1: System to actuator requirements
2: Reluctance actuator

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Date:

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0:
Short introductions

MI-Partners: What do we do?

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- What we deliver:
  - Development of prototypes
  - One of a kind equipment
- High-end:
  - Challenging: accuracy and/or speed
  - Innovative
- Examples Customers
  - ASML, Philips, LNLS (Synchrotron), Bosch-Rexroth, Zeiss, Sumitomo, FEI
- Examples Projects
  - Cross writer (NXP ⇒ ITEC)
  - Wafer stage (Nexperia ⇒ ITEC)

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System Architecting

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- Many definitions…
- At MI-Partners:
  - Definition phase: discuss & negotiate specs with customer
  - Concept design phase: Develop solution directions into concepts, concept ranking
  - Global design phase: Steer team to further reduce risks, detailing of solutions
    - Also: Design of Tests for FAT, SAT*
  - Detailed design phase (2D drawings), Ordering, Assemby
    - This time is usually used for reporting (design description)
  - Integration phase, FAT, SAT: support of test engineer, discussions with customer

*FAT/SAT: Factory/Site Acceptance

Confidential

1:
System to actuator requirements

References and preliminaries

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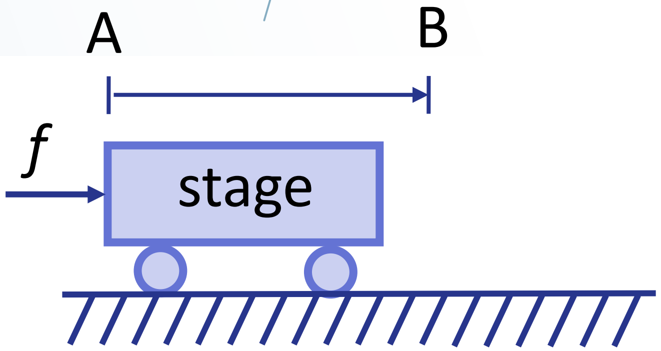
- References
  - Book of Munnig Schmidt, Schitter, Rankers, Eijk:
  - Course Notes EE4C05 – J.A. Ferreira
  - PhD thesis – L. Jabben

- Preliminaries:
  - Will consider current driven actuators
    - Lorentz, voice coil
    - Reluctance
  - Will consider Amplifier and Actuator in tandem
  - Many considerations and way of thinking may apply to other type of actuators
    - Piezo, hydraulic, etc

Feedforward based on Trajectory planning

Positioning (2nd order setpoint)

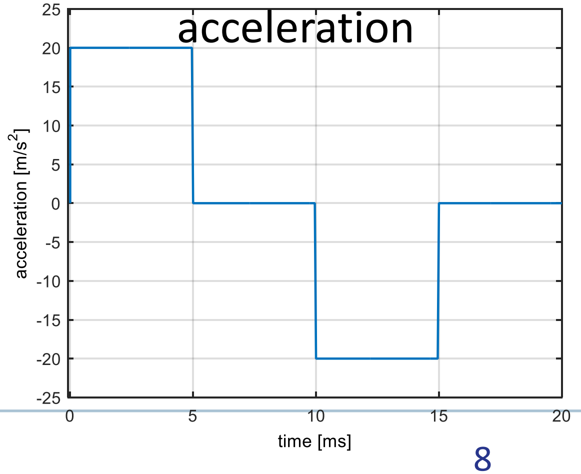


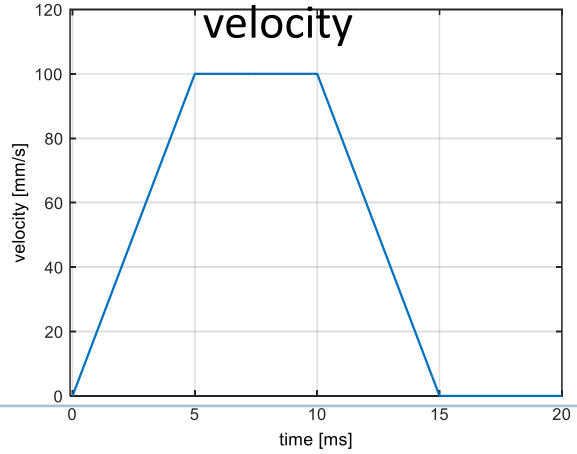
- Suppose a stage needs to move from A to B
  - Customer has specified: 1 mm in 17 msec, every 50 msec.
  - Settling time (within 17 ms): 2 ms ⇒ leaves 15 msec
- Need to accelerate-(constant velocity)-decelerate
  - Assume: 1/3 of step time for constant acce-/deceleration and constant velocity
  - Double integrate to get position:

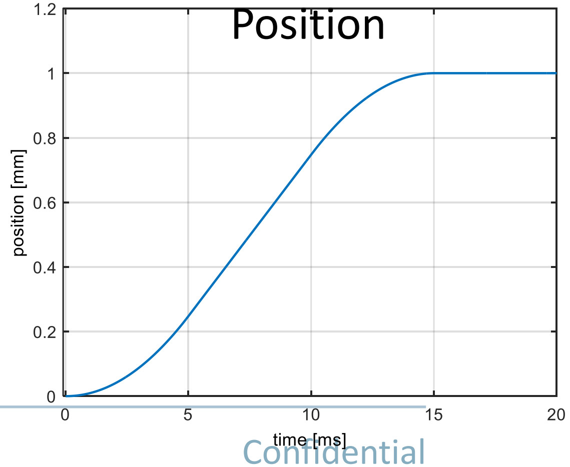
$$x = \frac{1}{2}a\left(\frac{1}{3}T_e\right)^2 + a\left(\frac{1}{3}T_e\right)^2 + \frac{1}{2}a\left(\frac{1}{3}T_e\right)^2 = \frac{2}{9}aT_e^2$$

  - $\Rightarrow a = \frac{9}{2}\frac{x}{T_e^2} \approx 5\frac{x}{T_e^2}$

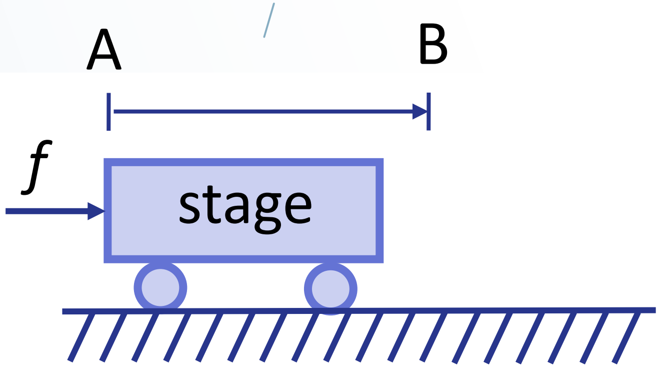
    $a \approx 22\ \mathrm{m/s^2}$





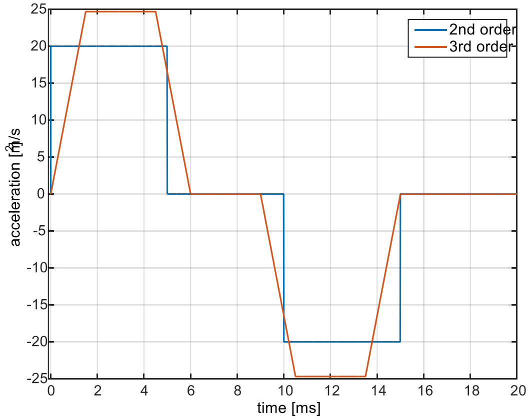


Positioning (3rd order setpoint)

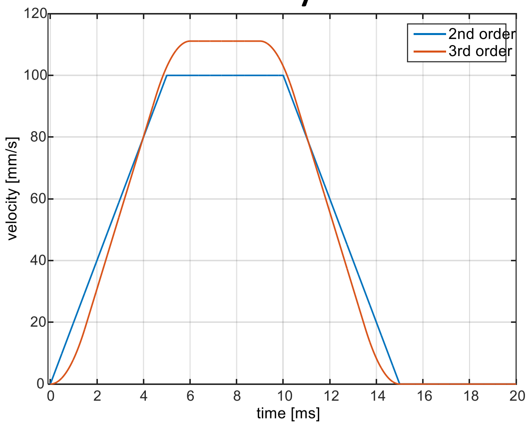


- Second order usually not used in high end machines
  - Requires infinite jerk ⇒ infinite voltage
  - Lots of dynamic excitation
- Assume
  - Constant jerk / acceleration / velocity duration: $\frac{1}{10}T_e$ / $\frac{2}{10}T_e$ / $\frac{2}{10}T_e$
  - Then: $a = \frac{100}{18}\frac{x}{T_e^2} \approx 6\frac{x}{T_e^2} = 27$ m/s²

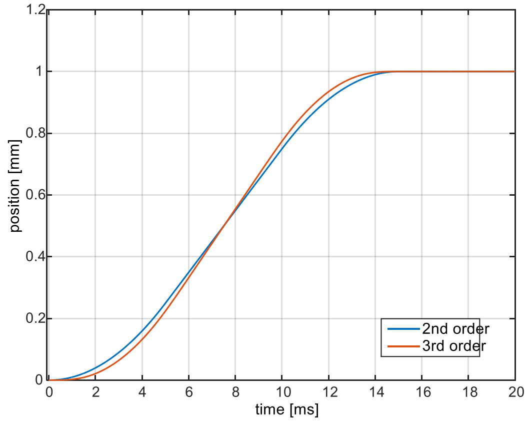
acceleration



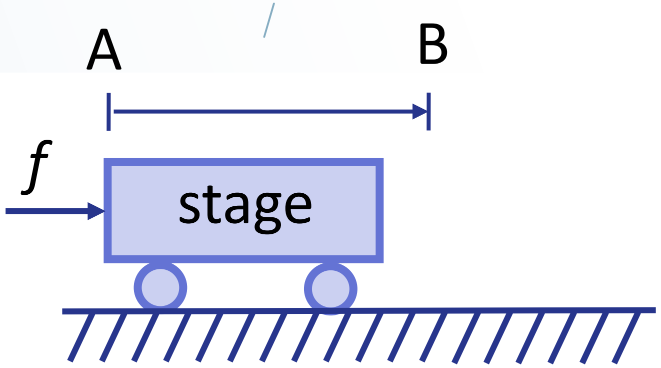
velocity



Position

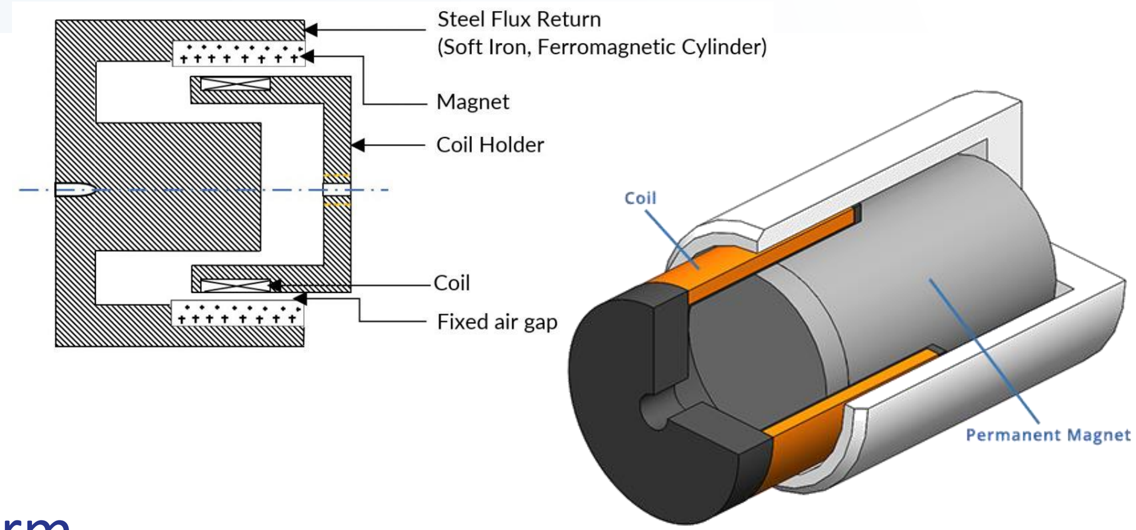


Force requirements

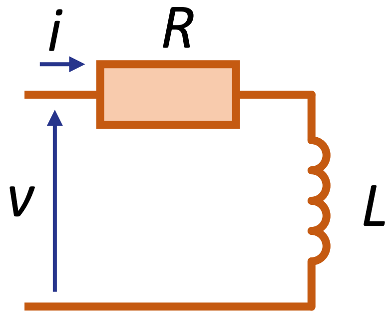


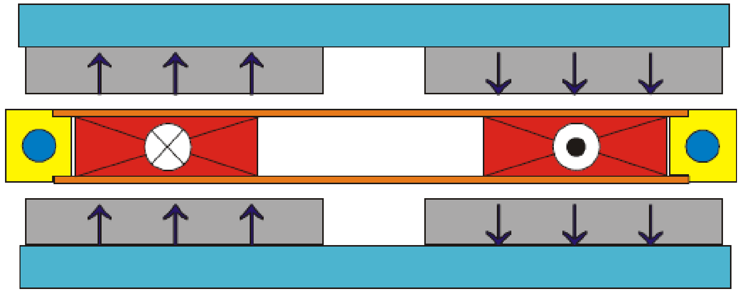
- Given a certain mass, a force trajectory can now be calculated, giving:
  - Peak force
  - RMS force
- Example:
  - 300 mm wafer on a foil.
  - Dynamically stiff structure: 9 kg
  - Peak force 25m/s^2·9kg = 225 N
    - Limited by amplifier peak current, voltage (next), (demagnetization PMs)
  - RMS: $a_{rms} = \sqrt{\frac{2 \cdot \frac{1}{3} T_e}{T_{cycle}}} a_{max}^2 \approx 11\ \mathrm{m/s^2} \Rightarrow f_{RMS} \approx 100\ \mathrm{N}$
    - Limited by thermal constraints (cooling): 1) actuator, 2) amplifier

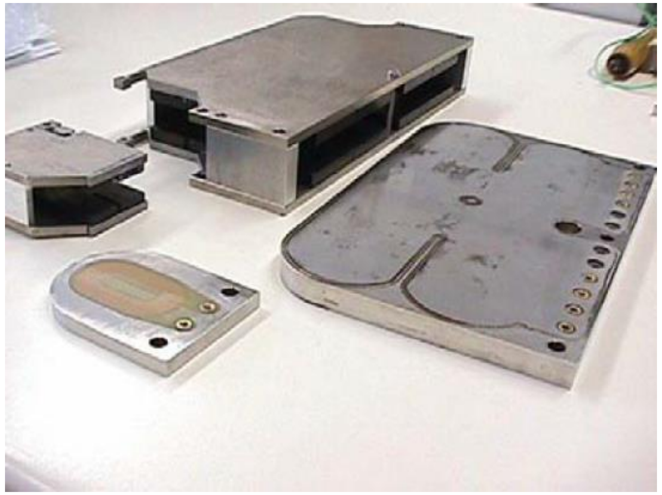
Voltage requirement: 1) non-moving coil



- Consider a Lorentz actuator
  - $f = k_{act} i$ [N]
    - i: current through coil [A]
    - k_{act}: motor force constant [N/A]
- The current goes through a coil
  - Hence impedance of coil has inductance term
  - Voltage: $u = Ri + L\frac{di}{dt}$ [V]
    - R: resistance coil [Ω], L: inductance coil [H]

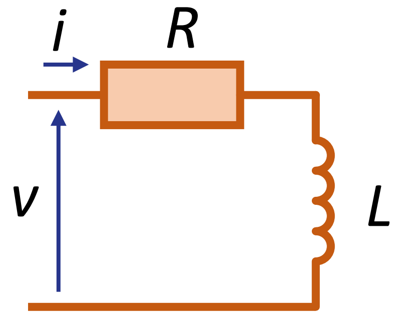






Voltage requirement: 2) due to jerk

- Voltage required for setpoint:
  - $u = Ri + L\frac{di}{dt} = \frac{1}{k_{act}}\left(Rf + L\frac{df}{dt}\right) = \frac{m}{k_{act}}\left(Ra + L\frac{da}{dt}\right)$ [V]
  - used: $f = k_{act}i$ & $f = ma$)
- Term *da/dt* is denoted *jerk* [m/s^3]
  - *(4th derivative dj/dt* [m/s^4] is denoted snap),
- Second order profile requires infinite jerk ⇒ infinite voltage…
  - For this reason third order profiles are used:
    - Jerk: $j \leq \frac{k_{act}}{Lm}(u_{bus} - Ri)$ [m/s^3] (u_{bus}: bus/supply voltage)
  - However, the calculated bus voltage only valid … *when not moving*!



Voltage requirement: back-emf

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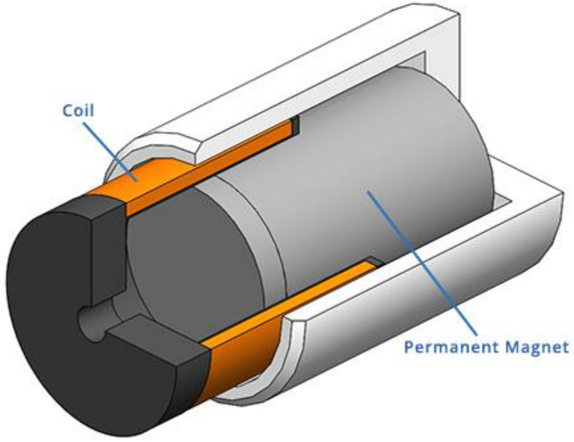
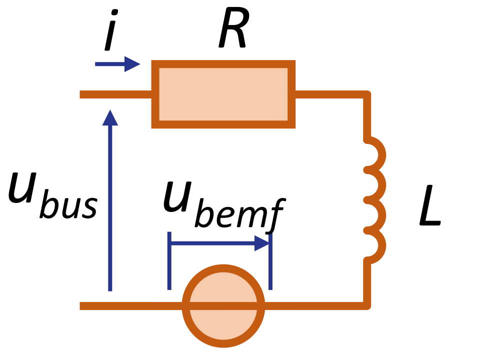
- Consider the same voice coil actuator ($f = k_{act} i$)
- Which is also a generator:
  - Back EMF: $u_{emf} = k_{act} v$ [V]
    - v: velocity of moving part [m/s]
  - Notice unit k_{act} : [N/A] & [V/(m/s)]!
    - Sanity check: V·s/m = W/A ·s/m = N·m/s /A ·s/m = N/A ⇒ same unit

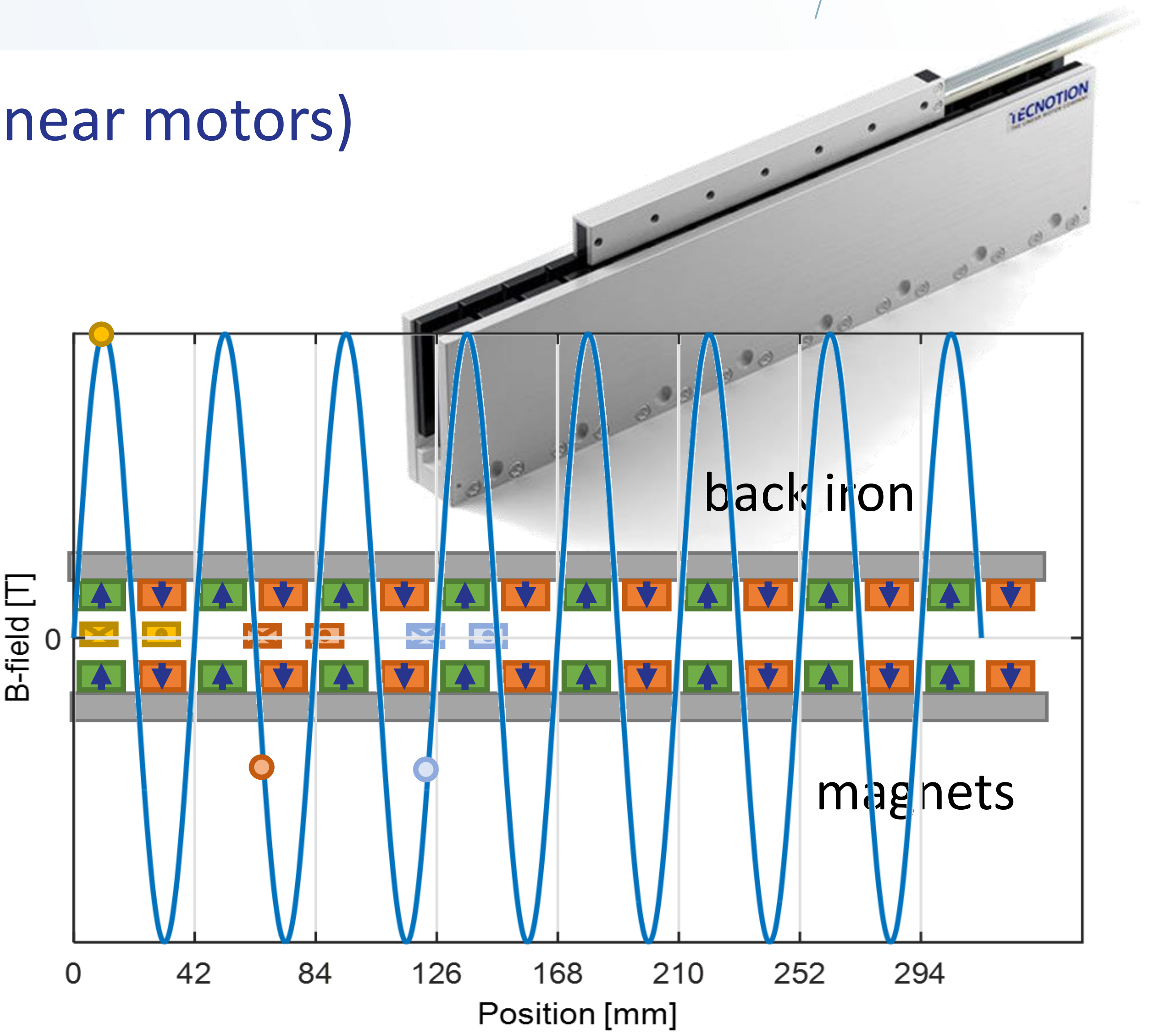


- Hence when moving, the actuator acts as a voltage source
  - Worst case, this source is opposite of what the amplifier is generating ⇒ Higher bus voltage is needed
  - $u_{bus} \geq \frac{m}{k_{act}}(Ra + Lj) + k_{act} v$
  - Careful, still not complete story!



Three phase actuators

- Why: to enable large stroke (for linear motors)
  - Constant power
- Commutation
  - Six step (based on hall sensors)
  - Sinusoidal (for precision)
    - Requires position information
- Sinusoidal current in phases i.c.w. sinusoidal magnetic flux results in constant force over position



Commutation three phase motors

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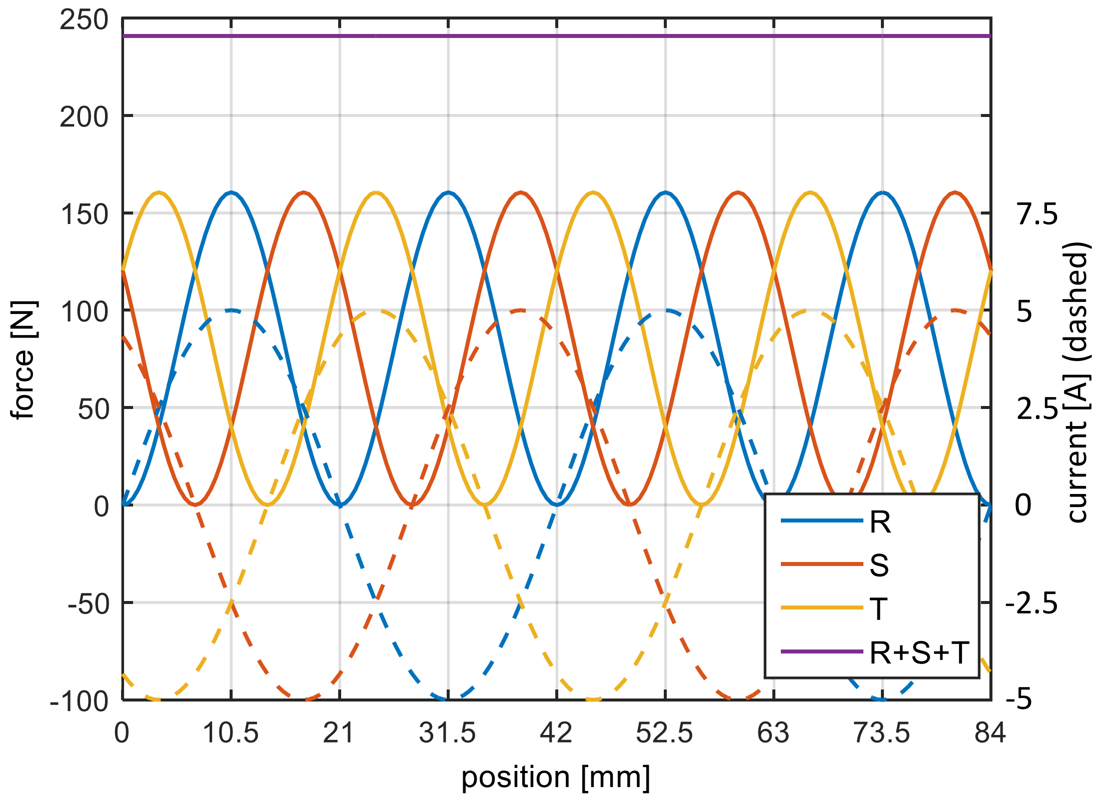
- Consider a UL3-N from Tecnotion

Parameter	Remarks	Symbol	Unit	UL3	
Winding type				N	S
Motortype, max voltage ph-ph					
Peak Force @ 20°C/s increase	magnet @ 25°C	F_p [I]	N	240	
Continuous Force*	coils @ 110°C	F_c	N	70	
Maximum Speed**	@ 300 V	v_{max}	m/s	5	12
Motor Force Constant	mount. sfc. @ 20°C	K	N/A_{rms}	68	27.5
Motor Constant	coils @ 25°C	S	N^2/W	97	
Peak Current	magnet @ 25°C	I_p	A_{rms}	3.5	8.7
Maximum Continuous Current	coils @ 110°C	I_c	A_{rms}	1.03	2.6
Magnet Pitch NN		τ	mm	42	



- Note spec of peak current: in A_{rms}
  - Actual current can be √2 higher at certain positions ⇒ twice the thermal load!

Voltage requirement: total

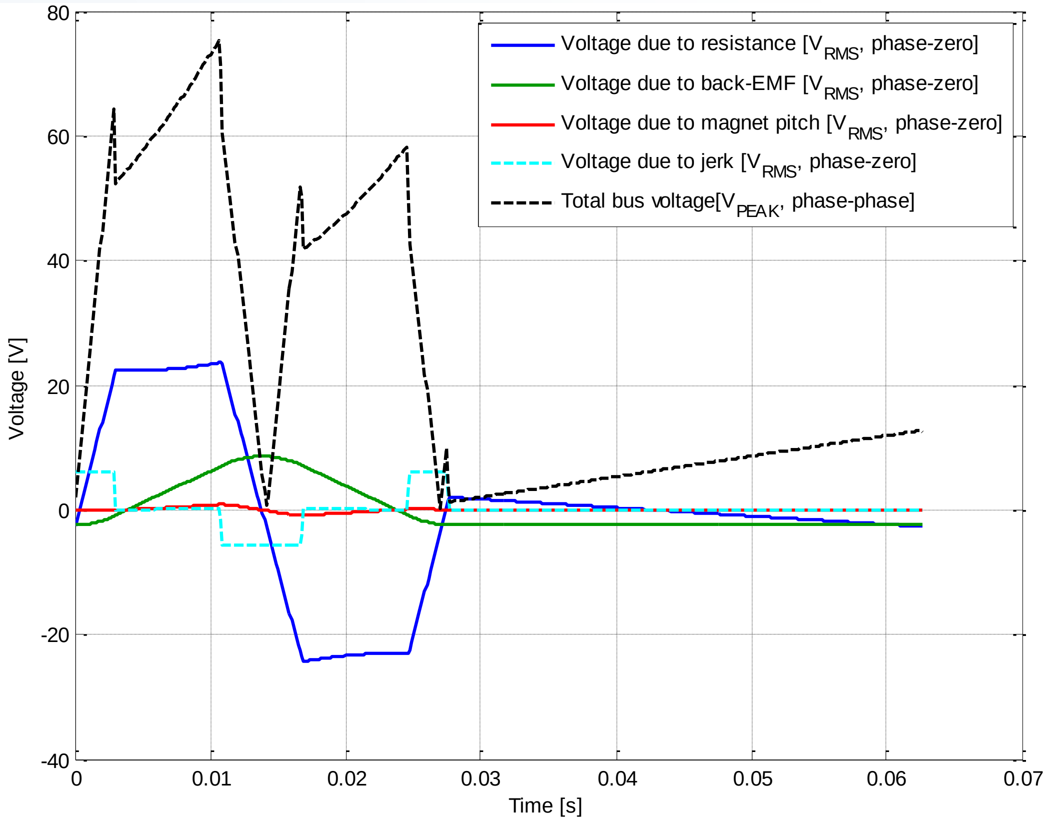
- Calculation of voltage phase-zero RMS:

$$V_{R,P0,RMS} = I_{RMS} \cdot R_{F0} \qquad \text{(Resistance)}$$

$$V_{B,P0,RMS} = v \cdot K_{U,F0,RMS} \qquad \text{(Back-emf)}$$

$$V_{M,P0,RMS} = I_{RMS} \cdot \frac{v \cdot 2\pi}{\tau_{NN}} \cdot L_{F0} \qquad \text{(3-phase)}$$

$$V_{J,P0,RMS} = \frac{dI_{RMS}}{dt} \cdot L_{F0} \qquad \text{(Jerk)}$$



- Calculation total voltage phase-phase peak:

$$V_{P0,RMS} = \sqrt{(V_{M,P0,RMS})^2 + (V_{R,P0,RMS} + V_{B,P0,RMS} + V_{J,P0,RMS})^2}$$

$$V_{PP,PEAK} = V_{BUS} = V_{P0,RMS} \cdot \sqrt{2} \cdot \sqrt{3}$$

Calculations of current, voltage and power according to: TU-Delft lecture notes ET4245WB Mechatronics 2003 by J.C.Compter, p.103, eq. 164

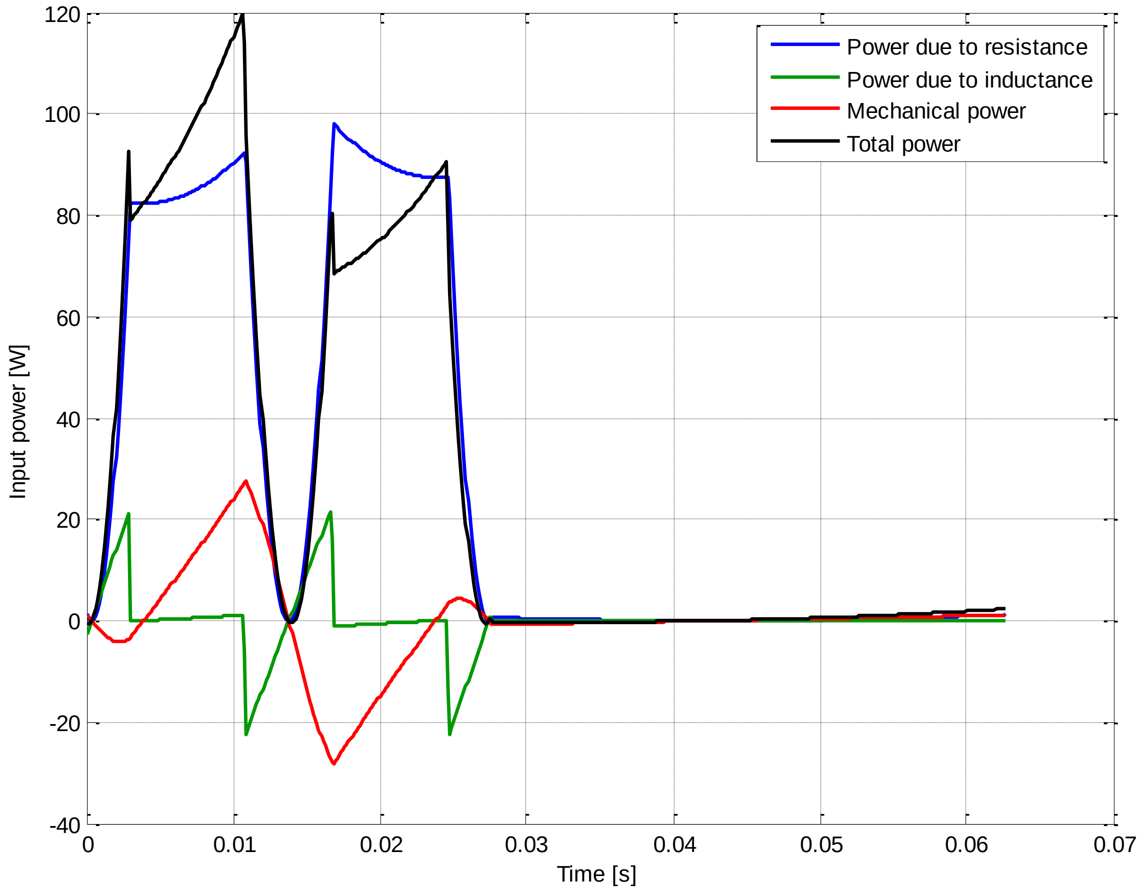
Power requirements

- With the current and voltage know, the power can be calculated

$$P(t) = 3 \cdot R_{FO} \cdot {I_{RMS}}^2 + 3 \cdot L_{FO} \cdot I_{RMS} \cdot \frac{dI_{RMS}}{dt} + v \cdot F$$

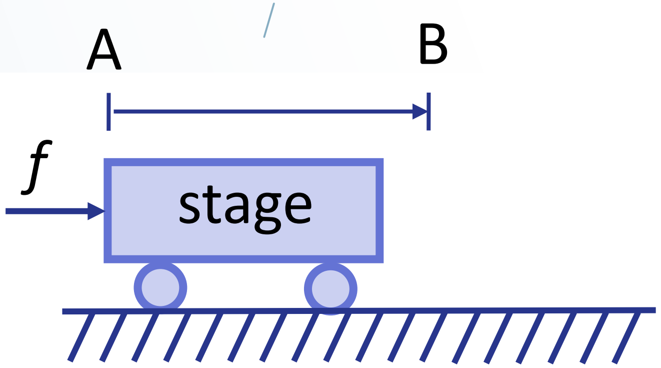
Resistive power　　Inductive power　　Mechanical power

- Resistive power: heats up actuator
- Inductive + mechanical power: “fed” back to amplifier:
  - Capacitor (reused),
  - Resistor (dissipated)
  - Grid (bi-directional power supply)



Calculations of current, voltage and power according to: TU-Delft lecture notes ET4245WB Mechatronics 2003 by J.C.Compter, p. 103, eq. 168

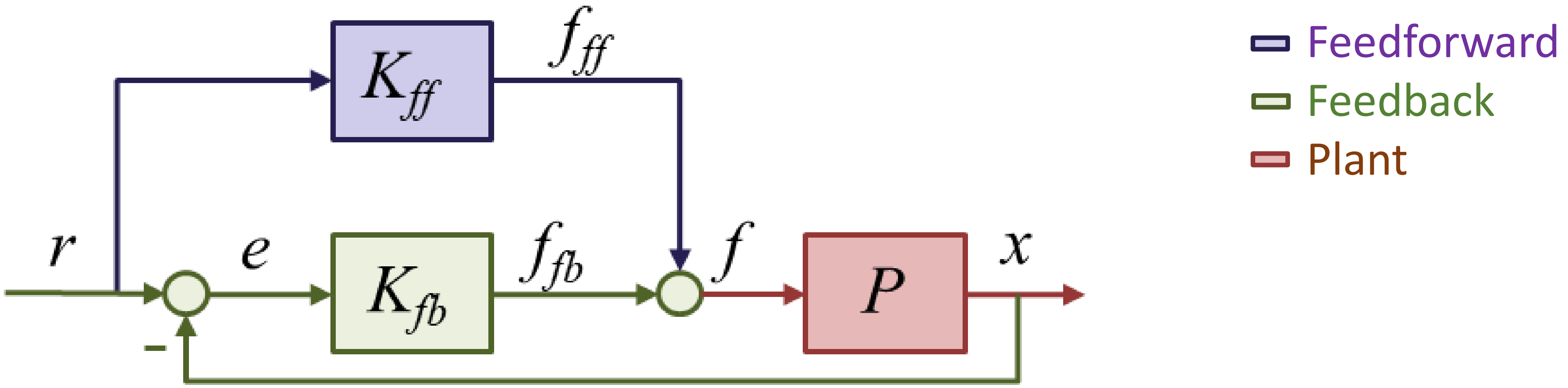
Feedforward performance



- Performance of feedforward disappoints in practise:
  - The actual mass may differ:
    - Varying payload or cable chain (⇒ varying mass with position)
    - Dynamics: mass decoupling at certain frequency
  - The actual actuator gain may differ:
    - Due to heating up of actuator
    - The actuator gain may vary with the amount of current
    - The actuator gain may vary with position (voice coil,
  - System may have coupling to environment:
    - Stiffness, e.g. cables, leaf spring guiding
    - Damping, e.g. viscous friction in bearings, eddy current damping
  - System may have dynamics excited by spectral content in feedforward
  - The actuator may introduce disturbance force (e.g. cogging)
- Need feedback to reduce the resulting error!

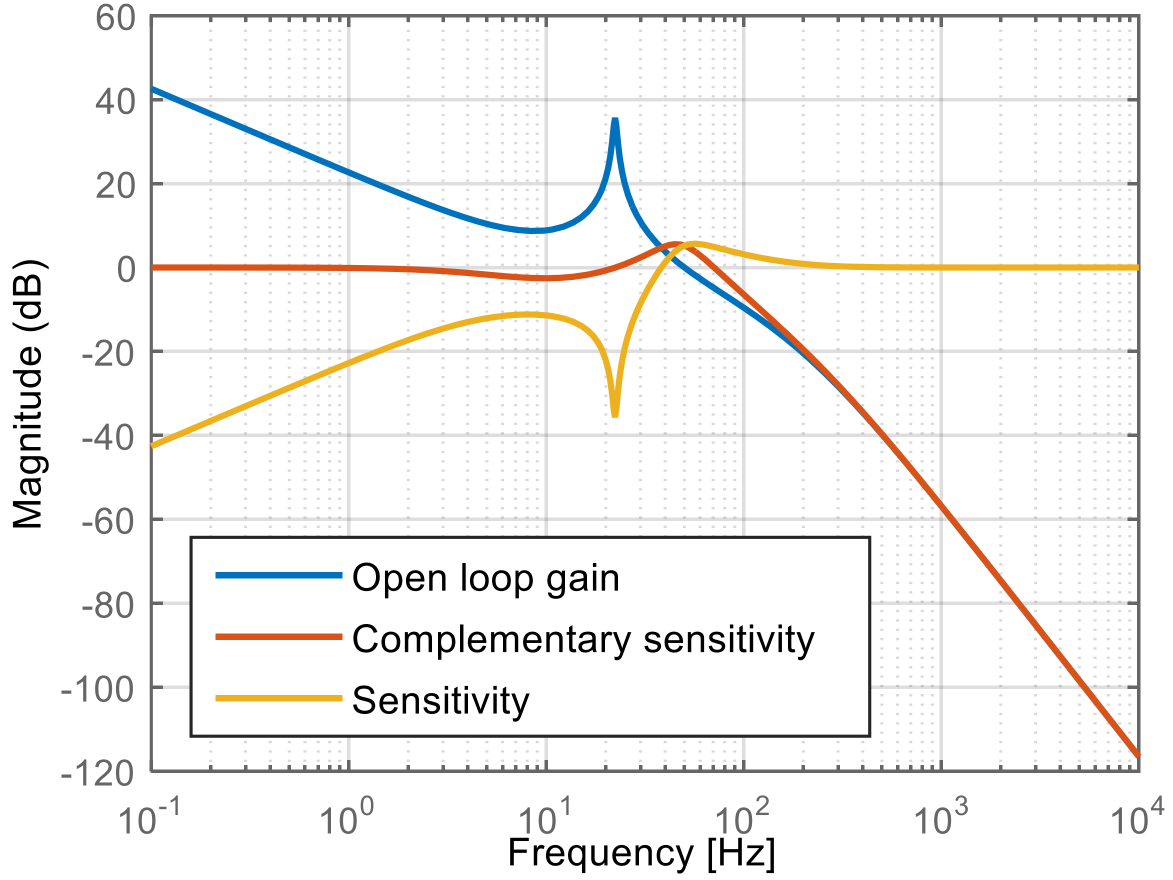
Feedback

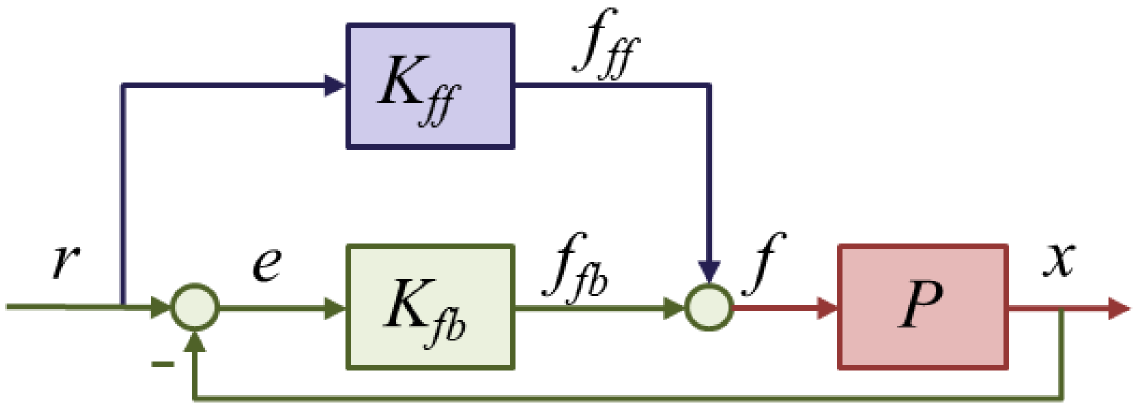
Feedback loop (i.c.w. feedforward)



- High level block diagram
  - Components like sensor, ADC, digital controller, DAC, Amplifier, Actuator all in K_{fb}
- Consider the unit of the controller K_{fb}
  - Controller can be interpreted as a “mechanical spring”…

Typical transfer functions





$$L = \frac{x}{e} = K_{fb}P$$ Loop gain

$$S = \frac{e}{r} = \frac{1}{1 + K_{fb}P}$$ Sensitivity

$$T = \frac{x}{r} = \frac{K_{fb}P}{1 + K_{fb}P}$$ Complementary Sensitivity

Bandwidth: $|L(\omega_{BW})| = 1$ (0dB)

Required bandwidth estimation

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- Suppose a mass modelling / actuator gain error c_{err}
- Hence, one makes a maximum feedforward force error of

$$ff_{err} = c_{err} a_{max} m$$

- With controller modelled as simple spring (k_{con}), the error becomes

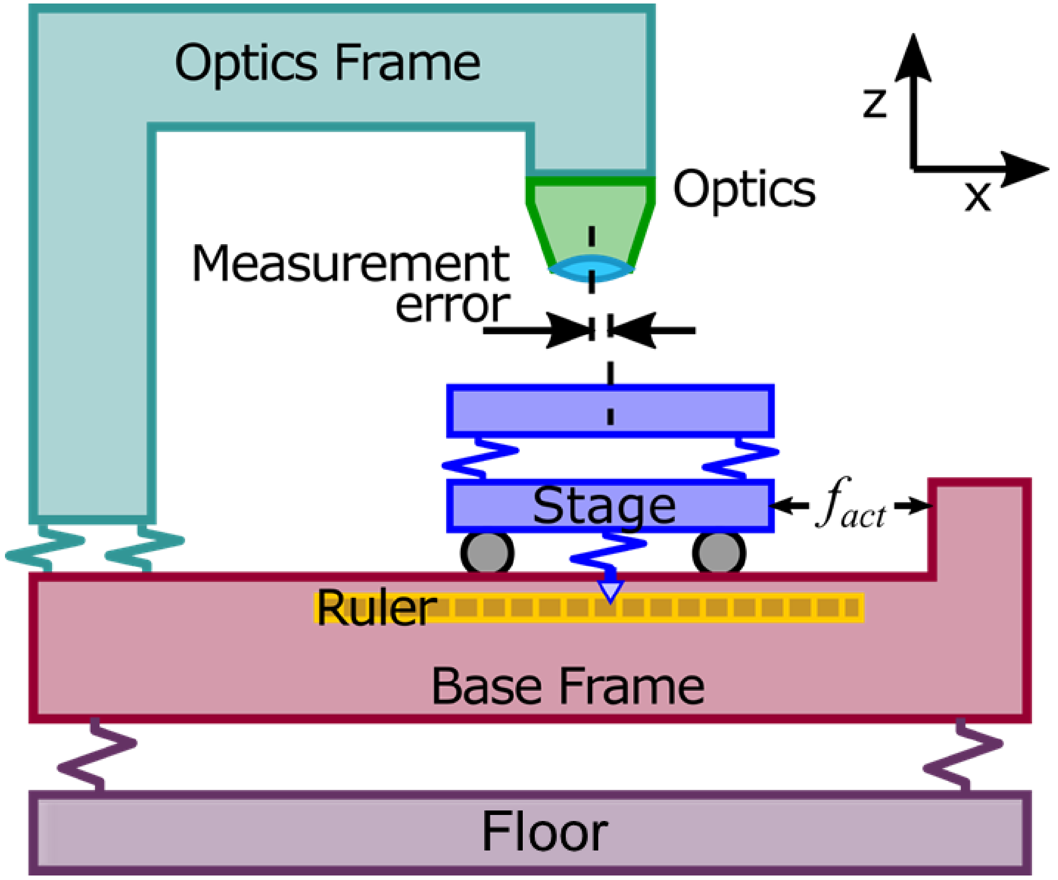
$$e = \frac{ff_{err}}{k_{con}} = c_{err} a_{max} \frac{m}{k_{con}} \Rightarrow \frac{k_{con}}{m} = \frac{c_{err} a_{max}}{e} = \omega_{bw}^2 = (2\pi f_{bw})^2 \Rightarrow$$

$$f_{bw} = \sqrt{\frac{c_{err} a_{max}}{e}}$$

- Example: tracking error: <2 µm, c_{err} = 2%, a_{max} = 22 m/s^2 $\Rightarrow$ f_{bw} > 75 Hz

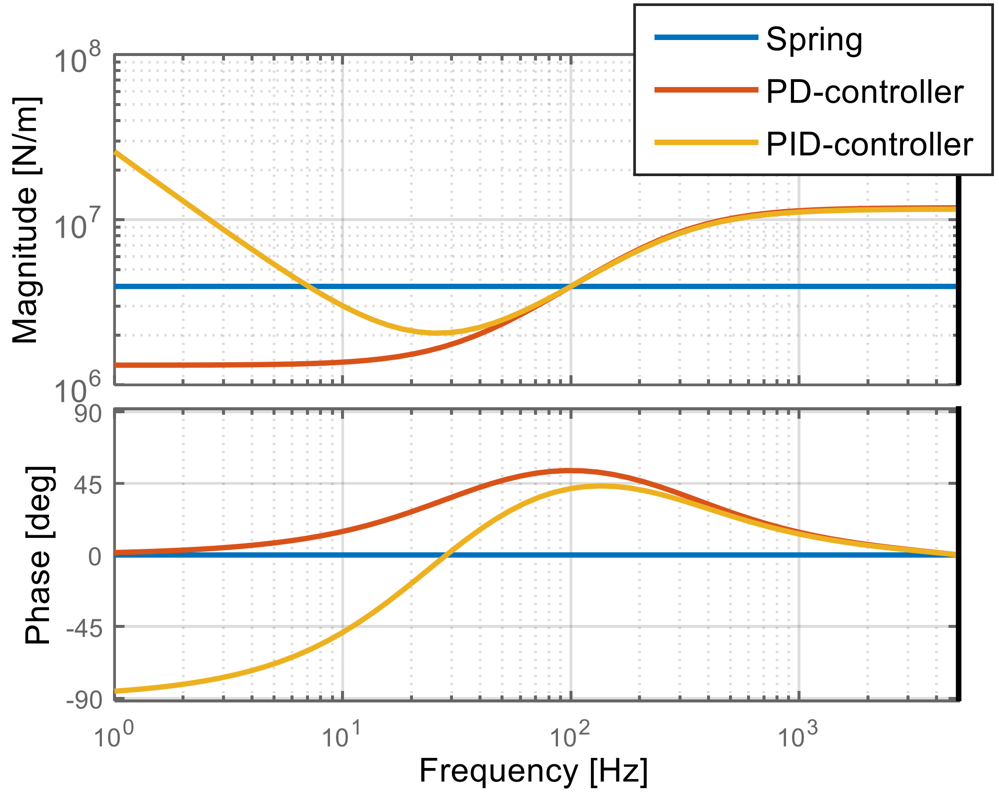
Bandwidth estimation, example 2

- Required force to move stage with the same vibrations: $m{\cdot}a_{frame}$
  - $ma_{frame} = k_{con}e \Rightarrow$
  - $\frac{k_{con}}{m} = \frac{a_{frame}}{e} = \omega_{bw}^2 = (2\pi f_{bw})^2$
- Stage positing with respect to a frame:
  - Frame vibrations: a_{frame} = 10 mm/s^2
  - Required stage positioning accuracy: e = 0.1 µm
- It follows f_{bw} > 50 Hz
  - Content of base frame accelerations should be below BW!

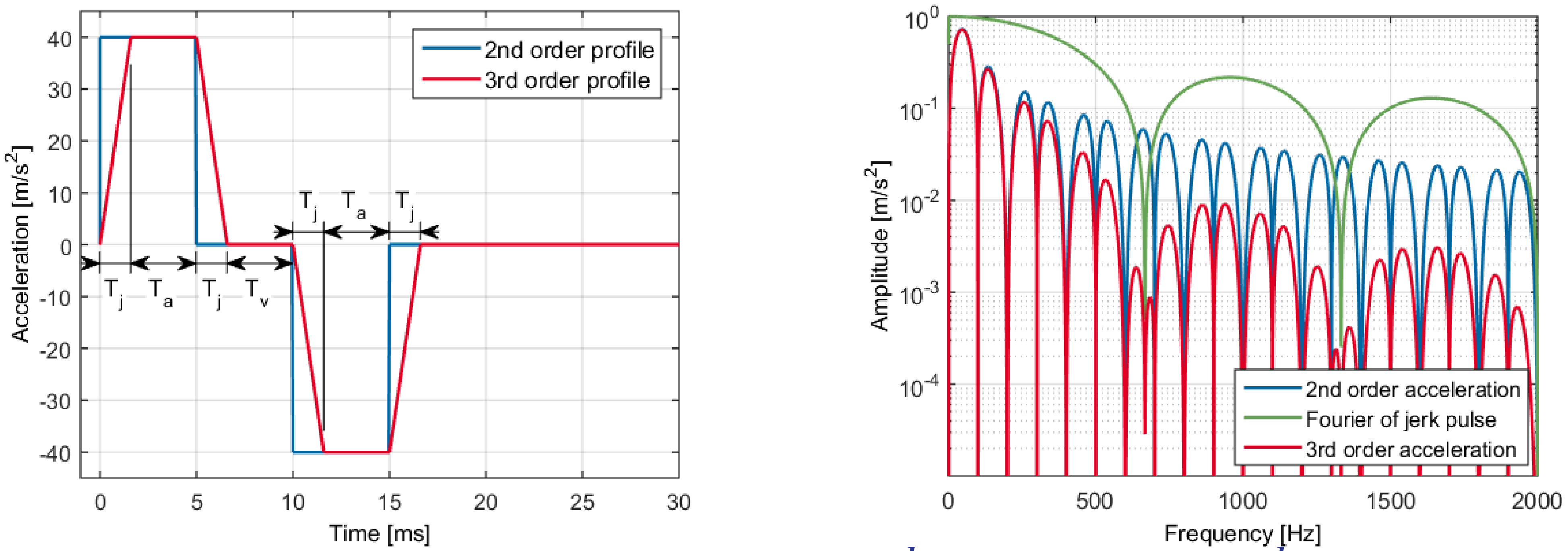


Real controller vs hand calculation

- Plant: free moving (in 1 DoF) mass of 10 kg
  - $P = \frac{1}{ms^2} = \frac{1}{10s^2}$ [m/N]
- Estimated bandwidth: f_{bw} = 100 Hz
  - "Stiffness": $k = m(2\pi f_{bw})^2 \approx 4 \cdot 10^6$ N/m
- Standard P(I)D controller
  - Phase lead needed for stability (PID: ~45°)
  - ⇒ Factor ≈3 lower stiffness below f_{bw}
  - Integral action: higher stiffness for $f \lesssim f_{bw}/15$
- So actual required BW can be √2 - √3 (≈1.5) higher
  - Other disturbance can further increase needed BW ⇒ Error budget



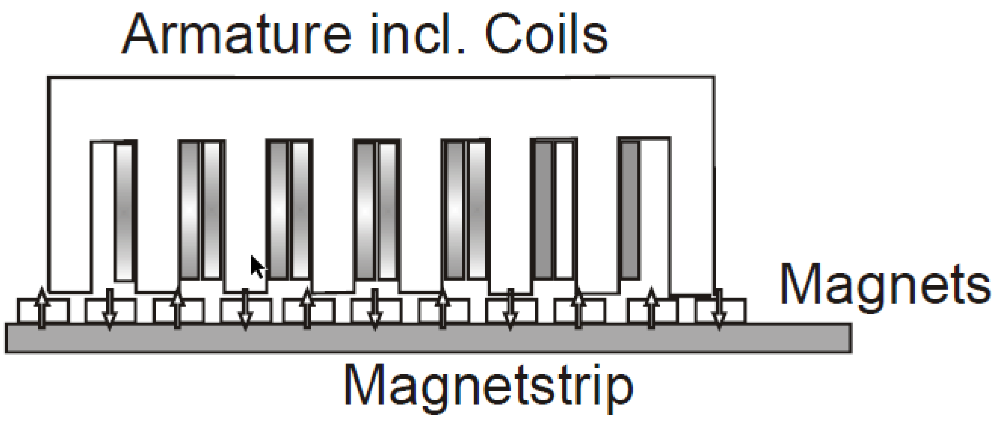
Dynamic content of trajectory

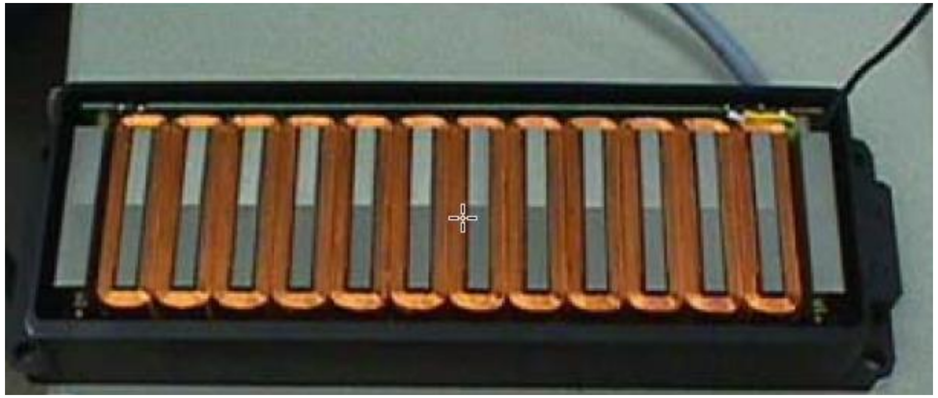


- Frequencies with zero content: $f_{0v} = \dfrac{k}{T_v+T_a+2T_j}$ & $f_{0a} = \dfrac{k}{T_a+T_j}$, $k \in \mathbb{N}$
  - Peaks in content roughly at $f_{pv} \approx \dfrac{2k+1}{2(T_v+T_a+2T_j)}$, $f_{pa} \approx \dfrac{2k+1}{2(T_a+T_j)}$, $k \in \mathbb{N}$
- Bulk spectral content should be below estimated BW
  - otherwise higher BW is needed!

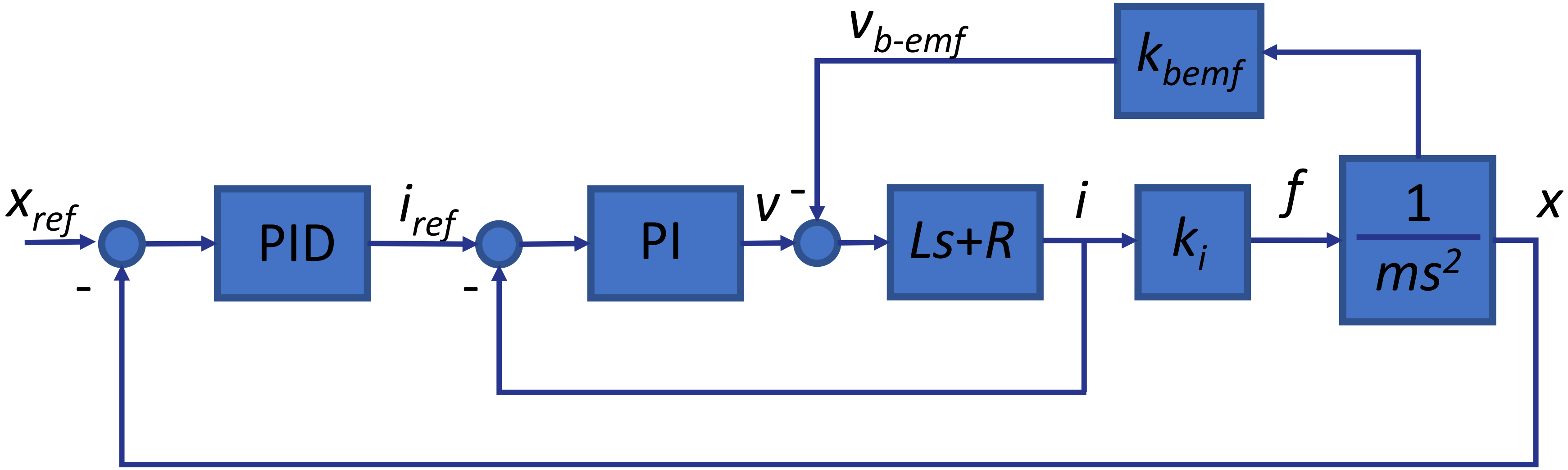
Dynamic content of disturbance force

- Consider an iron core motor
  - Due to iron in the coil ⇒ higher force density
  - Large attraction force!
- Has cogging
  - Preference positions
  - Force varying with position (and current)
  - Largely repeatable
  - Periodic with Magnet pitch and tooth pitch
- Hence with certain velocity the cogging will manifest itself at certain frequency (and harmonics)



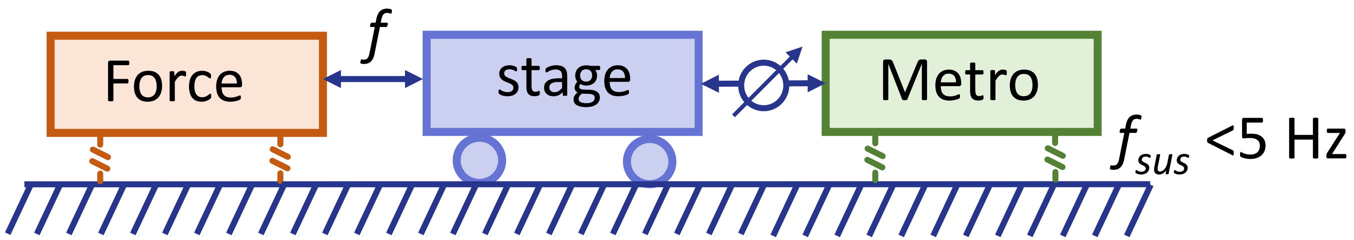


Current loop



- Current loop is needed to stabilize the current
  - Voltage amplifiers can be used (gives damping) but not (often) used
- BW current feedback loop (small signals) typically 10-20x position BW
  - To limit phase delay to few degrees
  - To reduce back-EMF effect

Machine concepts: Force / Metro frame

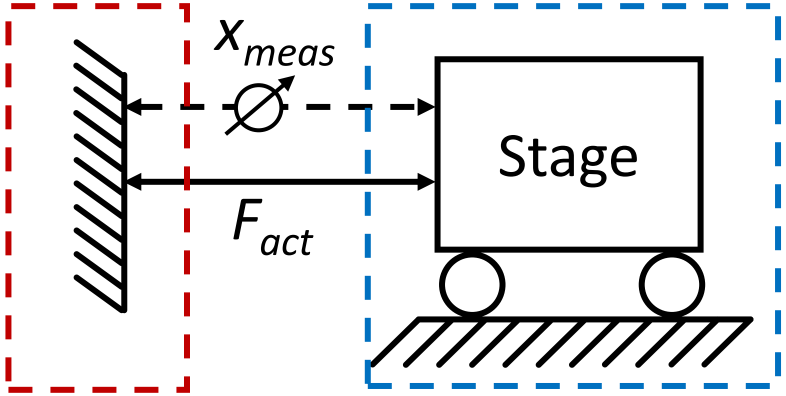


- Separate Metrology frame – Force frame
  - A quiet metrology frame (low accelerations) reduce the BW requirement
  - It decouples the forward path dynamics (stage) from the reaction path dynamics (reaction force towards sensor)
- The lower the position coupling of an actuator, the better this decoupling works
  - ⇒ Lorentz type actuators

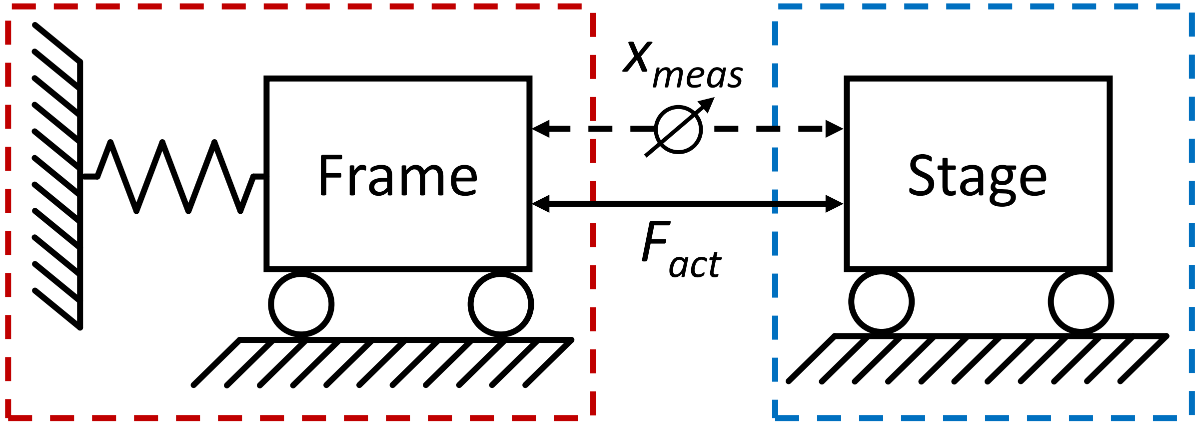
Reaction path dynamics

Sensors and actuators have two sides: Forward and Reaction Path

Measurement and actuation w.r.t.
ideal fixed world:



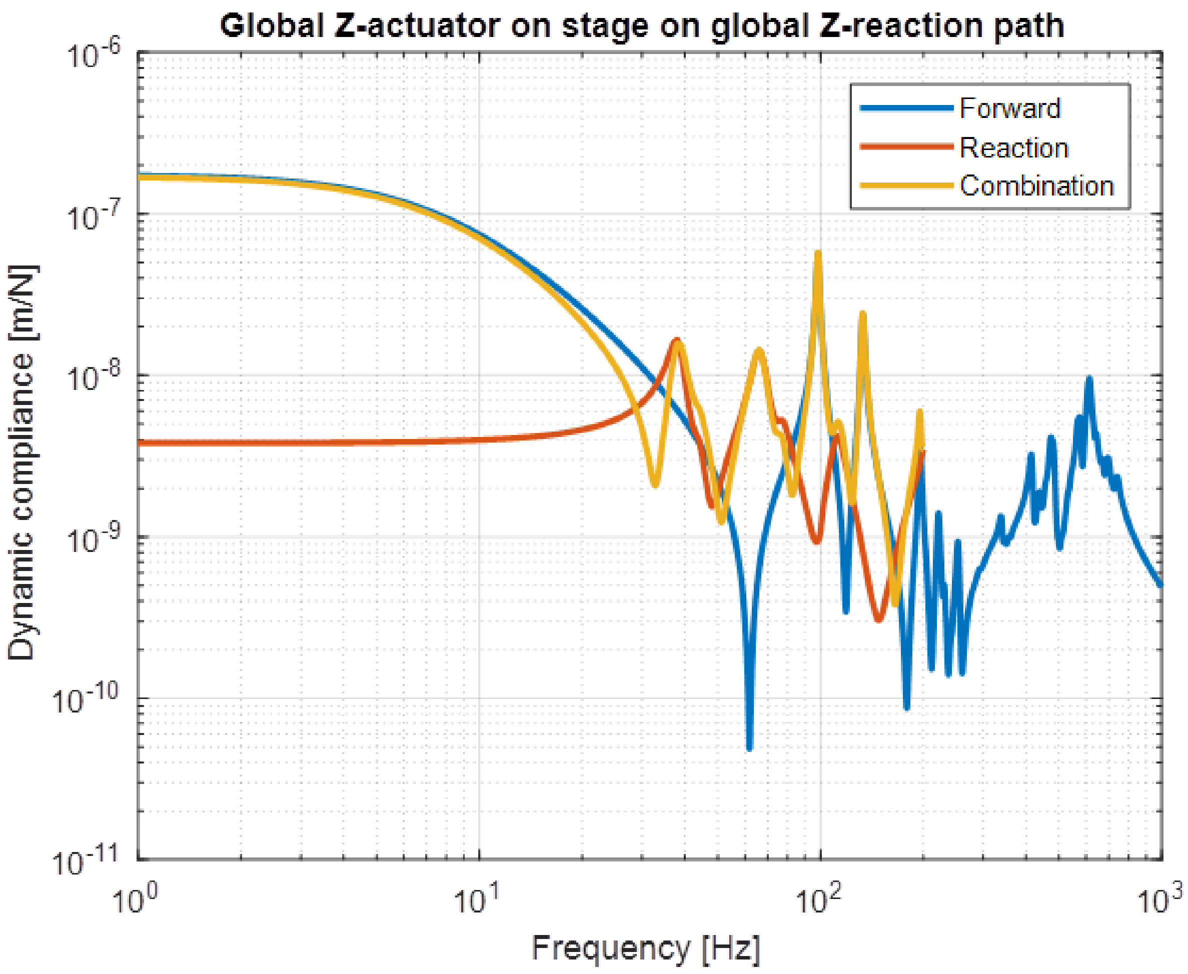
Reaction path Forward path



Reaction path Forward path

When actuating and sensing w.r.t. frame: Reaction path dynamics become visible in control loop!

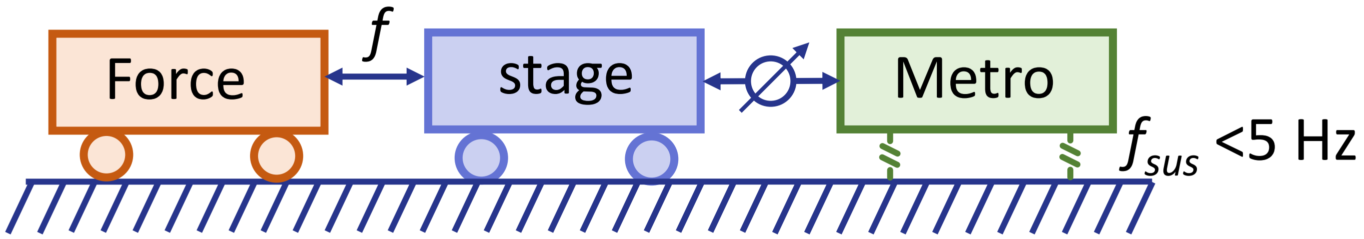
Example reaction path dynamics



- Reaction path dynamics can dominate the forward path dynamics

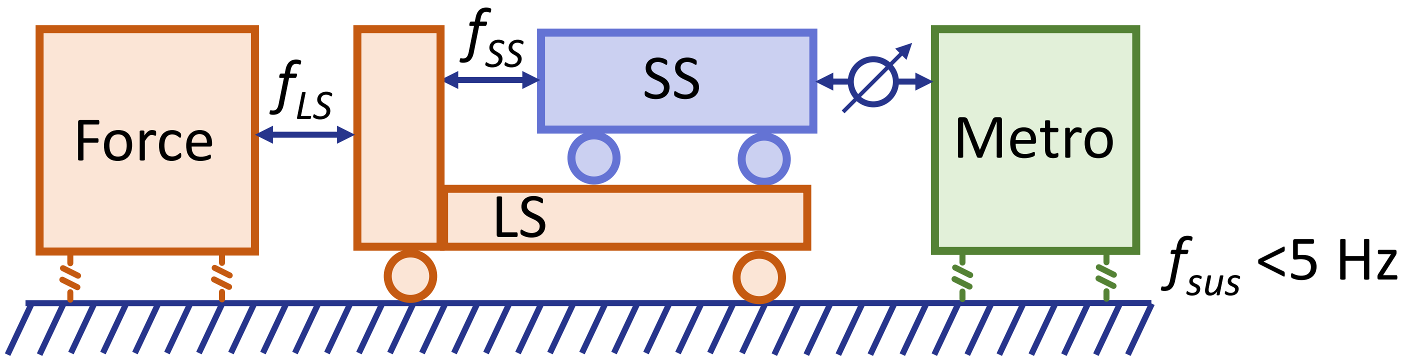
Machine concepts: Balance (reaction) mass

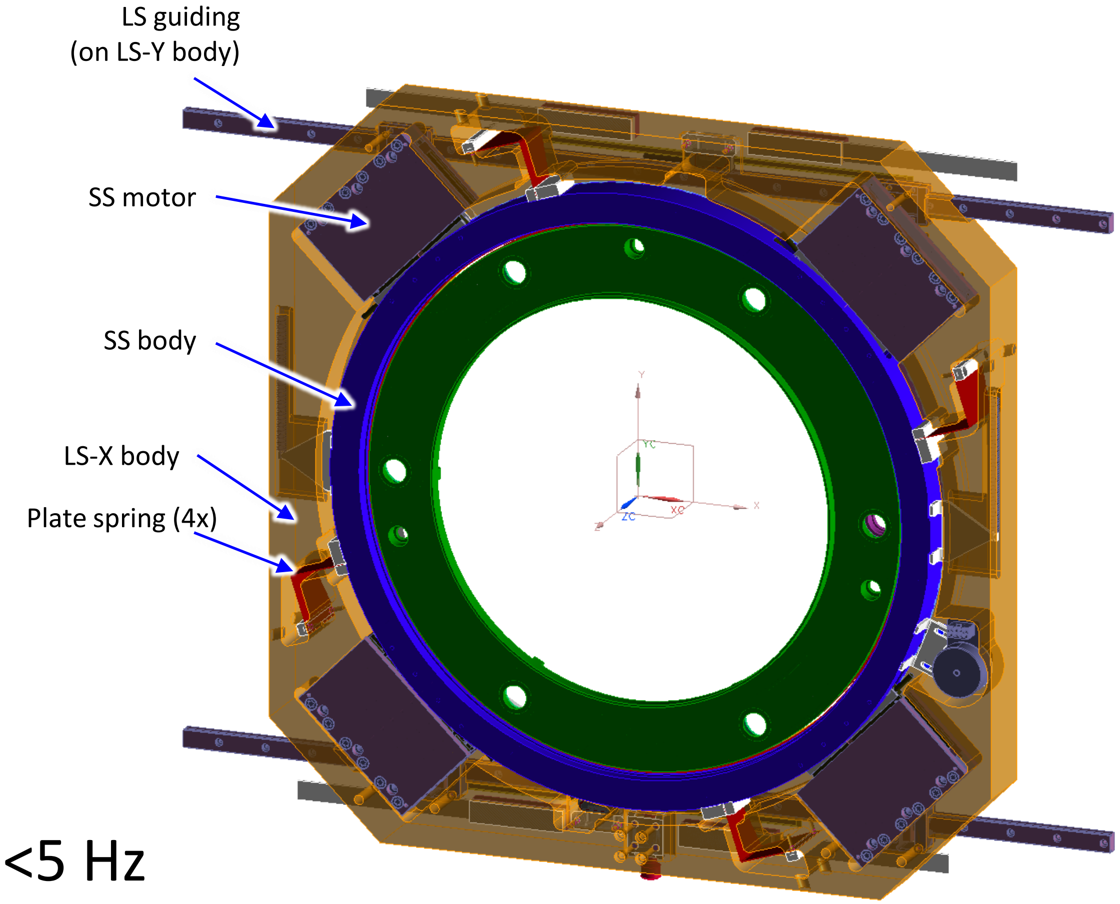
- Balance mass is a force frame but with relative large stroke
  - To accommodate a large stroke of the stage
  - Usually in one direction
- For commutation relative position between rotor (coils) and stator (magnets) is needed!



Machine concepts: Short stroke – Long stroke

- A short stroke stage is stacked on a long stroke stage
  - Long stroke: less accurate stage
  - Short stroke
    - Small stroke (e.g. using flexures)
    - Accurate
    - Fast





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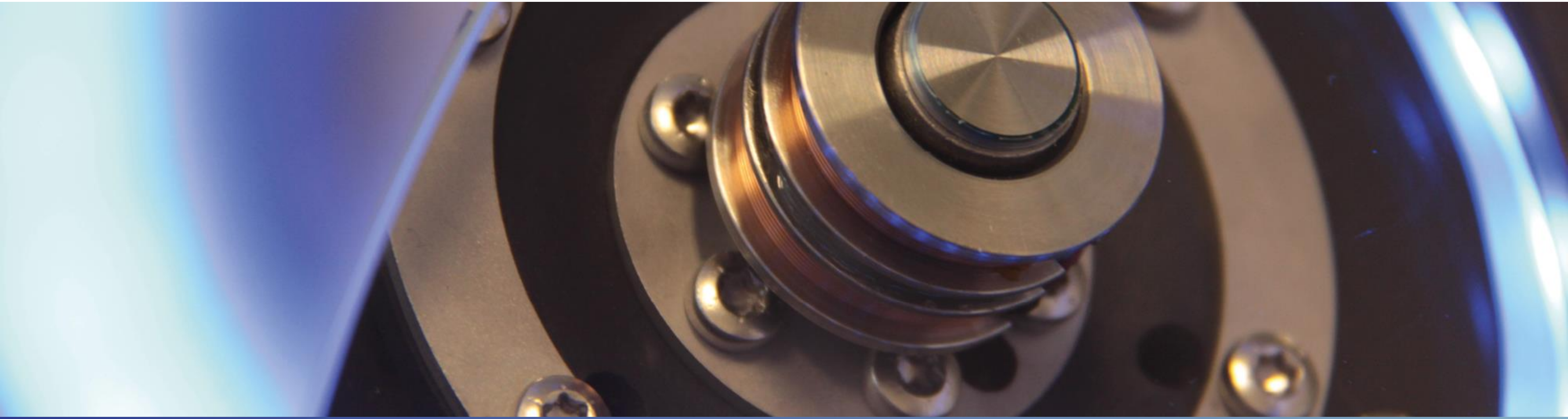

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