Aalto University
School of Engineering

Mechatronic Machine Design (MMD)

MEC-E5001,
Lecture 5

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Learning goals of this course

The student

1) can recognise mechatronic machines and analyse the fundamental functions of mechatronic machines: sensing, actuation, and control (should be already achieved and pre-exam is to check it).
2) can analyse the prevailing physics in common mechatronic machines including rigid-body mechanical systems, basic electrical systems, power transmission, and control.
3) can design and realise control systems for mechatronic machines.
4) can work in a team carrying out **design and numerical simulations of a mechatronic machine**.
5) can **evaluate scientific publications** on a selected mechatronic system
6) can report and present functionalities of the selected mechatronic machine.

HERE WE ARE!

Learning goals, this lecture, this week

Project work touches many/all learning goals

Lecture today:

1) Control synthesis for mechatronics systems
2) Prepare for the project work

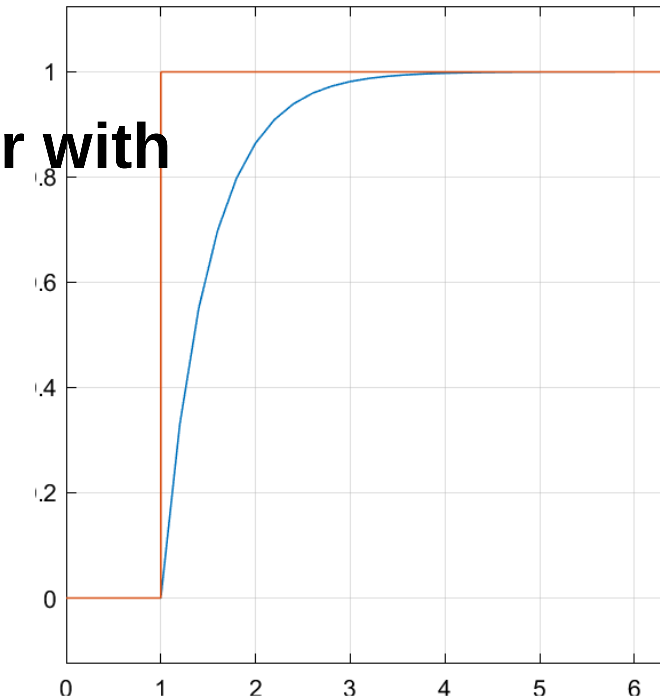
- **Discussion in groups**
- **Sharing ideas**

Exercises this week: System level simulations of mechatronic machines

Mechatronic system simulations

Simple speed control

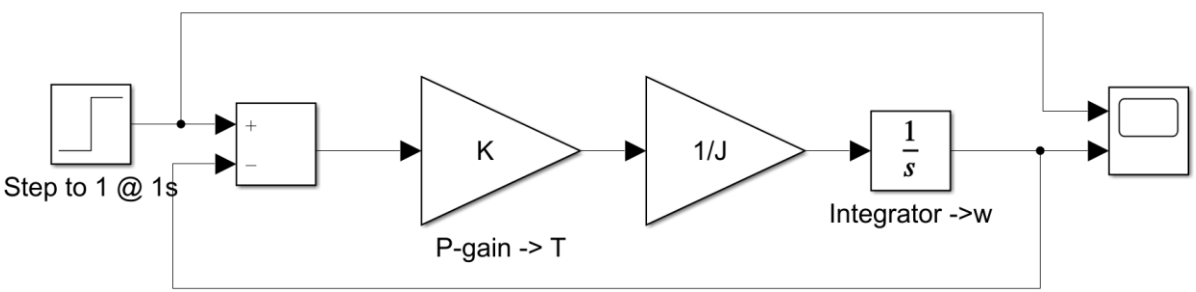
$$T = J\dot{\omega}$$
$$T = Js\omega$$



Proportional speed control of a motor with inertia

Proportional gain K=2, inertia J=1

What is time constant now?



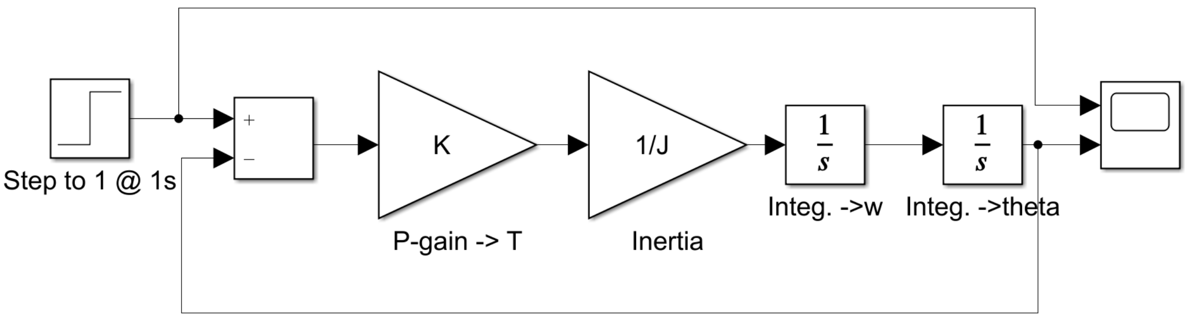
Simple position control – example on bad design

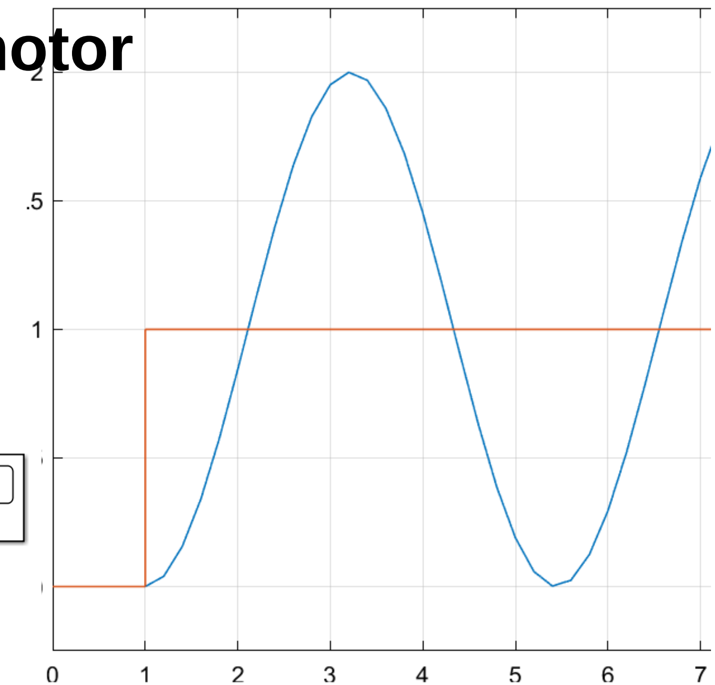
$$T = J\alpha$$
$$T = Js^2\theta$$

Proportional position control of a motor with inertia

Proportional gain K=2, inertia J=1

What is the problem here?





Find the problem in closed-loop transfer function

$$H_{cl} = \frac{CP}{1 + CP}$$

Let's analyse controller with proportional gain K_p only

Closed-loop system becomes a marginally-stable limit-cycle oscillator (see M11)

	$\frac{a}{s^2 + a^2}$	$\sin(at)$	M11

Ref: Ylén, J-P ja Virkkunen, J: Säätötekniikan harjoitustehtäviä, Otatieto 1993, (Otatieto 899)

$$H_{cl} = \frac{K/Js^2}{1 + K/Js^2} \quad \Big| \cdot s^2$$

$$H_{cl} = \frac{K/J}{s^2 + K/J}$$

Solve the problem in closed-loop transfer function

$$H_{cl} = \frac{CP}{1 + CP}$$

If we add derivative control $K_d s$, oscillator becomes damped (M9)

$\frac{1}{(s+a)(s+b)}$	$\frac{1}{a-b}(e^{-bt} - e^{-at})$	M9

$$H_{cl} = \frac{(K_d s + K)/Js^2}{1 + (K_d s + K)/Js^2} \quad \Big| \cdot s^2$$

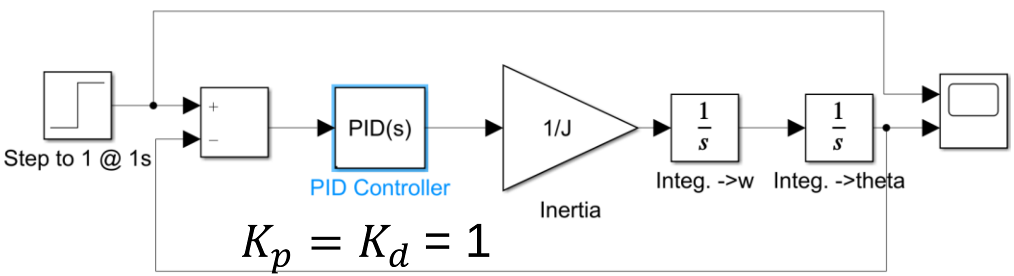
$$H_{cl} = \frac{K_d/J \, s + K/J}{s^2 + K_d/J \, s + K/J}$$

Note: roots *a* and *b* are complex conjugates

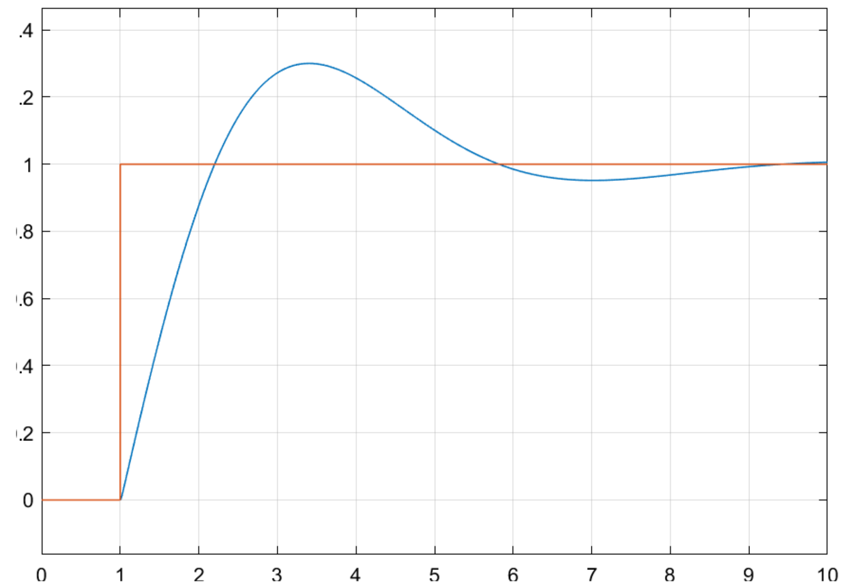
And then test by simulation

Now it works – oscillation dampens

Adding integral term in PID is not useful in this type of integrative processes



$K_p = K_d = 1$



Control under a known disturbance

Noise-cancelling headphones use incoming noise to minimize noise in human ear

The same idea has been used in several applications

- **Rotor vibration control**
- **Machining non-circular workpieces in lathe**
- **Airplane fuselage noise control**
- **Surgery of a beating heart!**
- **…**

Example on active rotor vibration control

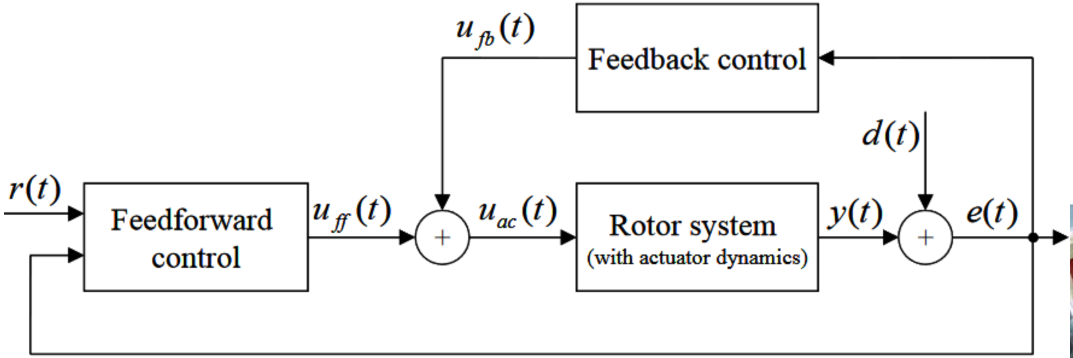


Figure 5. The feedback and feedforward controllers with the rotor system.

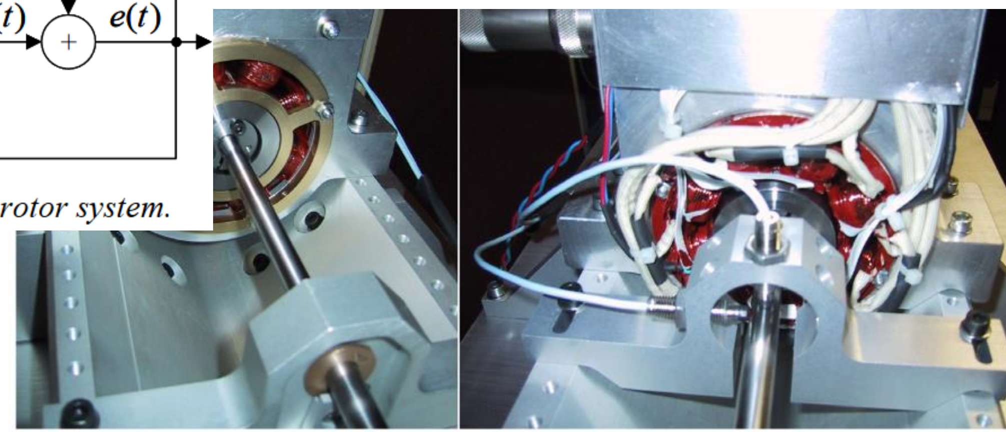


Figure 11. Left: the actuator seen from the drive end (in the collocated layout). The backup bearing is mounted in front of the coils. Right: the actuator seen from the non-drive end; the eddy current displacement transducers are located at the front.

If spectral content of *r*(*t*) **and** *d*(*t*) **are the same, error** *e*(*t*) **goes zero**

Ref: Tammi. *Active control of radial rotor vibrations.* 2007

Anti-sway control problem

Background information for anti-sway control

Video: https://www.youtube.com/watch?v=zs_xAxEOqeU

In project work, you are asked to derive the equations of motion for the crane trolley and pendulum

Luckily we know the answer! (see tips in this slide set)

Tips for anti-sway control – equations of motion

1. **Study Lagrangian approach to derive equations of motion – see project work material on mycourses**
2. **Derive non-linear equations of trolley and payload**
3. **Linearize the equations**
   - Approximation of sin & cos
4. **Equations to be achieved:**

$\cos(\theta) \approx 1, \sin(\theta) \approx \theta$
when $\theta \approx 0$

$$(m_1 + m_2)\ddot{x} + m_2 l\ddot{\theta}\cos(\theta) - m_2 l\dot{\theta}^2\sin(\theta) = F$$

$$l\ddot{\theta} + \ddot{x}\cos(\theta) + g\sin(\theta) = 0$$

Tips for anti-sway control – solve a differential equation by basic Simulink blocks

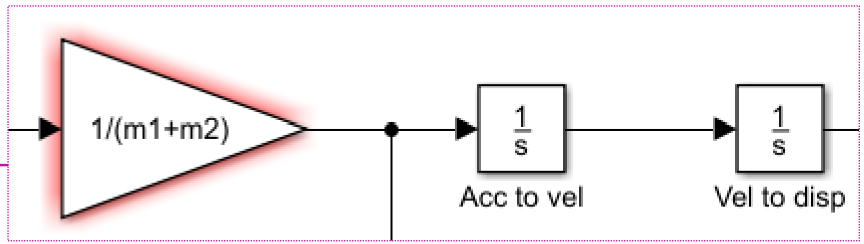
Linear models are easiest to construct from existing (transfer function) blocks

Non-linear models or other motivation to tweak model → derive equation and construct from basic blocks

Start from integrator (integral term left, the rest right in equation)

Tips for anti-sway control – model topology for control design

1. **Draft the Simulink model**
   - Non-linear model: start from double integrator
   - Linear model: use transfer function block
2. **Draft the control strategy**
3. **Draft control systems you need on block level**
4. **Recognise oscillatory behaviour and design controller**



Snapshot on Simulink model

Group work (and lecture quiz)

Group work & lecture quiz 5

Discuss with your pair. Write down your answers and use them to answer lecture quiz today.

1. Google and study noise-cancelling headphones (1 point)

2. If you know the disturbance, how can you compensate it?

3. Determine resonance frequency and roots of characteristic polynomial of position servo control $K = K_d = 2$, $J = 1$. Tip: analyse denominator (1 point)

$$H_d = \frac{K_d/J\, s + K/J}{s^2 + K_d/J\, s + K/J}$$