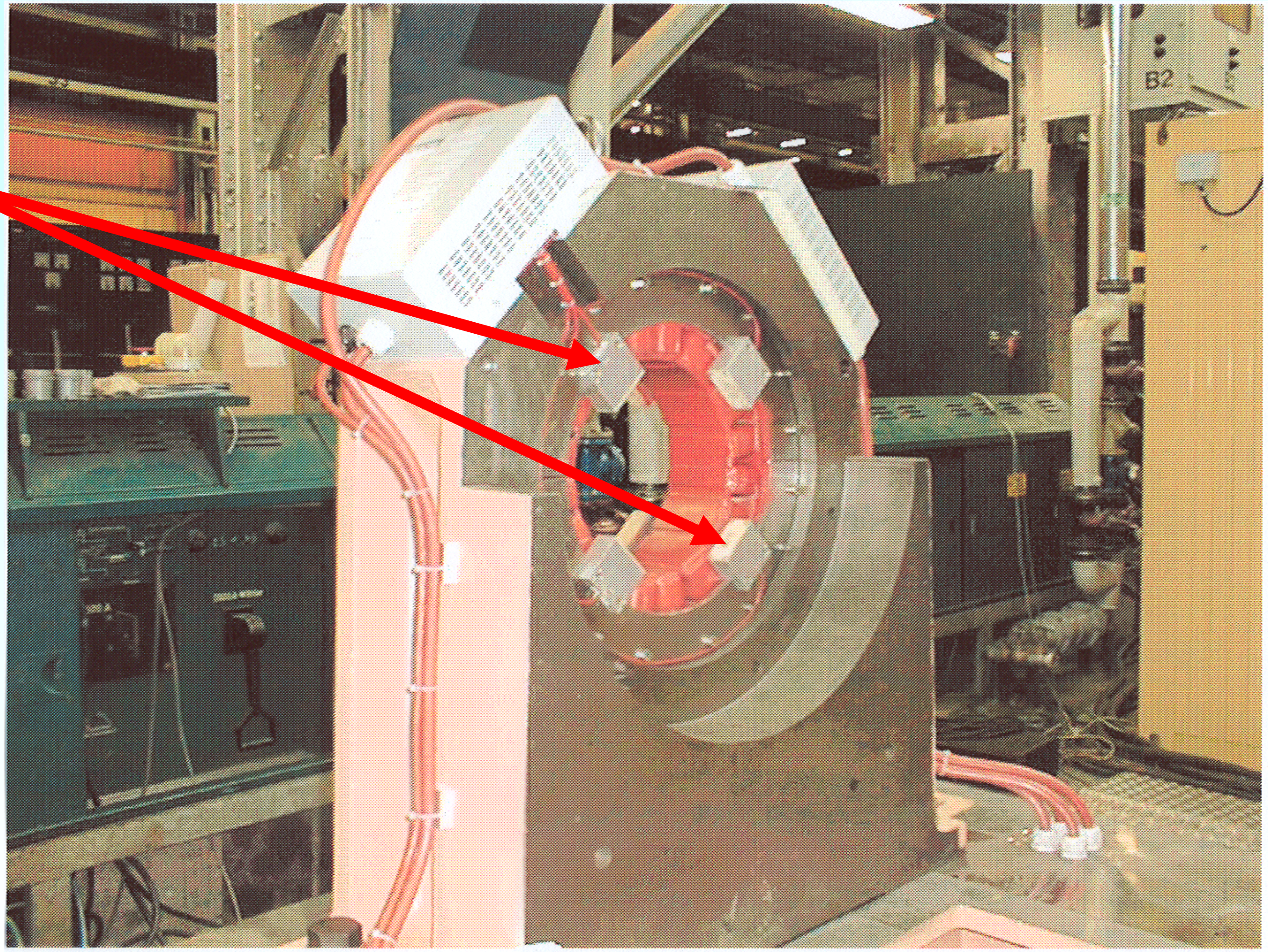
Magnetic radial bearing

Two distance sensors for each *x*- and *y*-axis, connected as differential sensors

Bearing air gap 2 mm

Redundant AMB design: 2 AMBs in one radial magnetic bearing = 4 x 4 = 16 poles

Digital bearing control



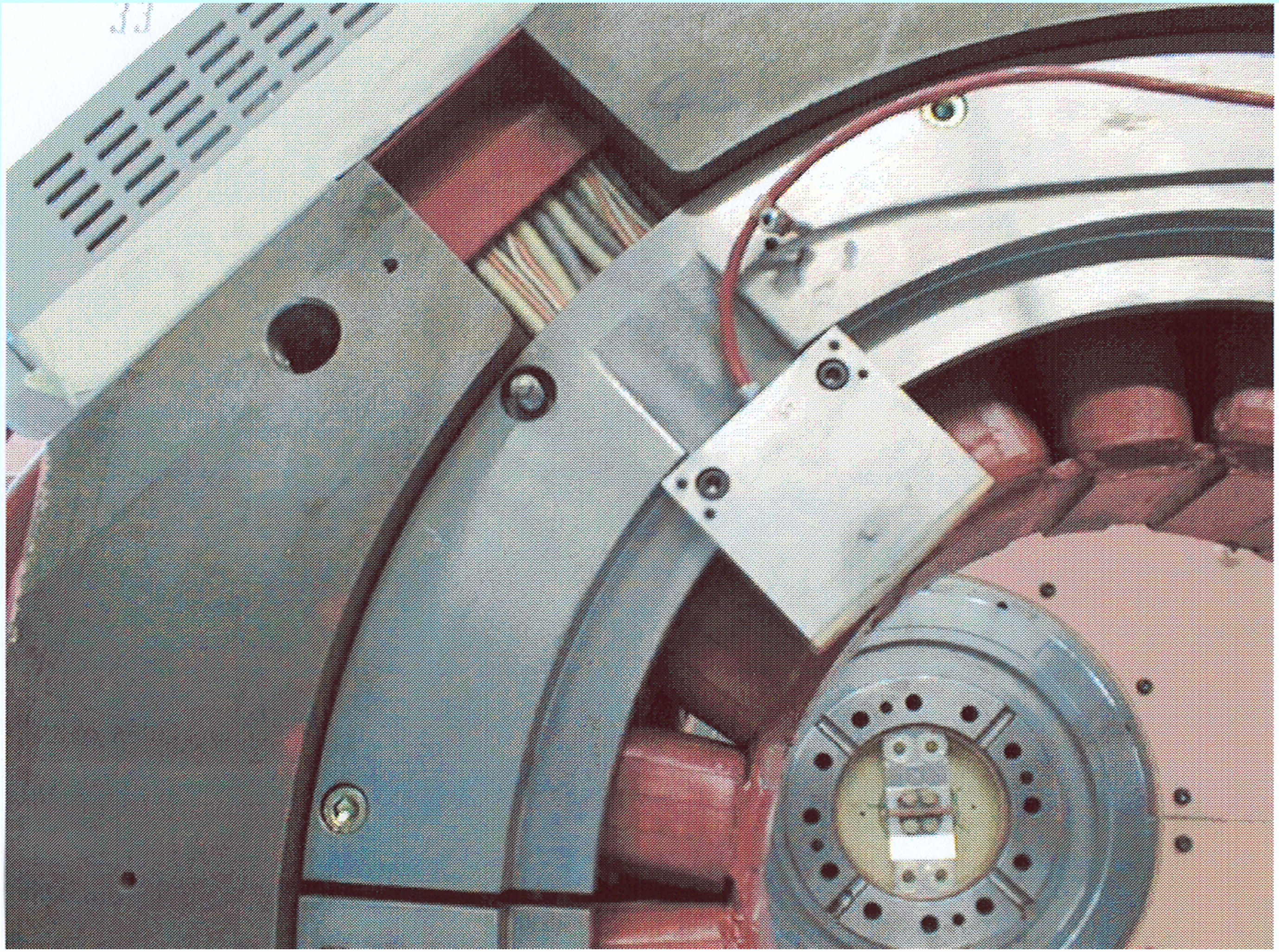
Source: Glacier Bearings, UK

Distance and radial velocity sensors

Enhanced rotor measurement system:

a) Distance and b) radial velocity sensors:
x- and *dx/dt*-measurement

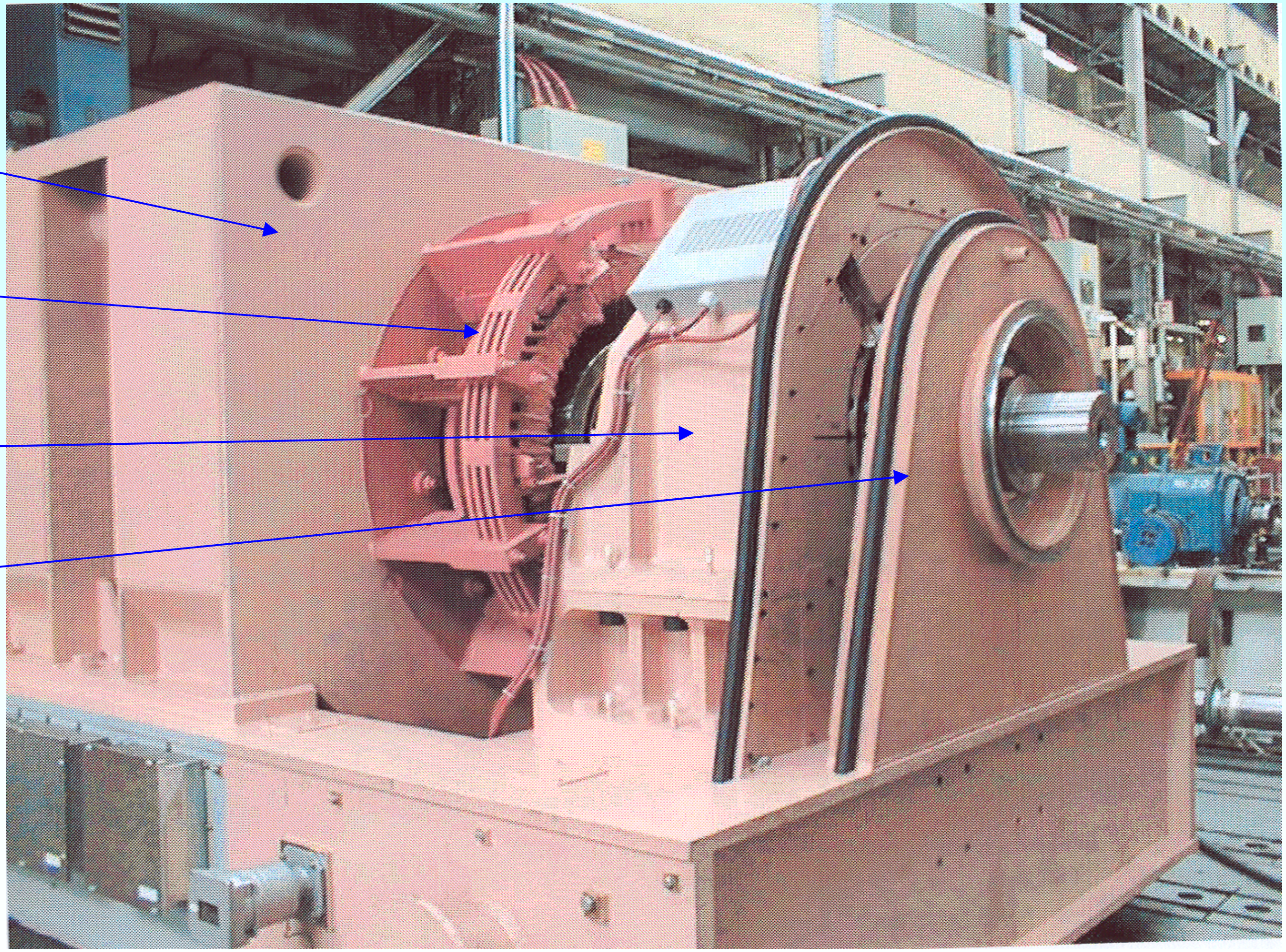
Bore diameter of magnetic radial bearing: ca. 400 mm



Source: Glacier Bearings, UK

2-pole 3-phase 23 MW synchronous motor with AMB

- 23 MW motor, air-air-cooler removed
- Stator end winding with coil connectors
- DE side radial magnetic bearing
- Auxiliary bearing



Source: Siemens AG, Germany

23 MW 2-pole synchronous motor with AMB during the test run

2-pole synchronous motor with AMB (Project *NAM, Netherlands*)

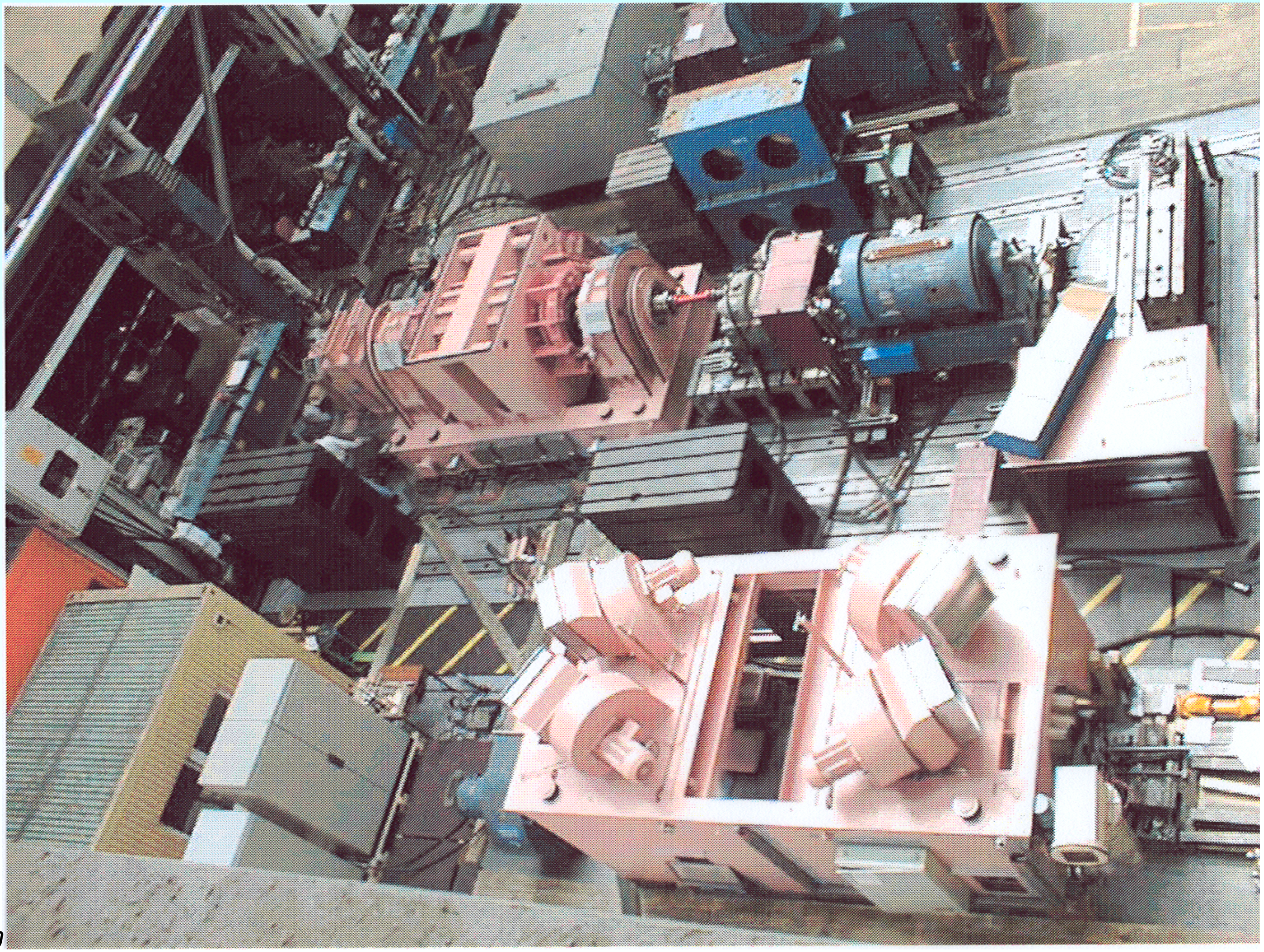
At the test bench of *Siemens AG, Dynamowerk, Berlin*

Load: Low speed water-cooled eddy current brake, coupled by a gearbox

Fans and air-air-cooler removed

Motor is designed explosion proof for E(Ex)p

Speed range:
5400 … 6300/min, which is above 1. critical bending speed (= first natural bending frequency)



Source: Siemens AG, Dynamowerk, Berlin

2-pole 23 MW synchronous motor with AMB at the gas field

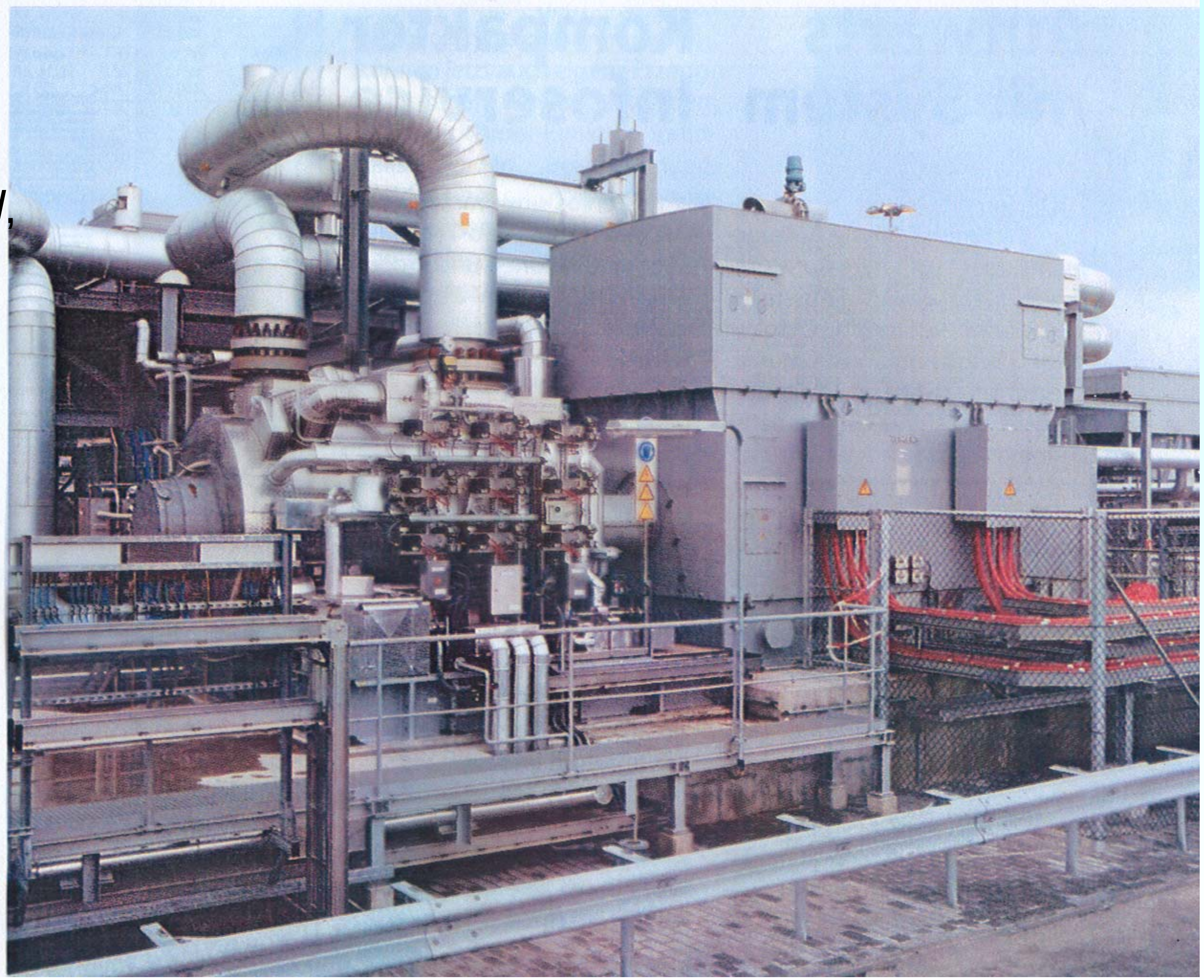
2-pole synchronous motor coupled with gas compressor, both with AMB

Natural gas field *Groningen/Holland*, Project NAM

Compressor with axial AMB, produces 60 bar gas pressure at nominal speed

Variable speed operation via two synchronous converters; Two 3-phase windings, shifted by 30° el., yielding a 6-phase system

Motor explosion proof E(Ex)p due the natural gas storage operation



Source: Siemens AG

High speed cage induction motors with AMB

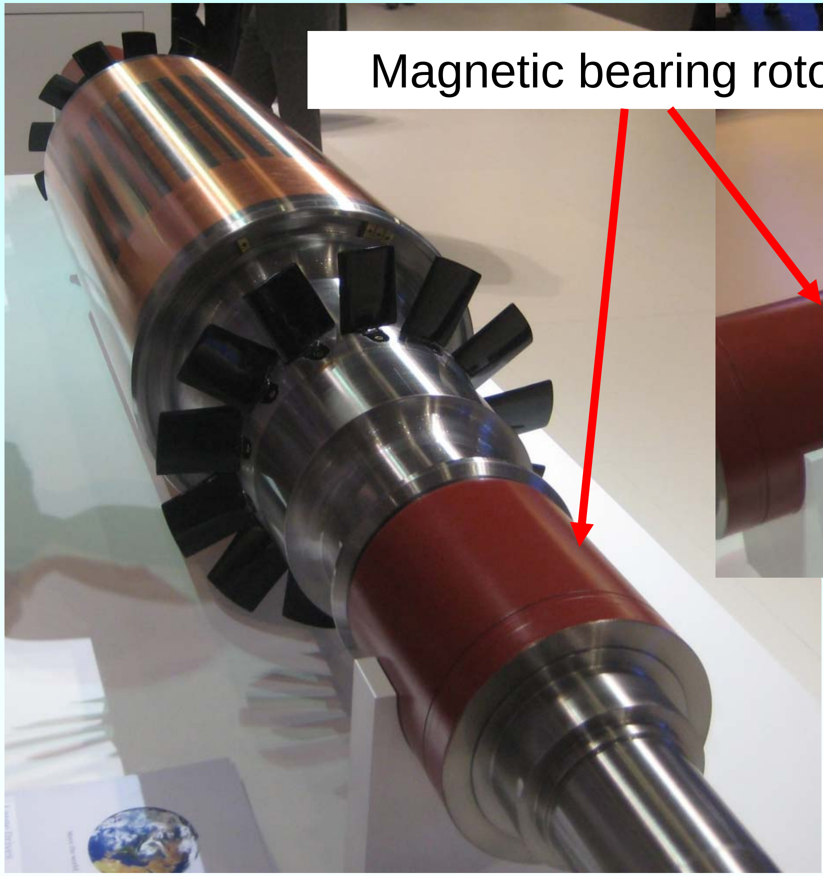
15000/min, 4 MW squirrel cage – induction motor

Source: Siemens AG

- Drive for gas pipe line compressors
- Motor series 4 MW, 15000/min, 2.5 kNm … 16 MW, 6000 /min, 25.5 kNm
- Copper cage, 2-pole motors, solid iron rotor, ca. 240 m/s circumferential speed
- Active Magnetic Bearing: Rotation above the first bending natural frequency
- Medium voltage IGBT-PWM-voltage source converter

3.2 Electromagnetic levitation

Massive rotor witch copper cage and AMB as a compressor drive

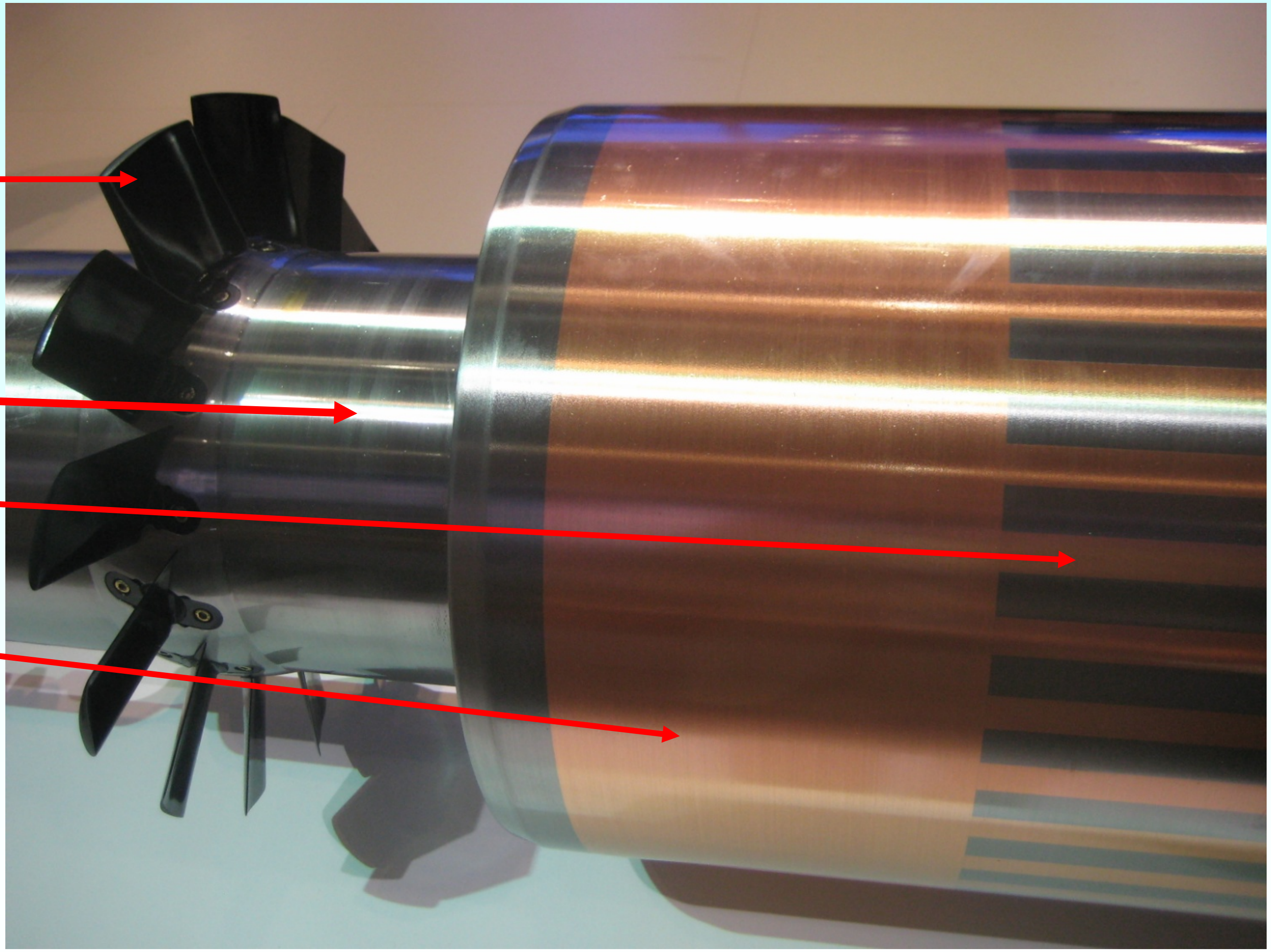


Source: *Siemens AG*

- Two pole high-speed prototype squirrel cage rotor
- Axial fan with high strength plastic blades for reduction of centrifugal forces
- Rotor from solid steel, welded copper squirrel cage (*Siemens* patent)

End region of the squirrel cage rotor for the compressor drive

- High strength plastic – axial fan blades for reduction of centrifugal forces
- Rotor from solid steel
- Welded copper squirrel cage
- Squirrel cage end ring



Source: Siemens AG

Magnetic levitation for industrial steam turbine (SIMOTICS)

AMB digital control duty cycle: 62.5 μs

AMB Stator:
Thermal Class H 180°C

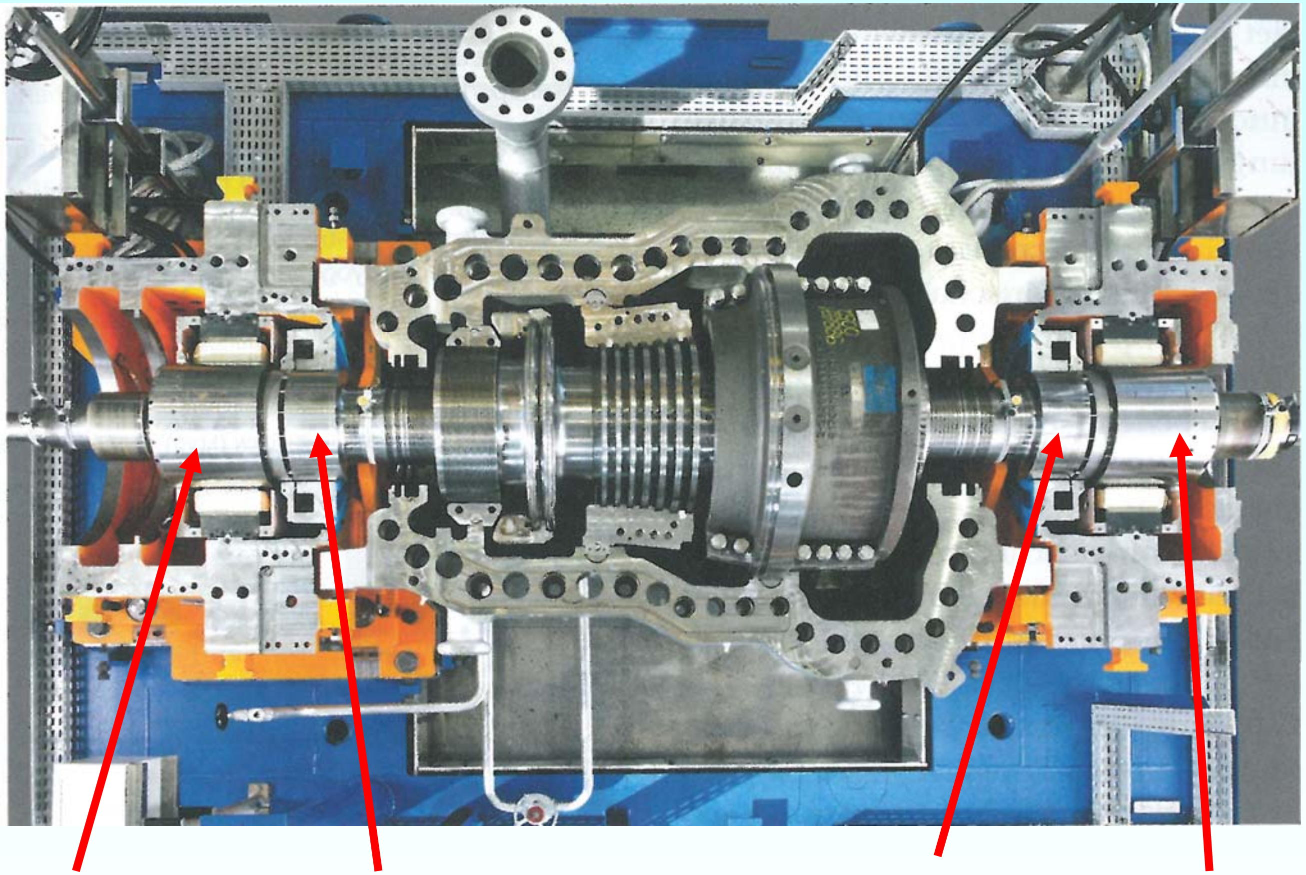
AMB Rotor 200°C
Cooling air inlet 40°C,
outlet 80°C

Steam turbine SST-600:

Used as a drive for water feeder pump in thermal power plant *Jänschwalde*, D

3600…5700/min
10 MW

535°C steam at 36 bar
Rotor mass 2.5 t



Source: Siemens AG, Germany

AMB power 10 kW, Auxiliary bearings: Twin-row ball bearings

Magnetic levitation for industrial steam turbine

Advantages:

- Instead of oil-lubricated sleeve bearings (which need a 4000 l oil tank)
- 10 kW steady state power = only 10% of sleeve-bearing losses
- Hence: Total efficiency increased by 1%
- Only 0.05% of original oil volume needed = strong reduction of danger of fire
- Reduced maintenance

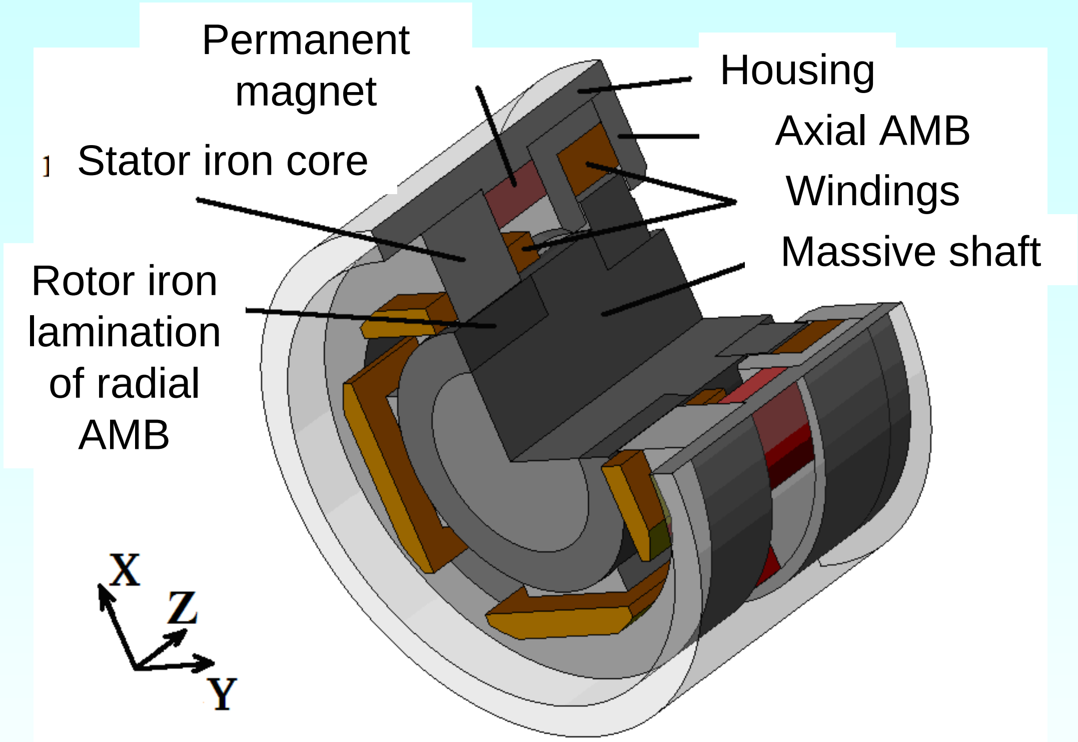
Disadvantages:

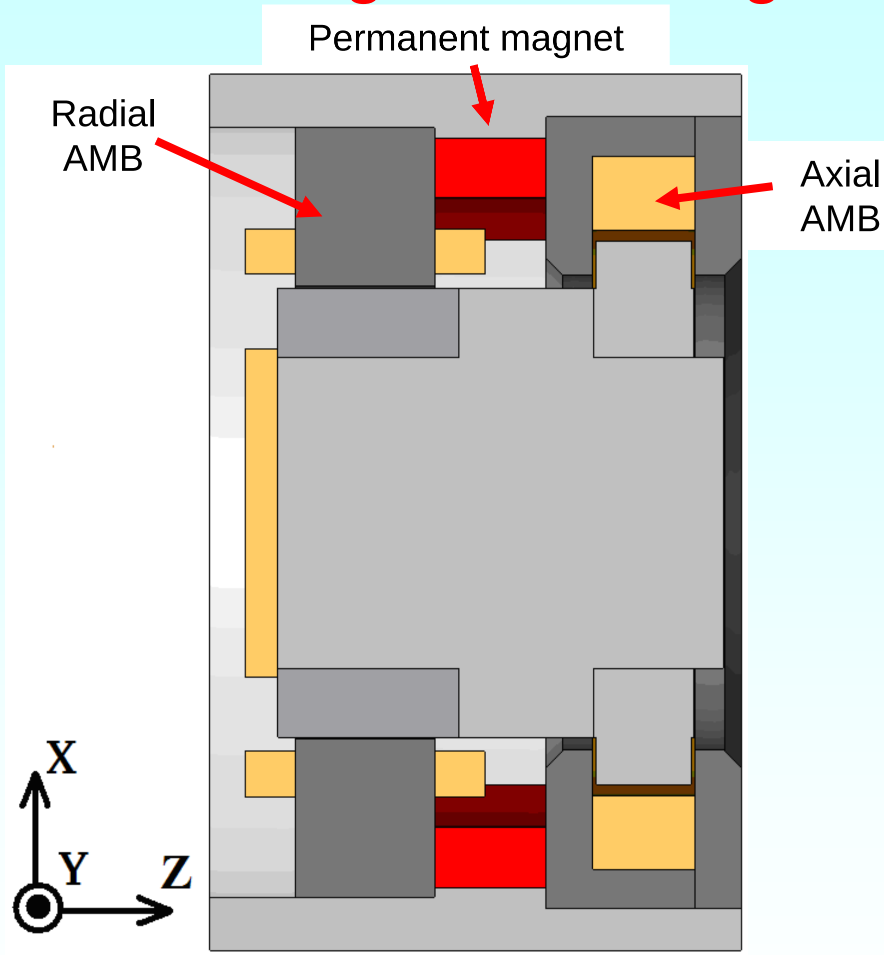
- AMB is more expensive = higher investment costs

Source:
BWK 67, 2015, no. 10, p. 42-43

Homopolar combined radial-axial active magnetic bearings

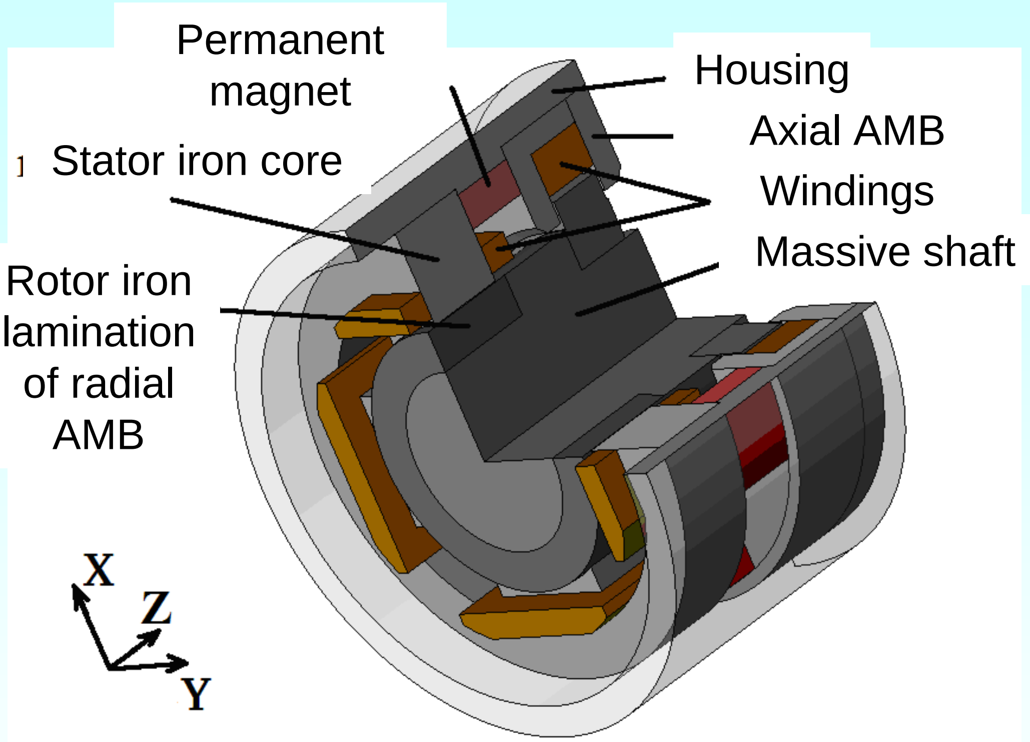
Homopolar combined radial-axial active magnetic bearings

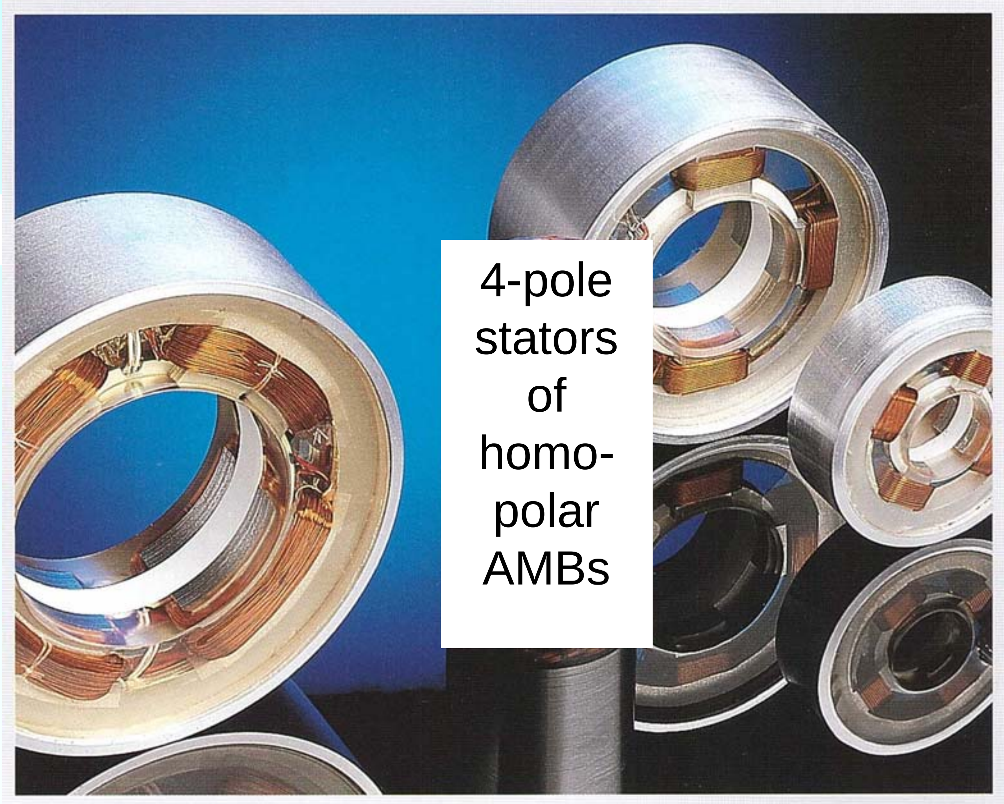




Source: Nissle, B.: Master thesis, TU Darmstadt, 2011

Homopolar combined radial-axial active magnetic bearings





Source: Nissle, B.: Master thesis, TU Darmstadt, 2011

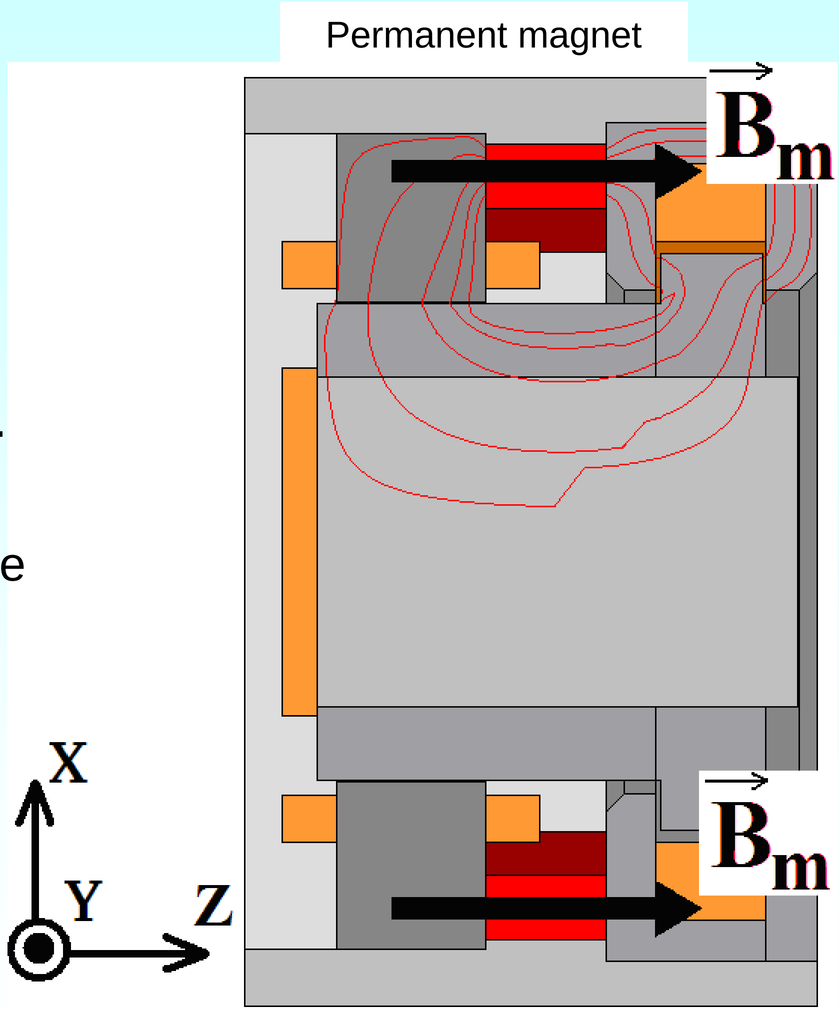
Source: Levitec, Lahnau, Germany

Homopolar base field excitation B_m by the PM ring

- Permanent magnet ring is axially magnetized
- It excites a field B_m, which is of uni-polar direction in the axial bearing (e.g. N-pole)

AND

- of uni-polar direction in the radial bearing (e.g. S-pole)
- Thus this is a "uni-polar" (or homo-polar) active magnetic bearing.



Source: Nissle, B.: Master thesis, TU Darmstadt, 2011

Radial levitation force in the homopolar AMB

- The x-axis stator coils excite a field B_r, which with B_m

a) adds at the upper pole,
b) reduces at the lower pole!

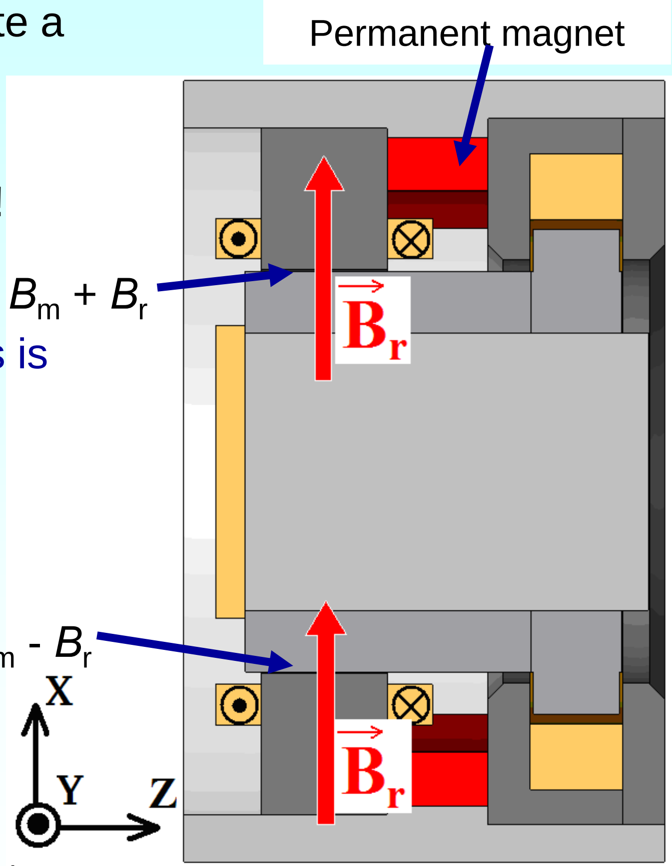
$B_{a)} = B_m + B_r$

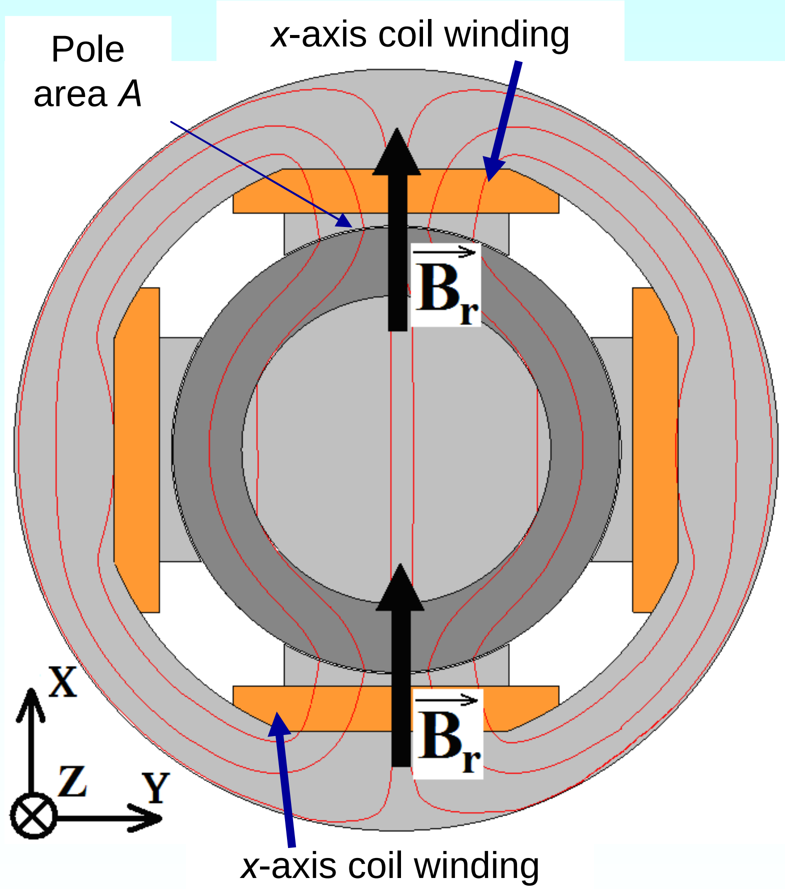
Resulting force in the *x*-axis is upward directed:

$$F_x = \left(\frac{B_{a)}^2}{2\mu_0} - \frac{B_{b)}^2}{2\mu_0} \right) \cdot A$$

$B_{b)} = B_m - B_r$

$$F_x = 2 B_m B_r \cdot A / \mu_0$$



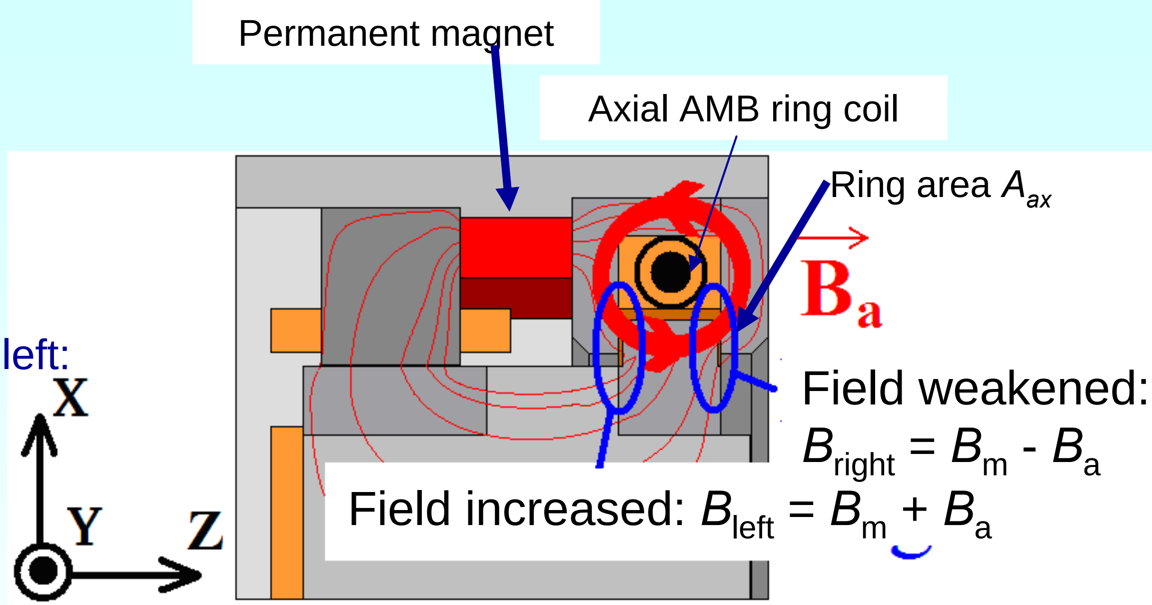


Source: Nissle, B.: Master thesis, TU Darmstadt, 2011

Axial magnetic force in the homopolar AMB

- The ring coil of the axial AMB excites a field B_a, which with B_m

a) adds at the left side,
b) substracts at the right side!



Resulting force is directed to the left:

$$F_{ax} = \left(\frac{B_{left}^2}{2\mu_0} - \frac{B_{right}^2}{2\mu_0} \right) \cdot A_{ax}$$

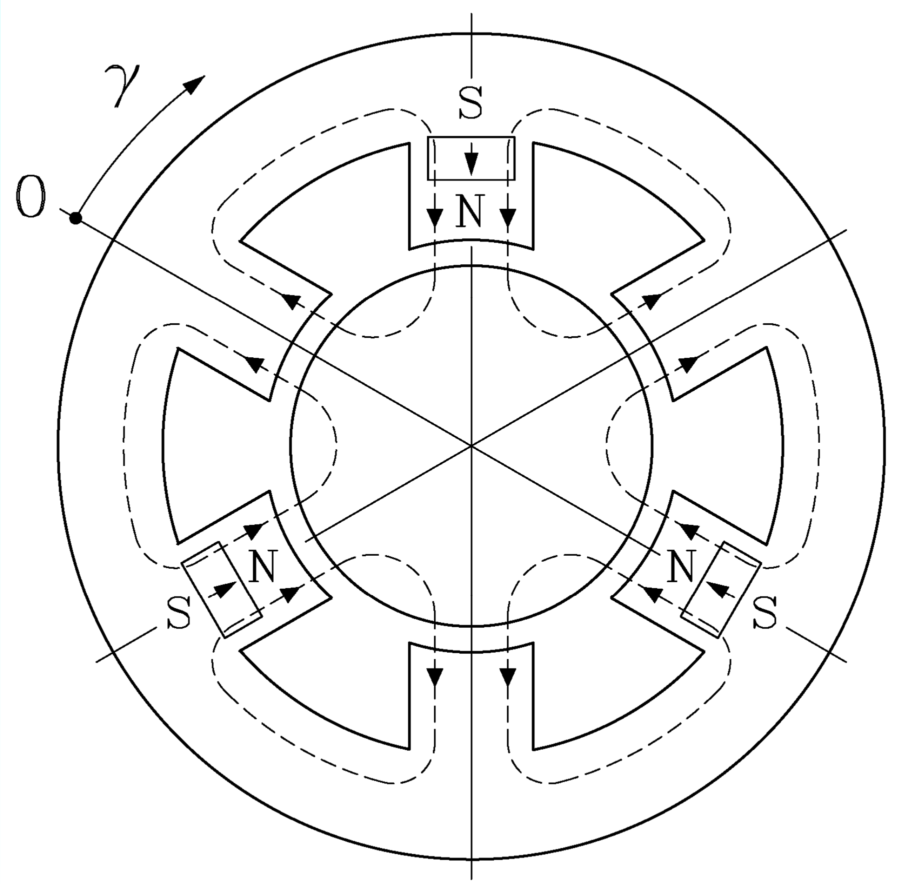
$$F_{ax} = 2 B_m B_a \cdot A_{ax} / \mu_0$$

- Reversing of force needs reversed coils currents for the radial and the axial AMB = bipolar current feeding! $F_{ax} \sim B_m B_a \rightarrow -F_{ax} \sim B_m \cdot (-B_a)$

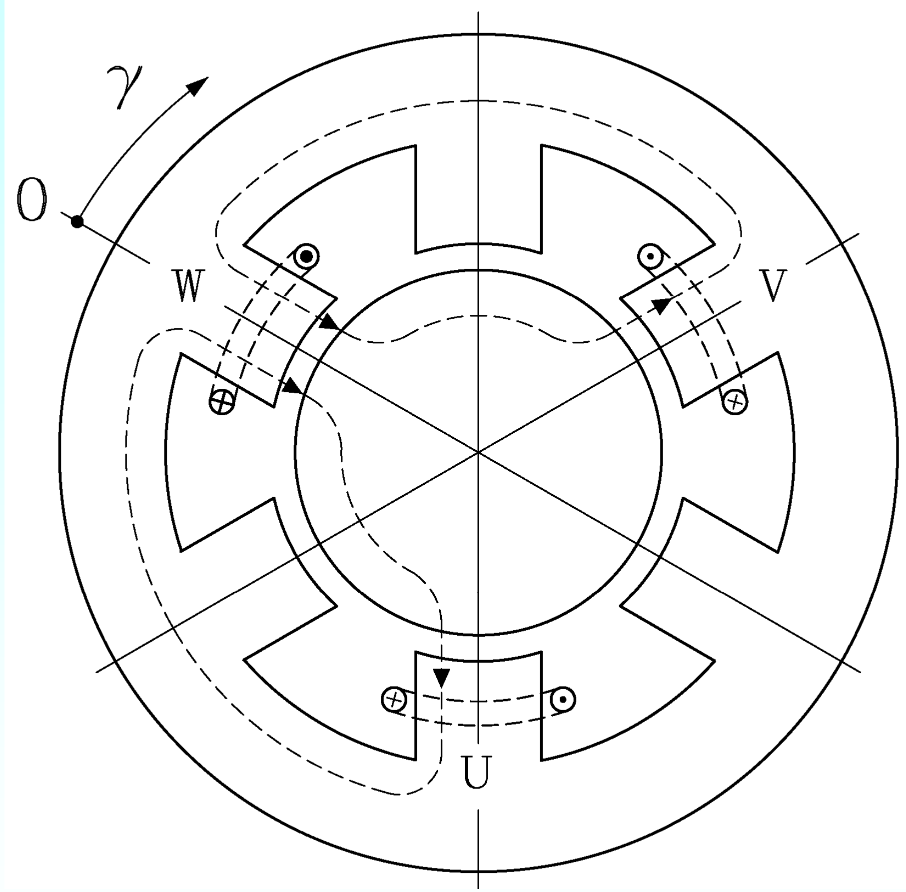
Source: Nissle, B.: Master thesis, TU Darmstadt, 2011

Three-phase radial active magnetic bearings

PM bias excitation and control excitation via three-phase inverter (operating at zero frequency = DC current)



PM bias excitation

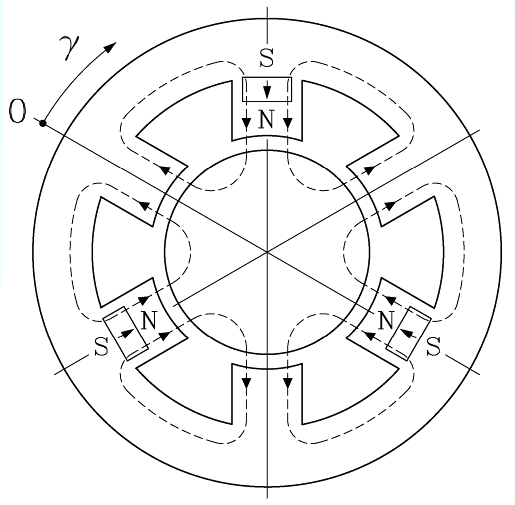


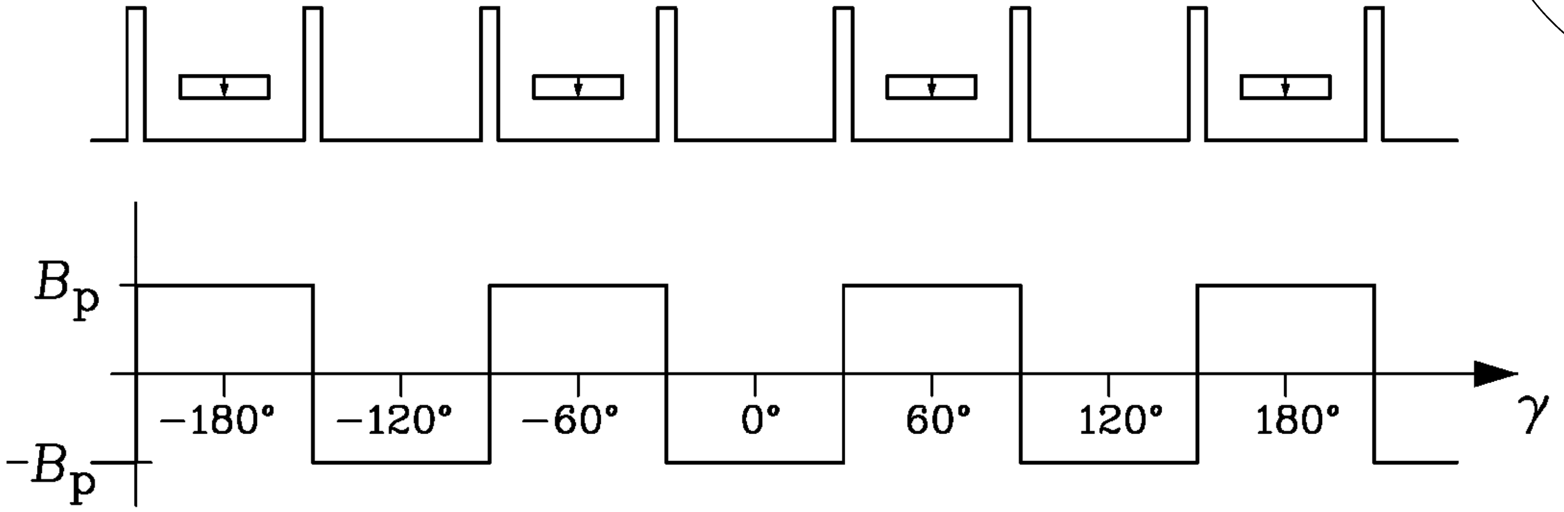
Control excitation

Example: $I_W = -I_U/2 = -I_V/2$, $I_U + I_V + I_W = 0$

Radial air-gap flux density distribution of PM bias excitation

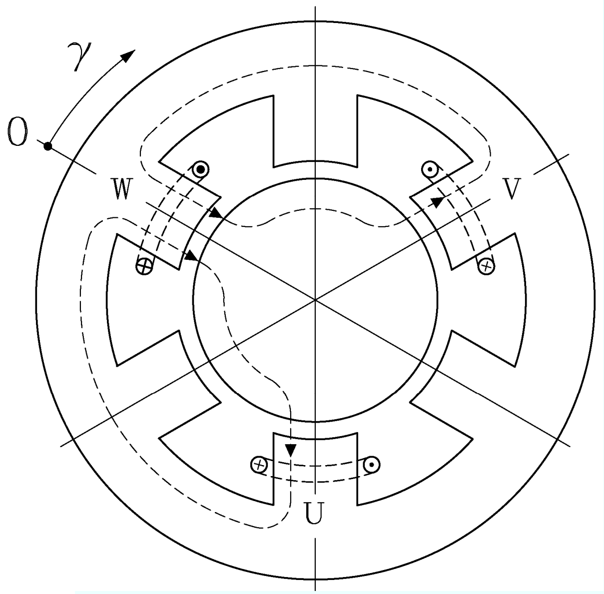
- PM flux density amplitude B_p
- Bias PM field as a 6-pole field

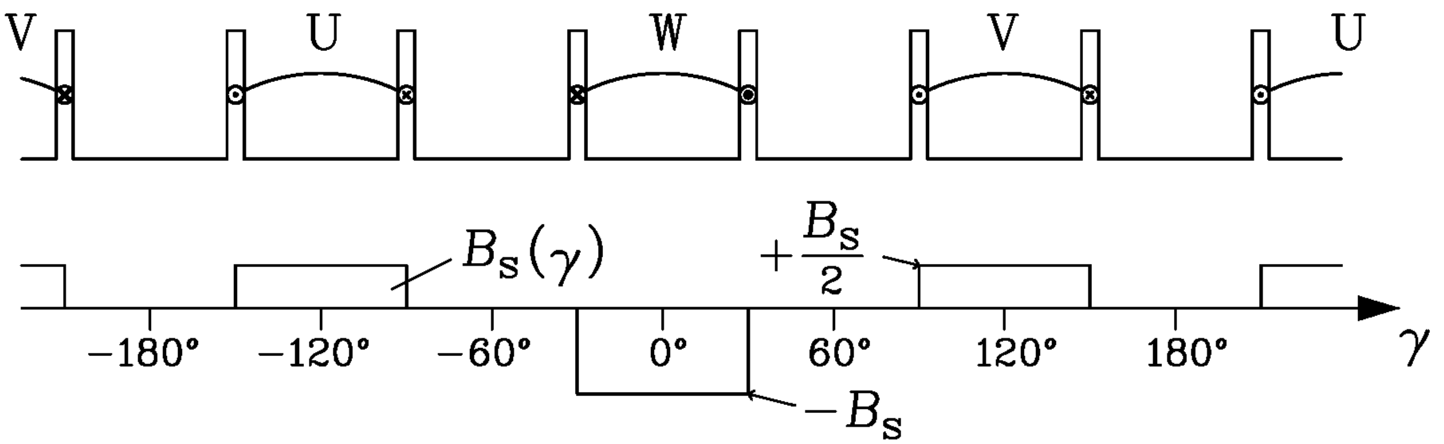




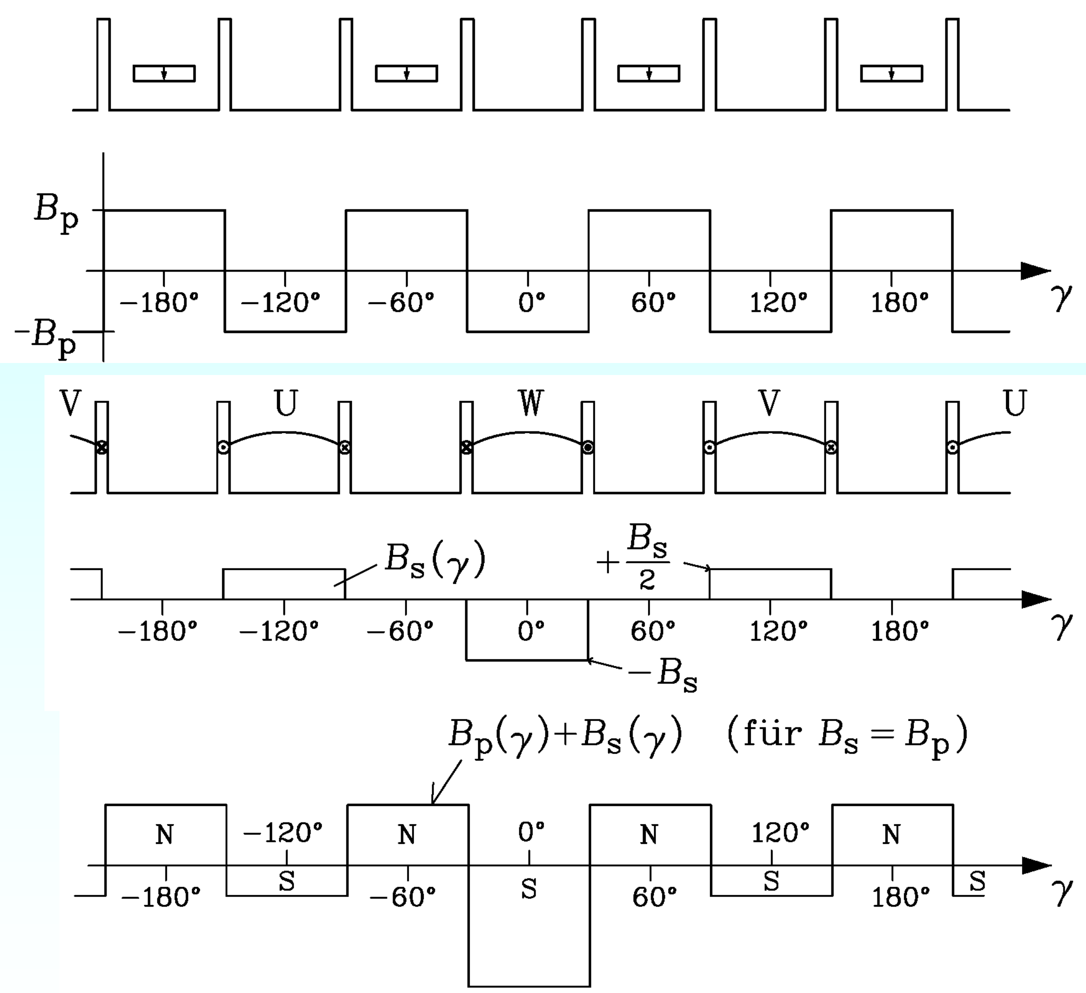
Radial air-gap flux density distribution of control excitation

- PM flux density amplitude B_s
- Two-pole field of control excitation
- Example: $I_W = -I_U/2 = -I_V/2$, $I_U + I_V + I_W = 0$





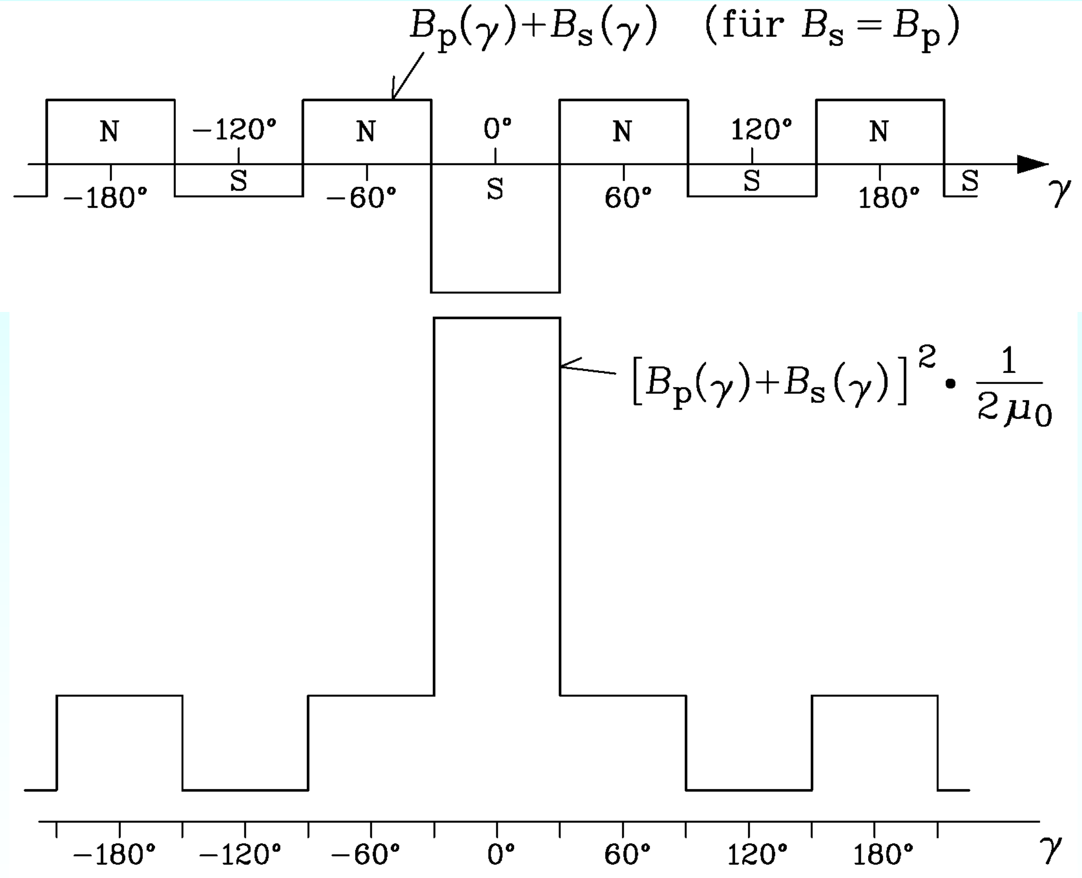
Superposition of bias and control field in the air-gap



- Operation of $B_p + B_s$ below 1.7 T
- Hence iron unsaturated
- Hence linear superposition of $B_p(\gamma) + B_s(\gamma)$
- Linear control operation possible via B_s
- Maximum field $B_p + B_s$ in the W-axis (where maximum coil current flows!)
- *Example:*
  $I_W = -I_U/2 = -I_V/2$, $I_U + I_V + I_W = 0$

  $B_p = B_s$

Resulting bias and control air-gap field and corresponding radial force density (for $\mu_{Fe} \to \infty$)



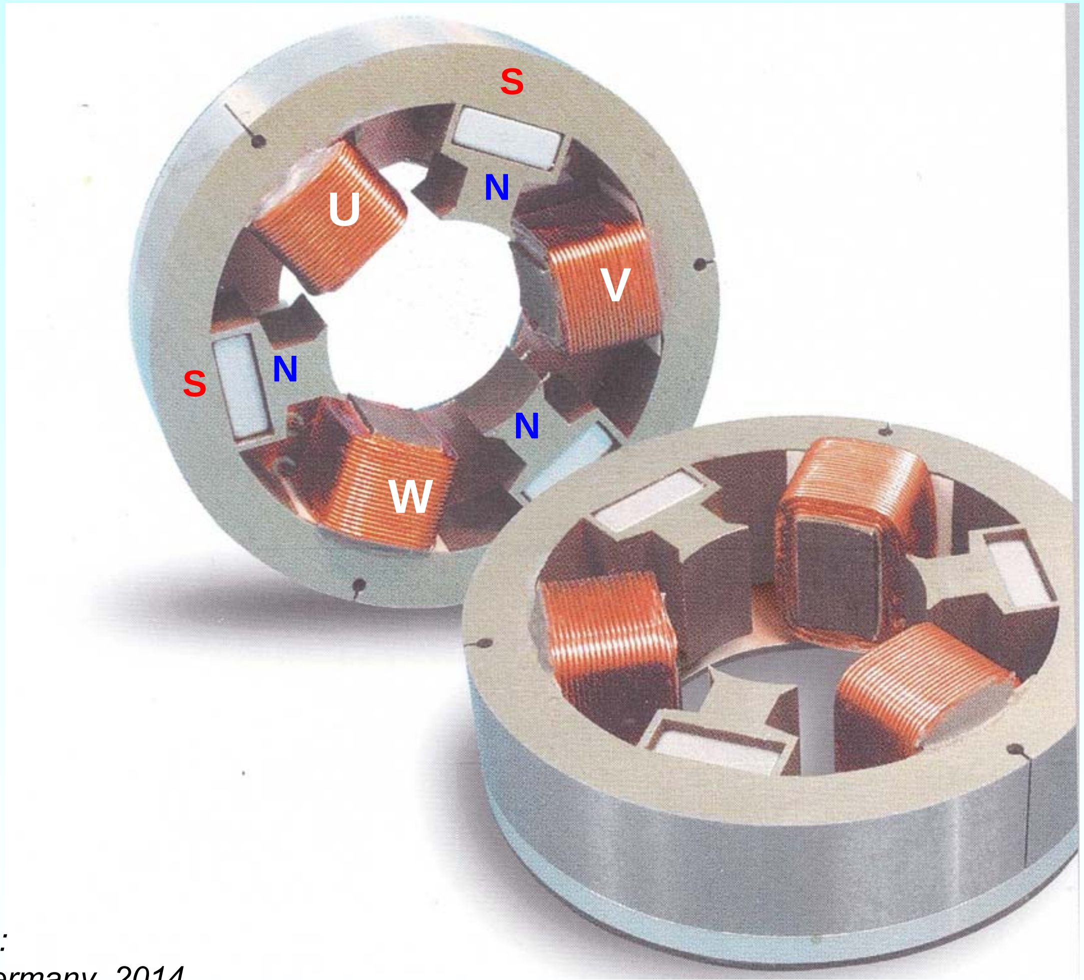
- Maximum radial force in the W-axis (where maximum coil current flows!)

- Hence: Via vector control of i_U, i_V, i_W via PWM of the three phase voltages the angular position of the radial force vector may be shifted within $-180° \leq \gamma \leq 180°$ continuously

- In the same way the radial force vector amplitude is adjusted continuously up to the limit value.

- *Example:*
  $I_W = -I_U/2 = -I_V/2$, $I_U + I_V + I_W = 0$
  $B_p = B_s$

Three-phase radial active magnetic bearings



Source:
Levitec, Lahnau, Germany, 2014

New technologies of electric energy converters and actuators

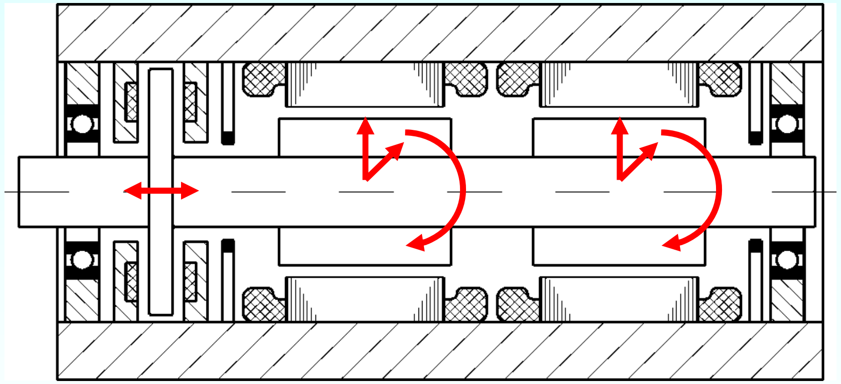
Summary:
Examples of magnetic bearings

- Wide range of power ratings for AMB from kW to MW-range
- Radial and axial magnetic bearings in commercial use
- Mainly for high speed, but also low speed applications
- Number of applications increase steadily
- Special combined axial-radial bearings with shorter total length available
- Special three-phase radial magnetic bearings with PM bias excitation allow the use of PWM three-phase inverter bridges
- Superposition of PM and electrical excitation to reduce losses

New technologies of electric energy converters and actuators

3.2 Electromagnetic levitation

Operation principles of bearingless motors



Advantages of bearingless motors

Principle: Integration the AMB into the active length of the motor

- No DC-excitation for the AMB, so a conventional 3-phase inverter sufficient is for one radial bearing
- No DC-controller for the AMB, so a conventional field-oriented drive controller is sufficient for radial force bearing control (*d*-*q*-current-control)
- No special rotor laminations for the AMB: The motor itself IS the radial bearing = no additional bearing = BEARINGLESS

- For disc-like motor shape: Motor takes also the role of axial bearing

- Reduction of motor length is possible in comparison to AMB levitation

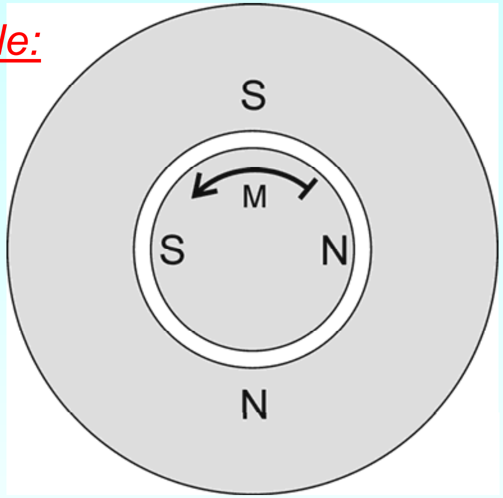
Also bearingless motors require: - Position measurement, - Auxiliary bearings

Lateral force generation in the motor air gap = Bearing force

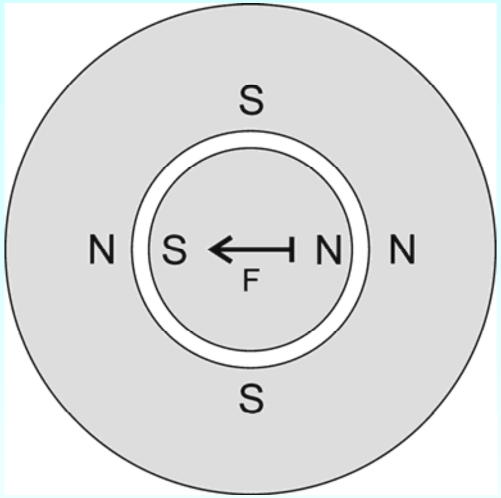
Generation of the torque M

Example:

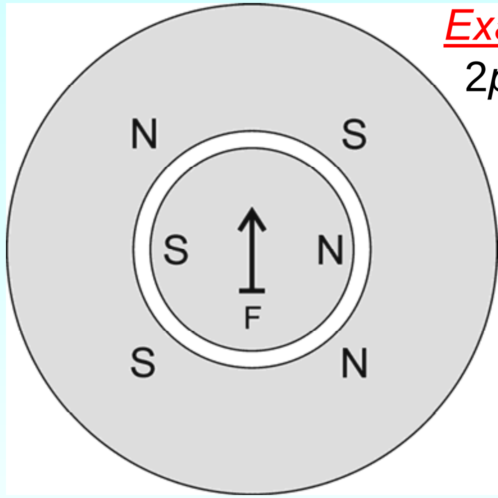
$2p_1 = 2$



Generation of a lateral force F in x-direction



Generation of a lateral force F in y-direction



Example:

$2p_1 = 2$

$2p_2 = 4$

Combination of a rotor field with p_1 pole pairs with a stator field of p_1 pole pairs generates the torque M

Combination of a rotor field with p_1 pole pairs with a stator field with $p_2 = p_1 \pm 1$ generates a lateral force F

(Sequenz, H.:, Die Wicklungen el. Maschinen, Bd. 3, Springer, 1954)

Calculation of the lateral force

- Superposition of two air-gap field waves p_1 and $p_2 = p_1 \pm 1$:

Drive field: e. g..: $2p_1 = 2$

$$B_1(\alpha,t) = \hat{B}_1 \cos(p_1\alpha - \omega_1 t - \varphi_1)$$

e. g. excited by rotor permanent magnets

Levitation field: e. g.: $2p_2 = 4$

$$B_2(\alpha,t) = \hat{B}_2 \sin(p_2\alpha - \omega_2 t - \varphi_2)$$

Excited by stator current loading:

$$A_2(\alpha,t) = \hat{A}_2 \cos(p_2\alpha - \omega_2 t - \varphi_2)$$

φ_1, φ_2: position angles of rotor field amplitude B_1 and stator current loading amplitude A_2 on the periphery (circumference angle α in mech. degrees)

Lateral force/area in the air gap: $f = F/A_\delta$ (r: radial, t: tangential, z: axial)

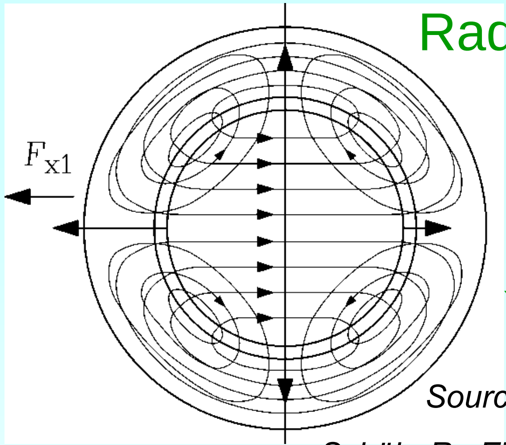
$$\vec{f} = \begin{pmatrix} f_\mathrm{r} \\ f_\mathrm{t} \\ f_\mathrm{z} \end{pmatrix} = \frac{1}{2\mu_0} \begin{pmatrix} B_{\delta,\mathrm{r}}^2 - B_{\delta,\mathrm{t}}^2 \\ 2\mu_0 B_{\delta,\mathrm{r}} A_2 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} f_r \\ f_t \end{pmatrix} \Rightarrow \begin{pmatrix} F_x \\ F_y \end{pmatrix}$$

F_x: Horizontal force

F_y: Vertical force

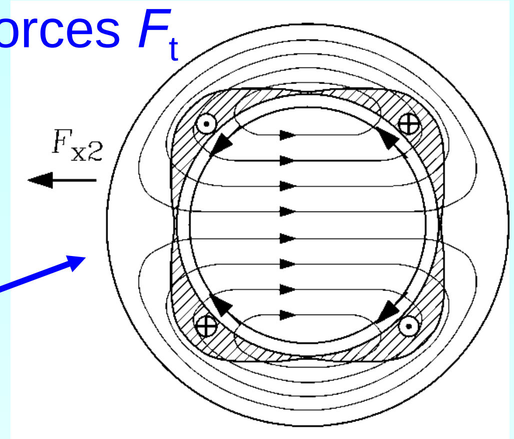
as levitation forces

Control of levitation force via *d-q*-current control



Radial forces F_r

Tangential forces F_t



Resulting total force F_x

$F_x = F_{x1} + F_{x2}$

Source: Schöb, R.; ETH Zürich

$\underline{Example}:$

$2p_2 = 4, 2p_1 = 2$

$$\vec{F} = \begin{pmatrix} F_x \\ F_y \end{pmatrix} = \frac{A_\delta}{2} \cdot \left[\overbrace{\frac{\hat{B}_1 \hat{B}_2}{2\mu_0}} \pm \overbrace{\frac{\hat{B}_1}{\sqrt{2}} A_2} \right] \cdot \begin{pmatrix} \sin(\varphi_1 - \varphi_2) \\ \pm\cos(\varphi_1 - \varphi_2) \end{pmatrix}$$

$+ : p_2 = p_1 + 1$

$- : p_2 = p_1 - 1$

- As $B_2 \sim A_2 \sim I_2$: Linear relationship between force F and levitation current I_2
- Direction of force F depends on relative position of B_1 und A_2, given by $\varphi_1 - \varphi_2$
- Frequencies in motor and levitation winding must be equal: $\omega_1 = \omega_2$. The lateral forces are independent of frequency!

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = k_i \cdot I_2 \cdot \begin{pmatrix} \sin(\varphi_1 - \varphi_2) \\ \pm\cos(\varphi_1 - \varphi_2) \end{pmatrix} = k_i \cdot \begin{pmatrix} -I_{2,d} \\ \pm I_{2,q} \end{pmatrix}$$

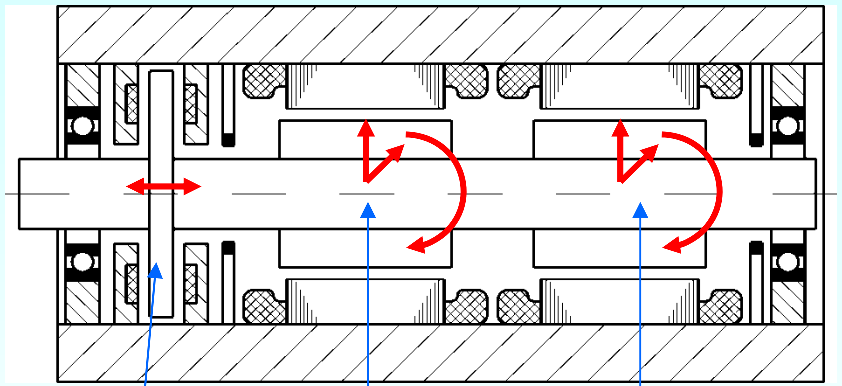
***d*-current - component**

***q*-current - component**

Bearingless motor concepts

2 Half motors + Axial bearing

Bigger power/High-Speed: ***cylindrical rotor***

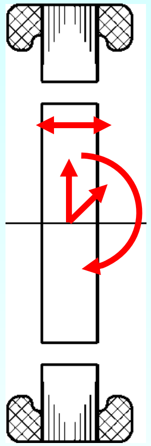


Axial bearing **Radial bearing 1** **Radial bearing 2**

= Half motor 1 **= Half motor 2**

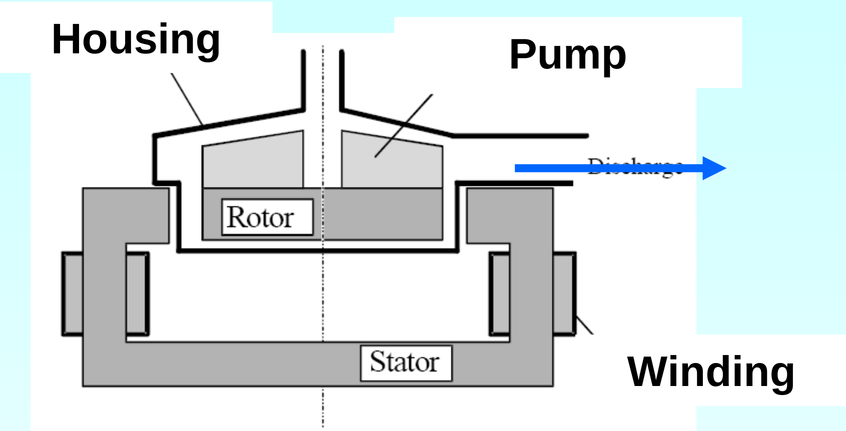
1 short bearingless motor ("disc" type)

Small power/Low-Speed: ***Pancake rotor***



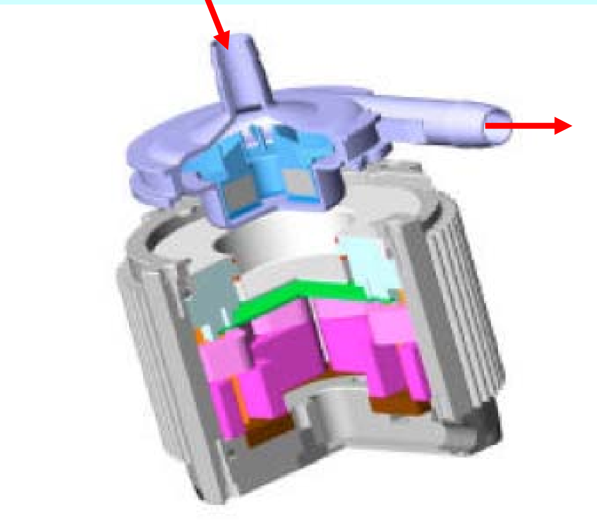
- **Axial bearing via magnetic pull of PM-rotor with big air gap:**
- **Stabilization of tilting rotor via magnet pull ⇒ only <u>one</u> controlled bearingless motor is necessary, if the motor is axially short!**

"Disc" type bearingless PM motor „Temple type"



Source: Levitronix, Schweiz

Bearingless blood pump



Source: Levitronix, Schweiz

Advantages:

Hermetically encapsulated pump

- no pollution of the medium
- no rotating seals
- no leakage
- simply exchangeable impeller rotor
- no wear, high life time

In addition:

Additional information can be acquired via the feeding electronics about the machine operation data:

- Measurement of flow rate, pressure, etc. without additional sensors

3.2 Electromagnetic levitation

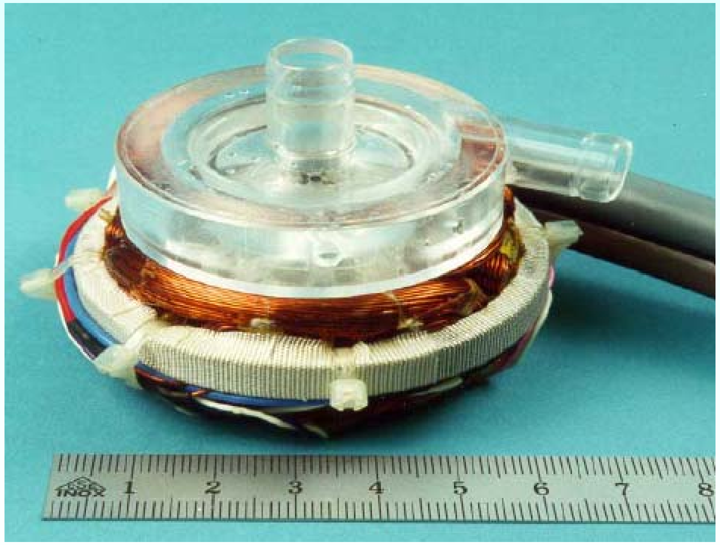
“Disc” type bearingless PM motor 2nd generation = recued size

- Bearingless drive for the semiconductor technology (clean room)
- Bearingless mixer in biology und medicine technology
- Bearingless pumps for sensitive mediums

  e. g.: bearingless blood pumps as
  - extracorporeal blood pumps,
  - implantable blood pumps.

Typical power & speed range :

100 W … 4 kW
1000 … 4 000 /min



Extra-corporeal blood pump drive with bearingless disc PM motor 20 W

Source: ETH Zürich Sulzer AG Switzerland

Extra-corporeal blood pump drive with bearingless disc PM motor 4 800 /min, 8.1 W, “HeartMate III”

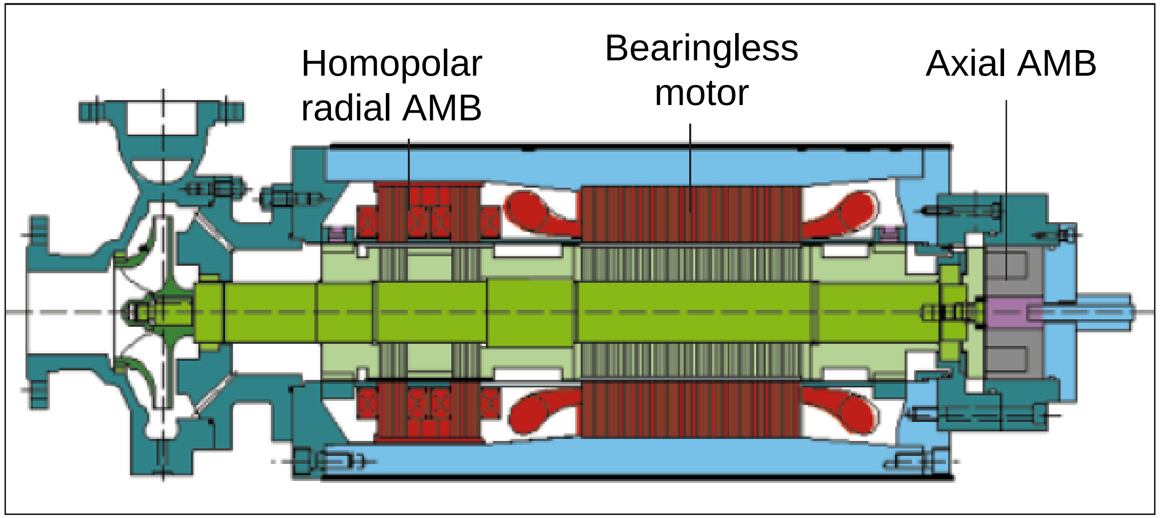
Source: HeartMate III, Levitronix, Switzerland Thoratec Corp., USA

Bearingless combi motor: Bearingless motor + magnetic bearing

- For bigger powers rating in the kW-range:

Example: Prototype for „Canned rotor pump": P_N = 30 kW, n_N = 3 000 /min
(= hermetically encapsulated pump rotor for dangerous or sensitive medium)

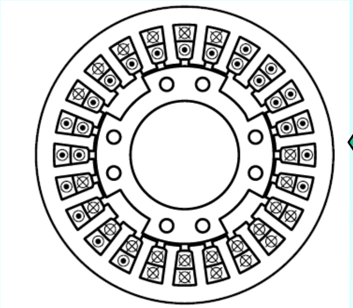
Conventional bearing system of canned rotor pumps:
Sealed stator, wet rotor with wet sleeve bearings, featuring bearing wear, endangered by dry run



Source: ETH Zürich, Fa. Sulzer, Switzerland

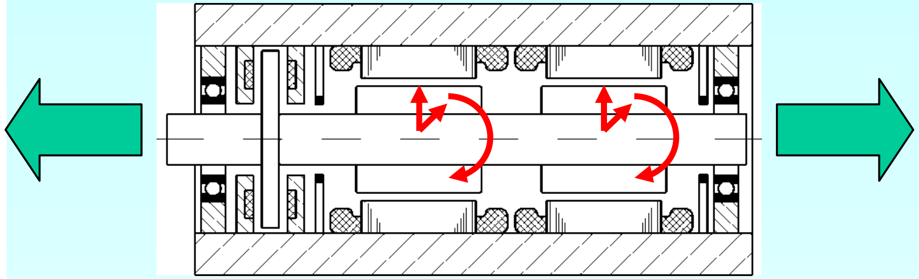
Advantages of bearingless Combi Motor:
- no mechanical bearings (except aux. bearings)
- high operation life time
- Pumping also possible for medias, which are not producing a necessary lubrication film in the sleeve bearings

Bearingless motors: Research - development



Four pole reluctance rotor

Source: TU Chemnitz/TU Dresden



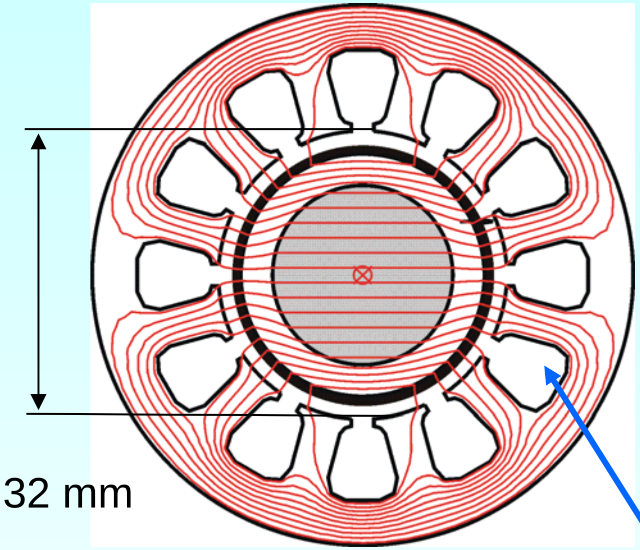
Bearingless induction machine

Source: ETH Zürich

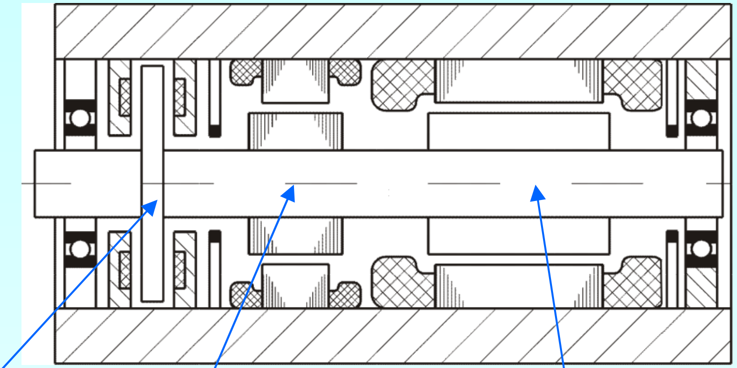
- All main types of poly-phase AC motors were built as prototypes !
  - Induction rotor (wound for the purpose of rotor loss reduction)
  - Special squirrel cage rotors
  - PM Synchronous rotor
  - Synchronous Reluctance Motor / Switched-Reluctance Motor

- Mainly universities research since ca. 1990:
  - *ETH Zürich/Switzerland, Tokyo/Japan, Linz/Austria, TU Darmstadt, TU Dresden*

Prototype: Bearingless combi motor for 60 000 /min



Magnetic field lines no load
(Program FEMAG)



Axial und Radial magnetic bearing

bearingless PM motor

P_N = 600 W n_N = 60 000 /min

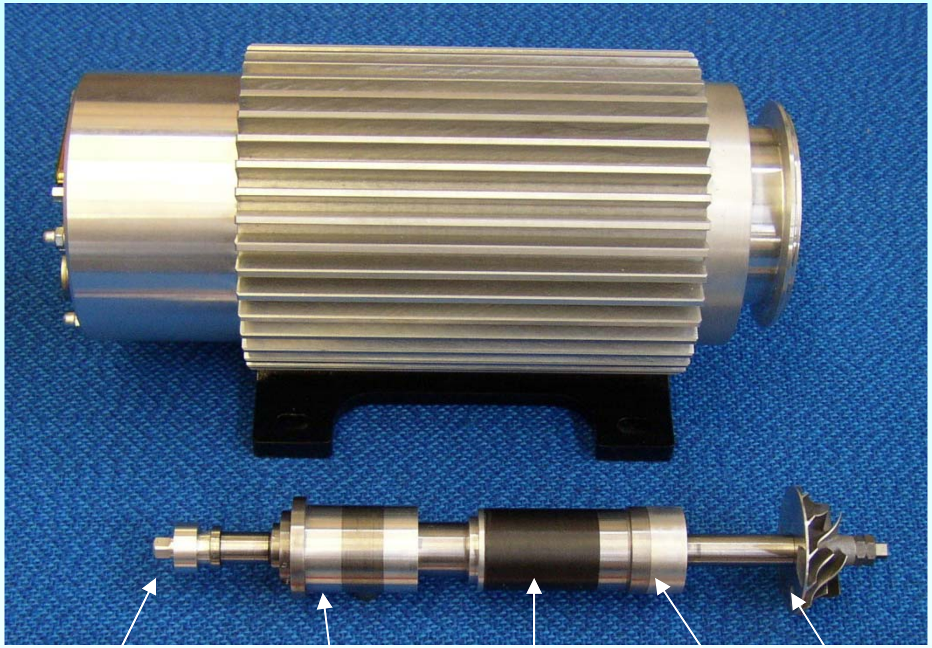
d_{si} = 32 mm B_δ = 0,352 T

Source:
TU Darmstadt

Stator is ***wound*** with ***two*** poly-phase windings systems:

- Two pole drive winding $p_1 = 1$
- Four pole levitation winding $p_2 = 2$

Bearingless combi motor prototype 600 W / 60 000 /min



Axial sensor measuring track
Magnetic axial & radial bearing
PM-Rotor
Measuring track
Compressor runner

Bearingless motor

Control of combi motor by ML51008 (*LEViTEC*)

Source:

TU Darmstadt & Levitec, Lahnau

Completed Tests:

- Rotation up to 60 000 /min
- For 60 000 /min: Controller-optimization of *d*-*q*-current-controller for the levitation winding
- Losses measurement
- Presented at *Hannover Fair Industry 2007*

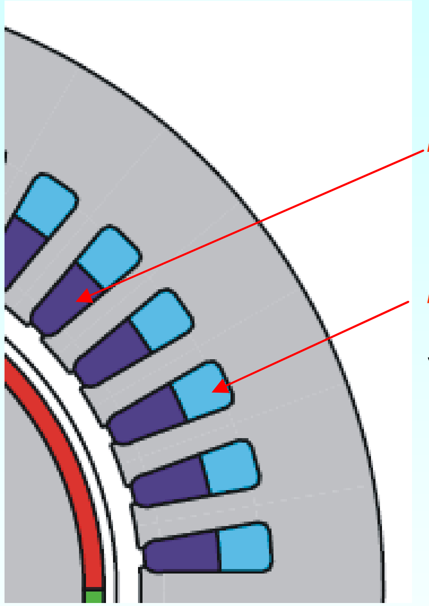
- Stator: Surface natural air flow cooling
- Rotor: PM-rotor: NdFeB-Magnets as sleeves
- Carbon fiber bandage

Calculation of bearingless PM motor 40 kW / 40 000 /min

- Numerical field calculation for levitation force

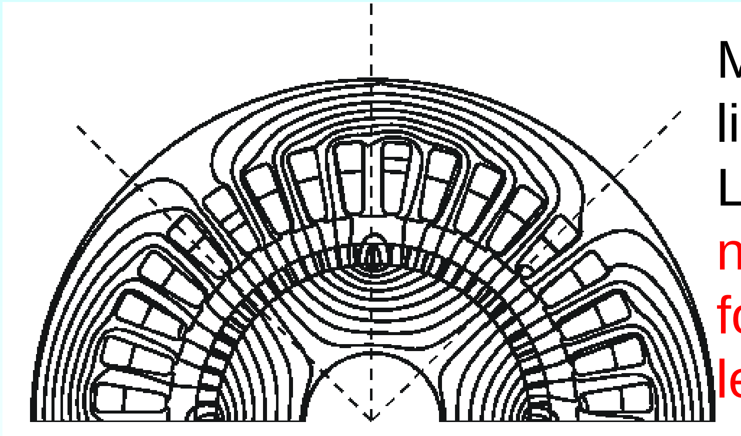
Source: TU Darmstadt

Example: 20 kW half motor: Active iron length: l_{Fe} = 60 mm, mech. air gap: 1 mm



Drive winding:
Four poles (p_1 = 2)

Levitation winding:
Six poles (p_2 = 3)

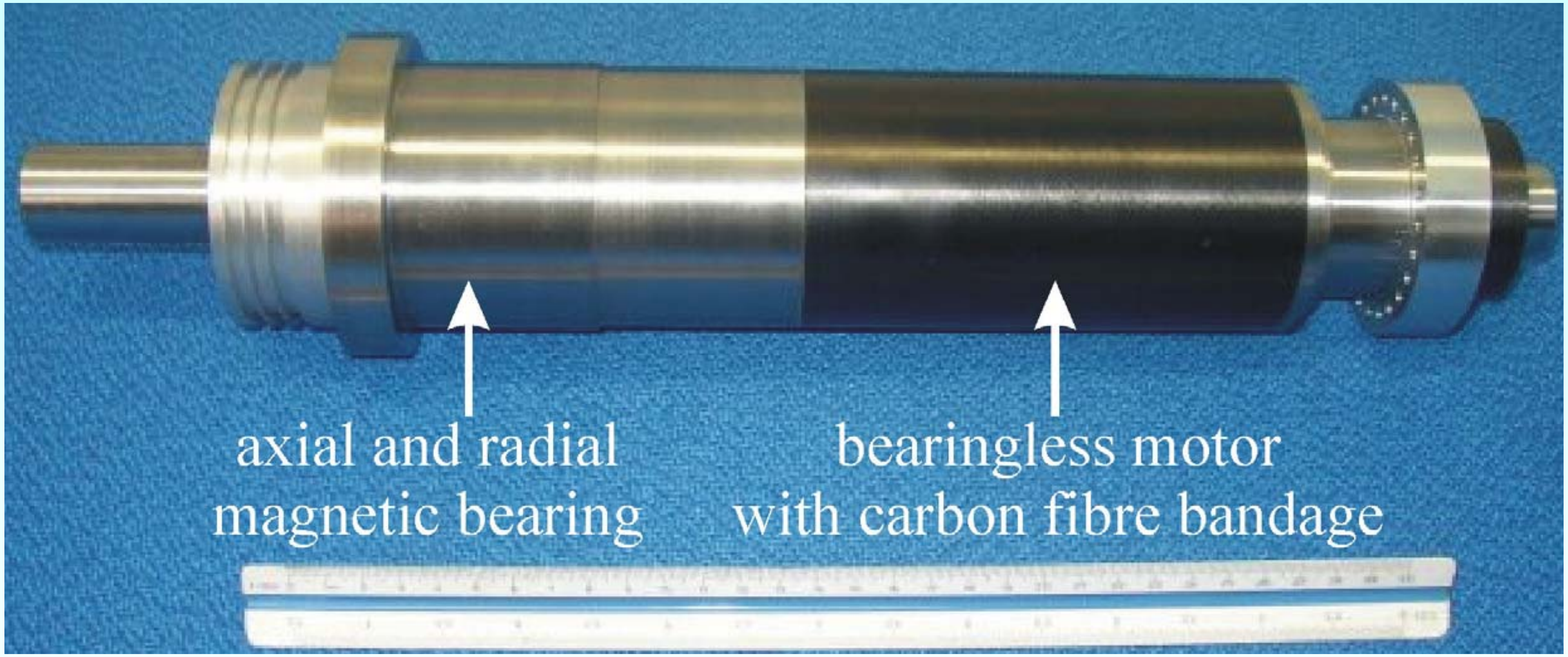


Magnetic field lines
Leading to the nominal lateral force as levitation force

	analytical values	FE results	*Deviation*
$B_{\delta,1}$ (No load)	0.51 T	0.514 T	0.8 %
Nominal torque M_N	5.31 Nm	5.41 Nm	1.9 %
Nominal lateral force F_N	144 N	144 N	0 %

Rotor of a bearingless PM combi motor 40 kW, 40000/min

Source: TU Darmstadt & Levitec, Lahnau



40000/min

40 kW

Four pole

f = 1333 Hz

167 m/s

Bearingless motor:

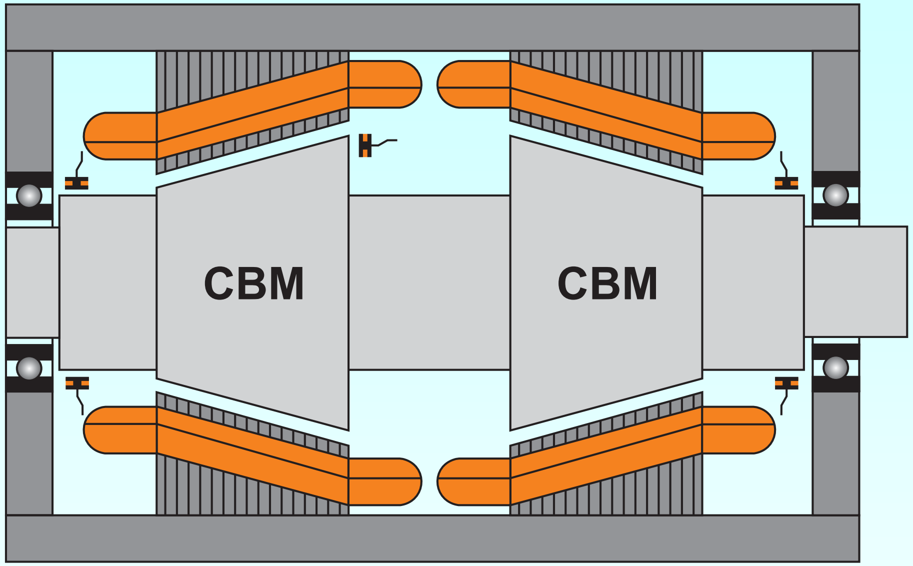
***Two* 3-phase Stator windings:**

- **Four poles: Drive winding $2p_1 = 4$**
- **Six poles: Levitation windings $2p_2 = 6$**

- Over-speed test for the rotor successful up to 44000/min (185 m/s)

- Electric tests up to nominal speed successful

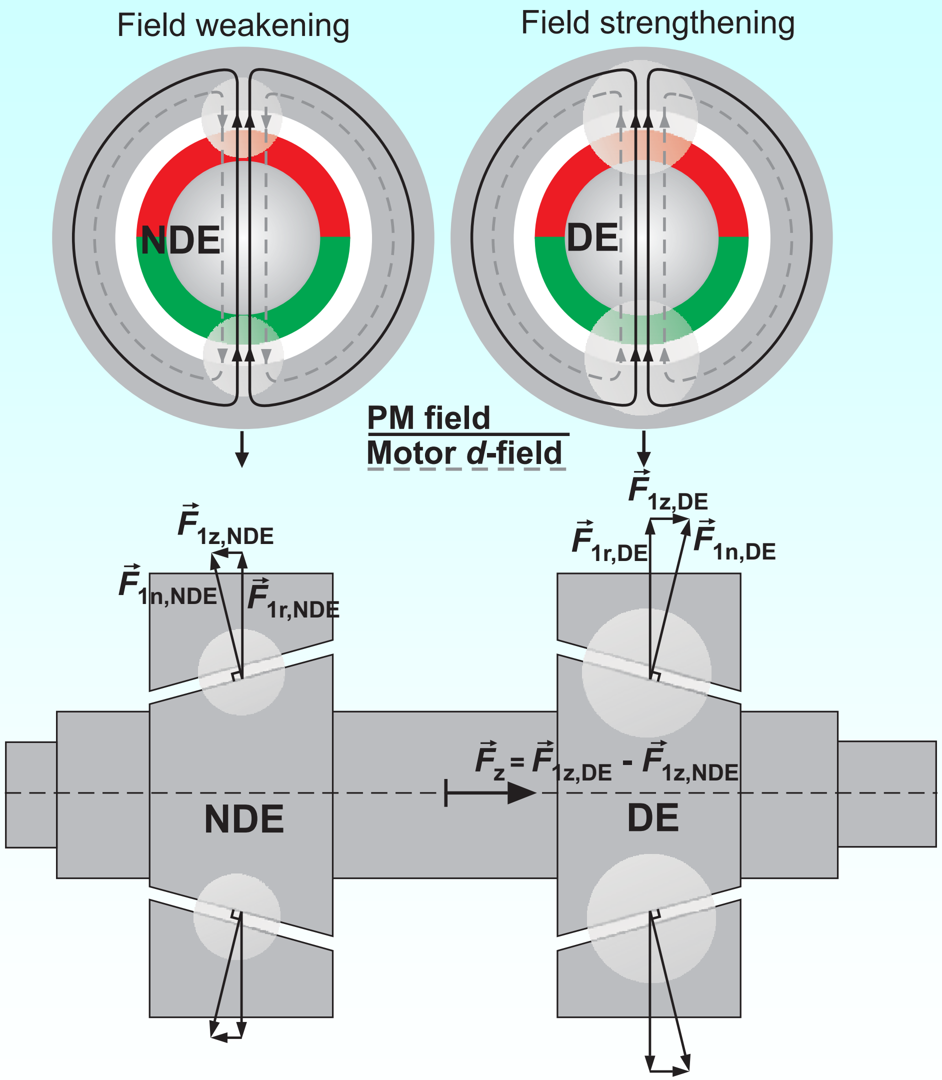
Totally bearingless PM motor



- Two half bearingless machines represent the two radial magnetic AMB.
- Due to their conical shape (CBM = conical bearingless motor) at different field components in the left and right half machine an additional axial force is generated.
- No extra axial AMB is needed = "Totally" bearingless system!

Source: TU Darmstadt, G. Munteanu, 2012

d-*q*-Current control for the totally bearingless PM motor



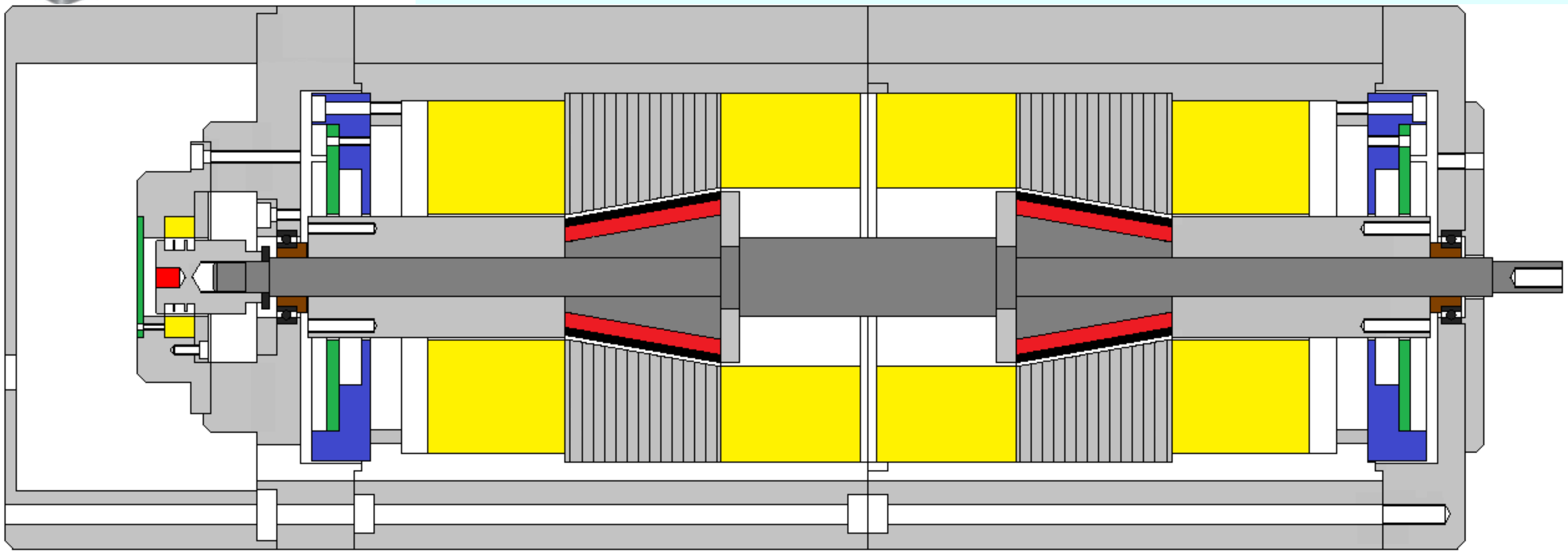
- The torque per half machine is generated by the I_q-current of the drive winding with the rotor PM field.
- The radial levitation force per half machine is generated via the I_d- and I_q-current of the levitation winding with the rotor PM field.
- The axial force per half machine is generated by the axial component of the resulting magnetic pull due to the I_d-current of the drive winding with the rotor PM field.
- The I_d-current of the drive winding does not generate a torque with the rotor PM field, but is only increasing or decreasing the total air gap field.
- By decreasing (left) and increasing (right) the air-gap field, a resulting axial force to the right is generated.

Source: TU Darmstadt, G. Munteanu, 2012

DE: Drive End, NDE Non-drive End

Prototype of totally bearingless PM motor

Prototype: 18000/min, 1 kW: Per half machine: 500 W with 2-pole drive and 4-pole levitation winding. Successfully tested!



Source: TU Darmstadt, G. Munteanu, 2012

Summary:
Bearingless motors

- Combination of motor propulsion and levitation force = motor is bearing!
- Two motor halves give two radial bearings
- Separate poly-phase levitation and drive winding in stator necessary
- Different bearingless motor types possible, but PM synchronous machine dominates
- Three-phase inverter with field-oriented control also for levitation winding
- With conical rotor also the axial bearing force is generated by the machine
- Bearingless motors up to now only for small power (e.g. extra-corporal blood pumps) in commercial use