University of Twente
The Netherlands

Control Laboratory

Review
Realistic Example

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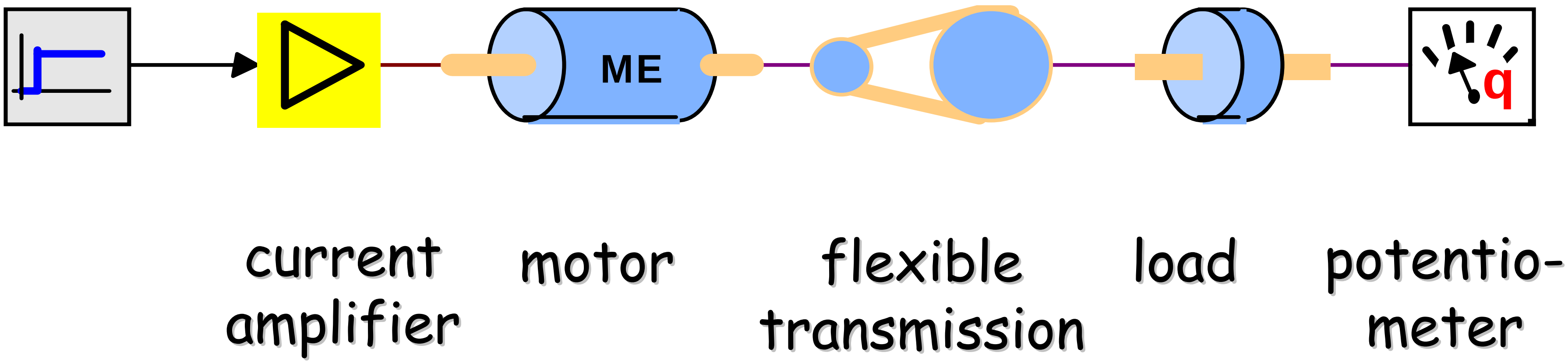
Contents

- Design of controllers for a realistic servo system
- Fourth order servo system
  - Tacho feedback
  - Saturation

Example of lecture 2



Example of lecture 2

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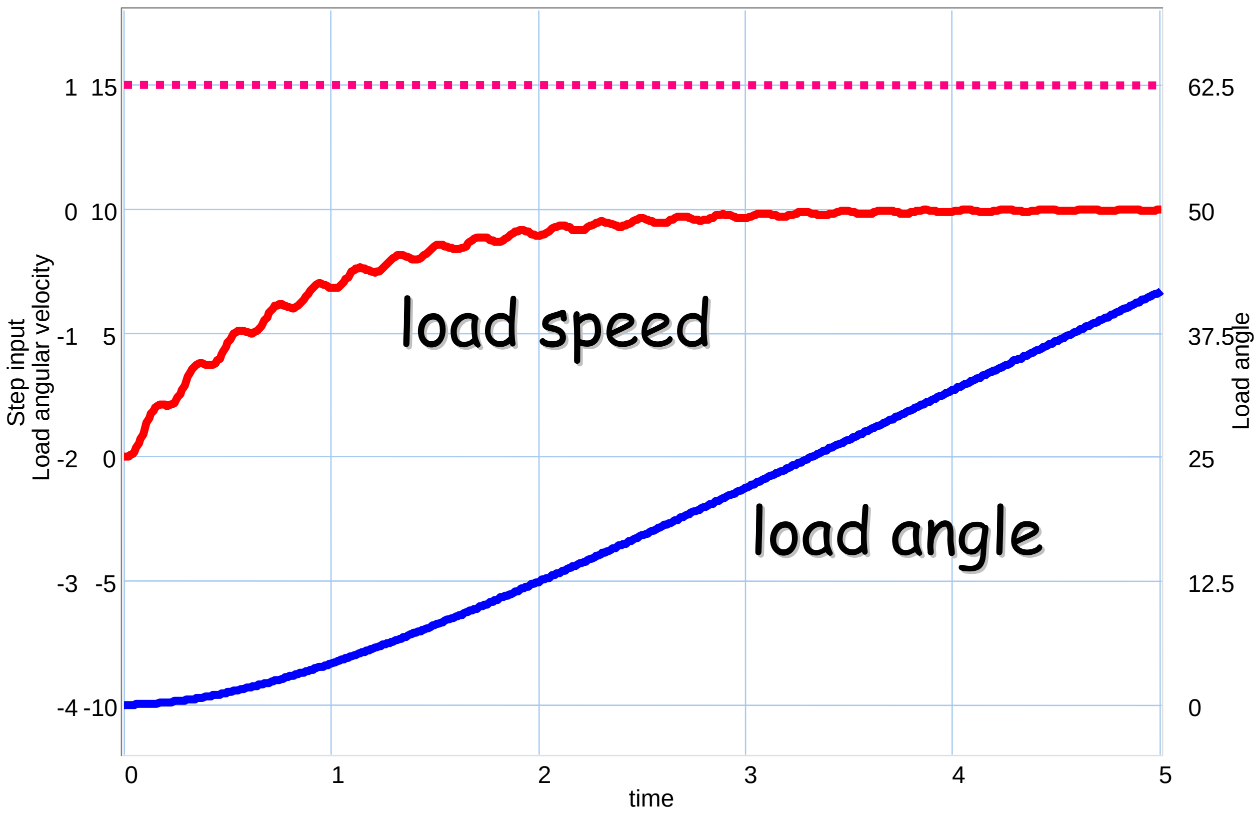
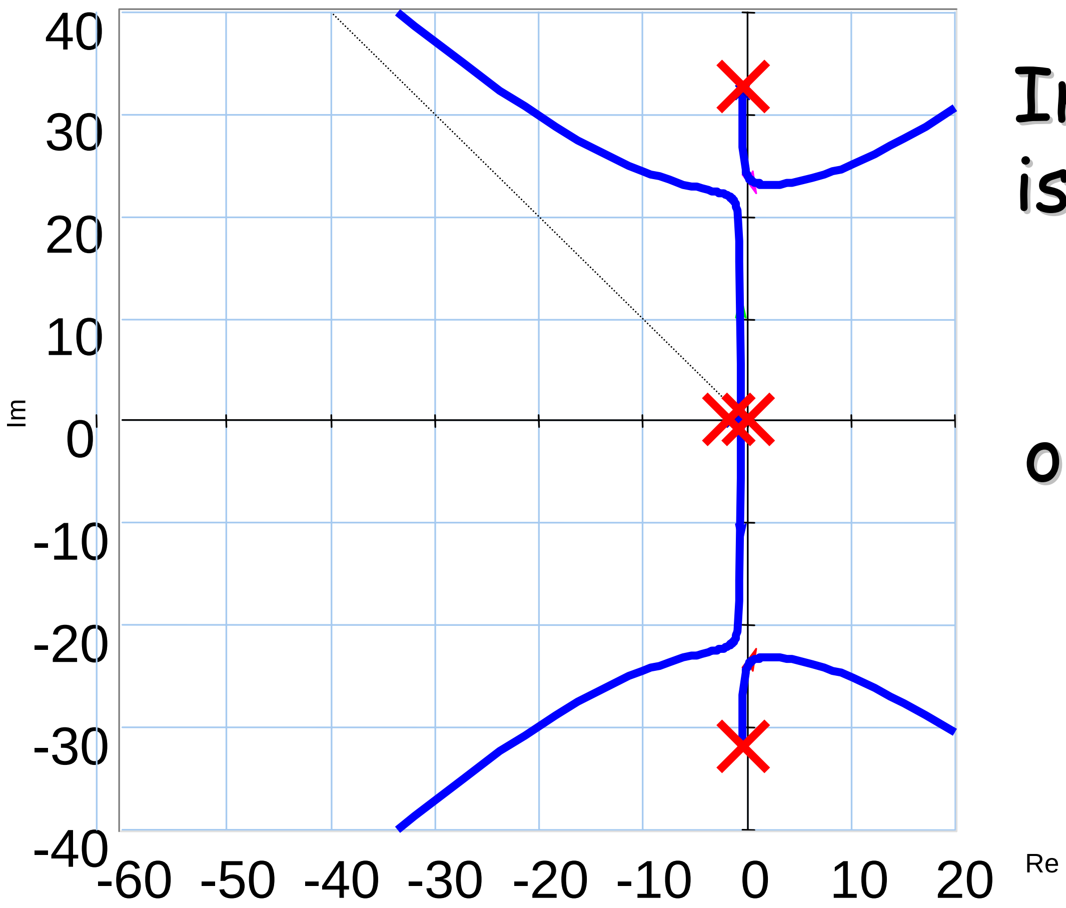


A_Model_for_identification.em

Linearise in 20-sim



In practice this option is not always available:

Black Box modelling
or Grey Box modelling

Bode plot

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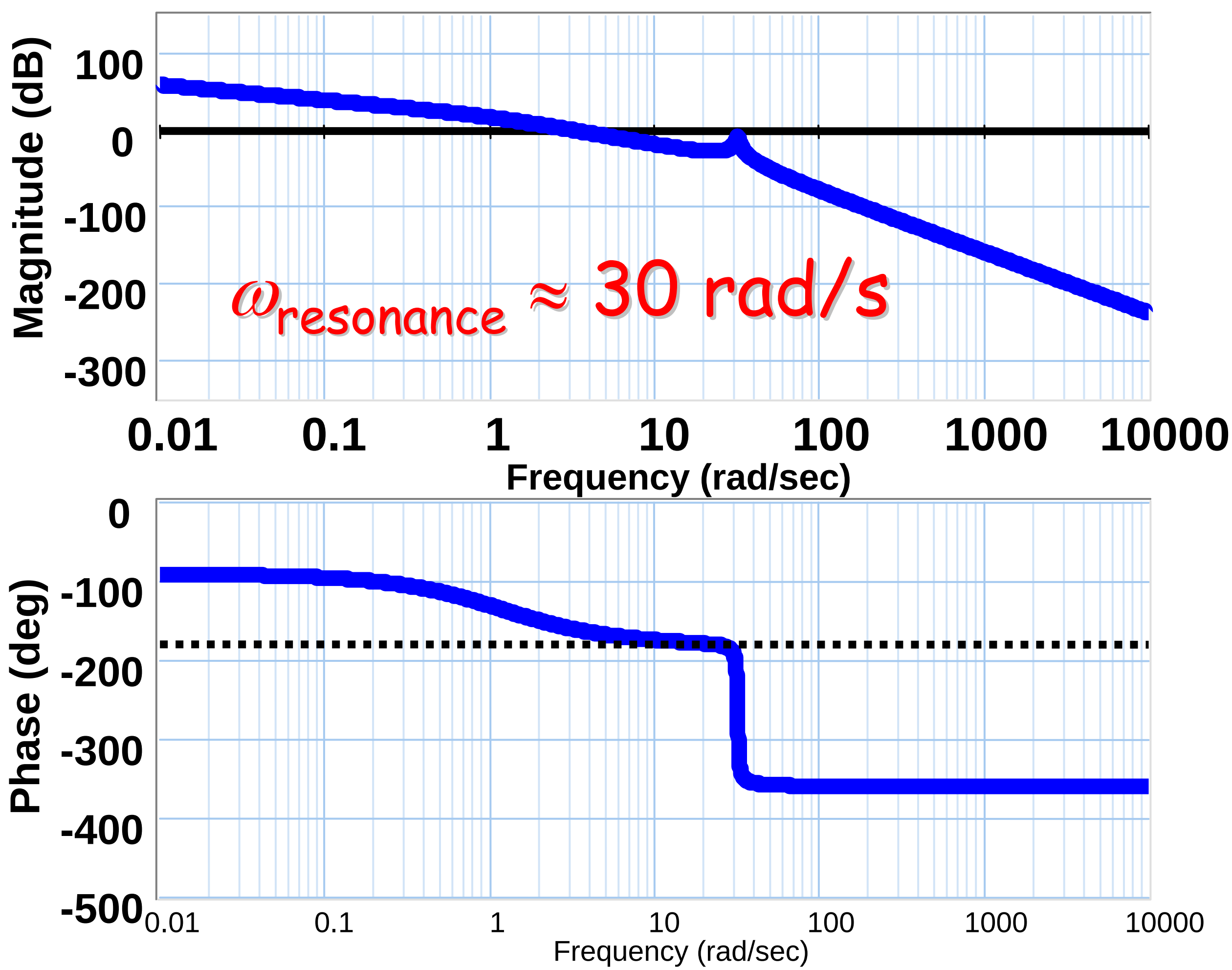
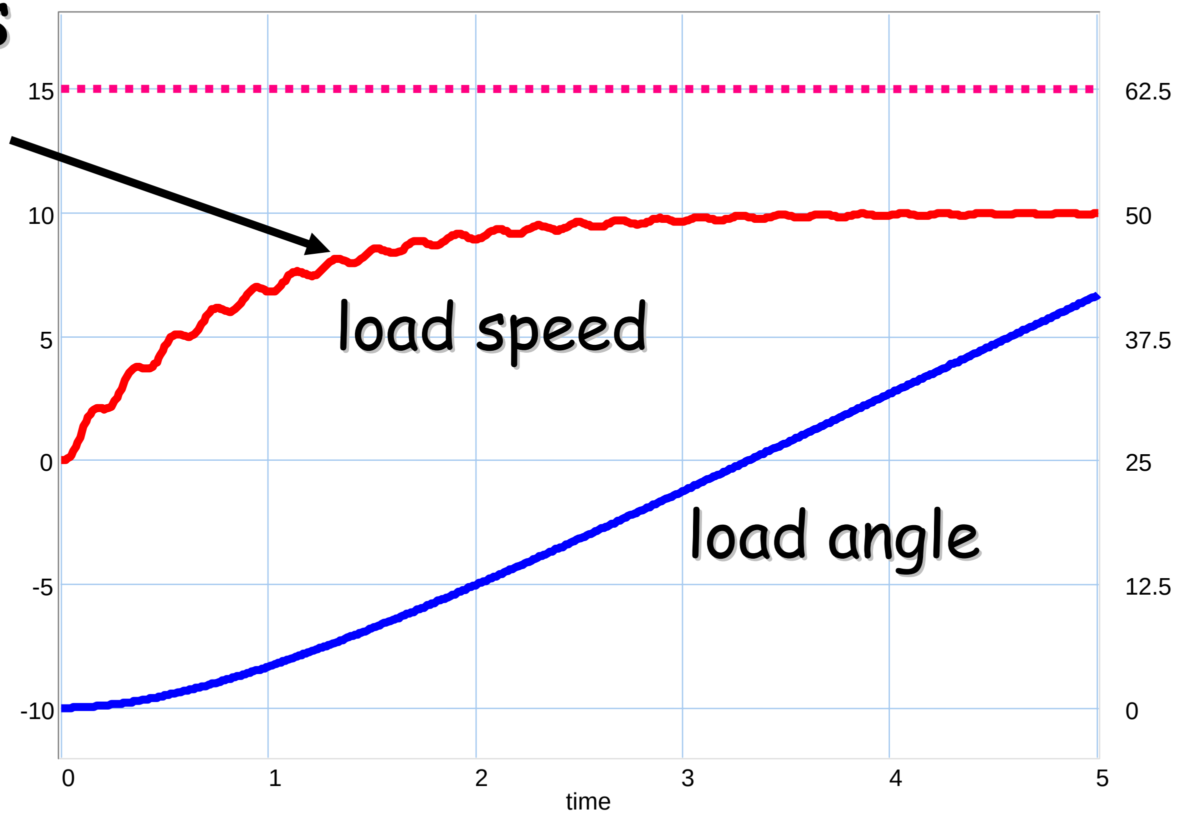


Example of lecture 2

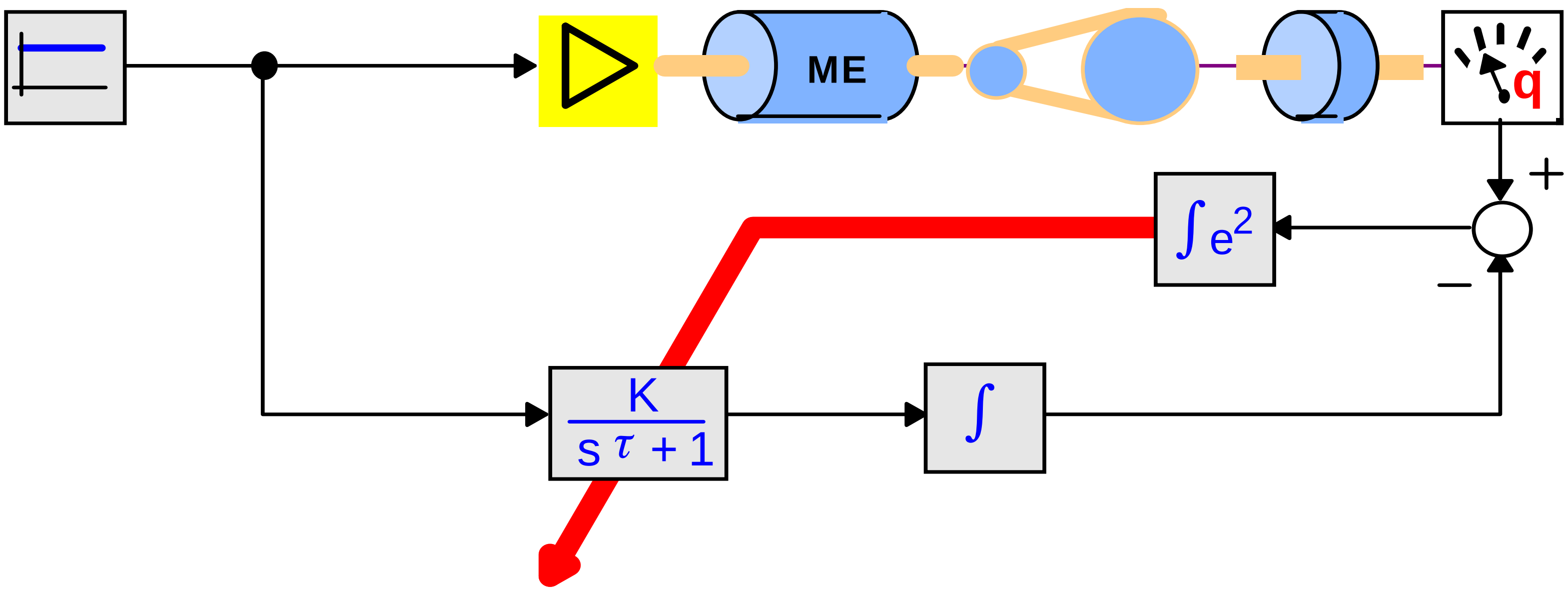
$T_{resonance} \approx 0.2$ s

$\omega_{resonance} \approx 30$

Response of load angle suggests poles in 0 and -a



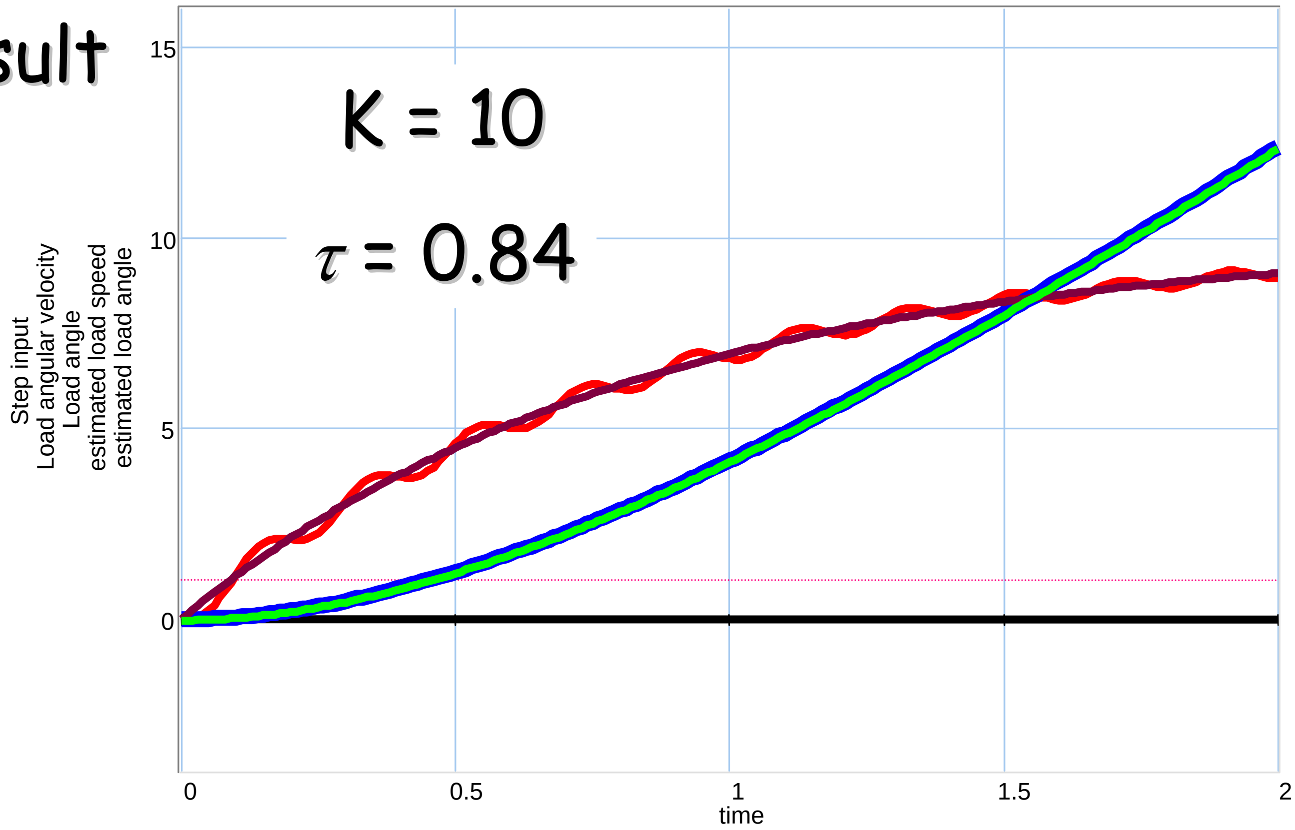
Identification experiment



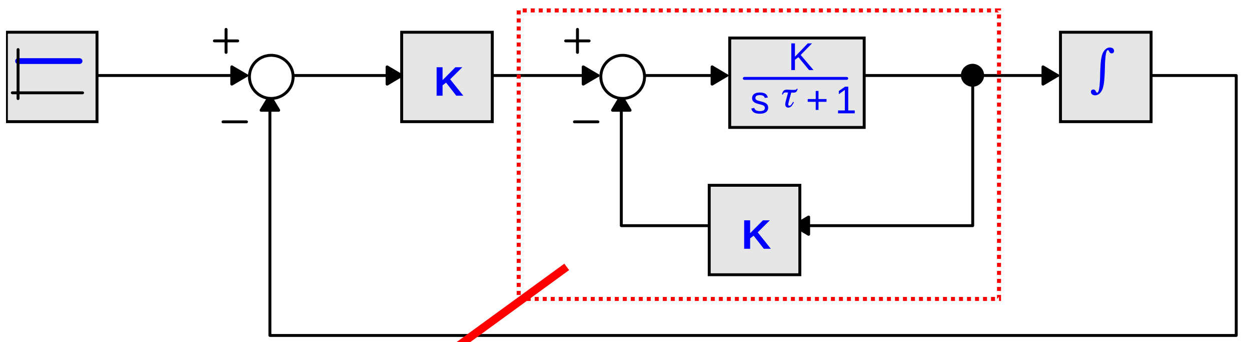
A1_Model_for_(exp)_identification.em

Identification experiment

Result



Proposed control structure



$$\frac{K'}{s+a+K'K_d}$$

$$\frac{K'K_p}{s\left(s+a+K'K_d\right)+K'K_p}$$

$$-\frac{1}{K_d}=\frac{K's}{s\left(s+a\right)+K'K_p}$$

$$-\frac{1}{K_p}=\frac{K'}{s\left(s+a\right)}$$

Root locus K_p

$$-\frac{1}{K_p} = \frac{K'}{s(s+a)}$$

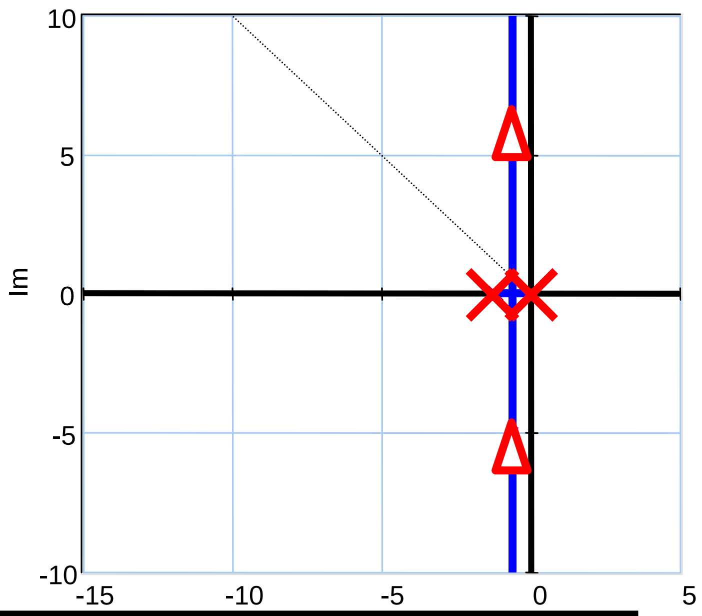
$a = -1.2$

$K' = 10 \cdot 1.2 = 12$

Stay away from the resonance frequency (30 rad/s):

e.g. ω_n = 6 rad/s

$K_p \approx 36/12 = 3$



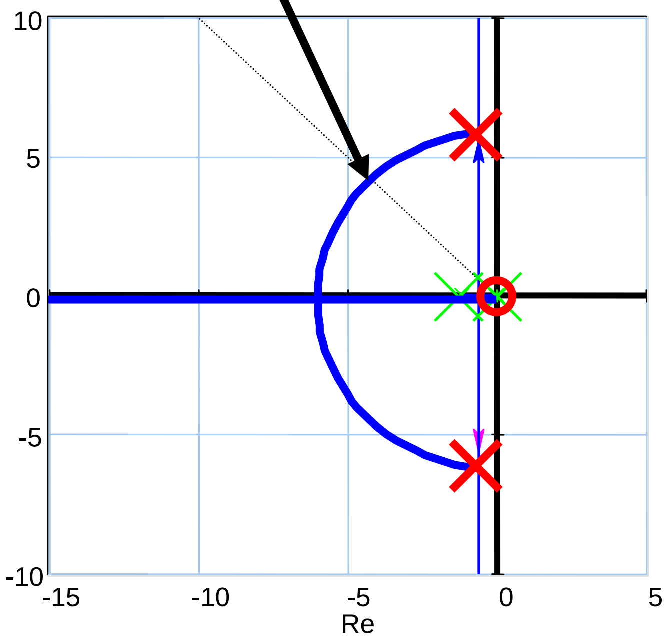
Design goal based on mechanical limitations

Root locus K_d

$$-\frac{1}{K_d} = \frac{K's}{s(s+a)+K'K_p}$$

In a similar way
we can find
for K_p = 4
K_d = 0.8
(ω_n = 7 rad/s)

$K_d \approx 0.6$



Response of 'ideal' system

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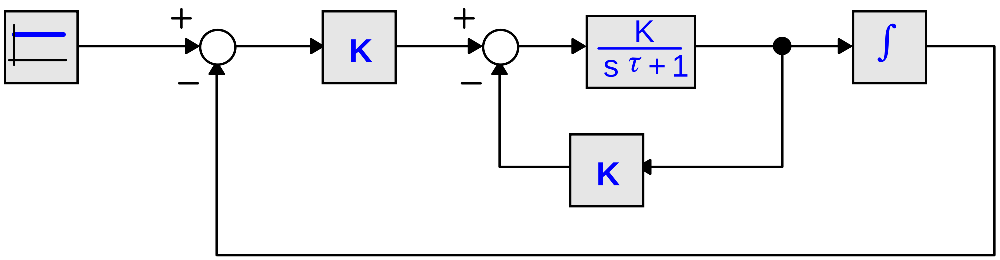
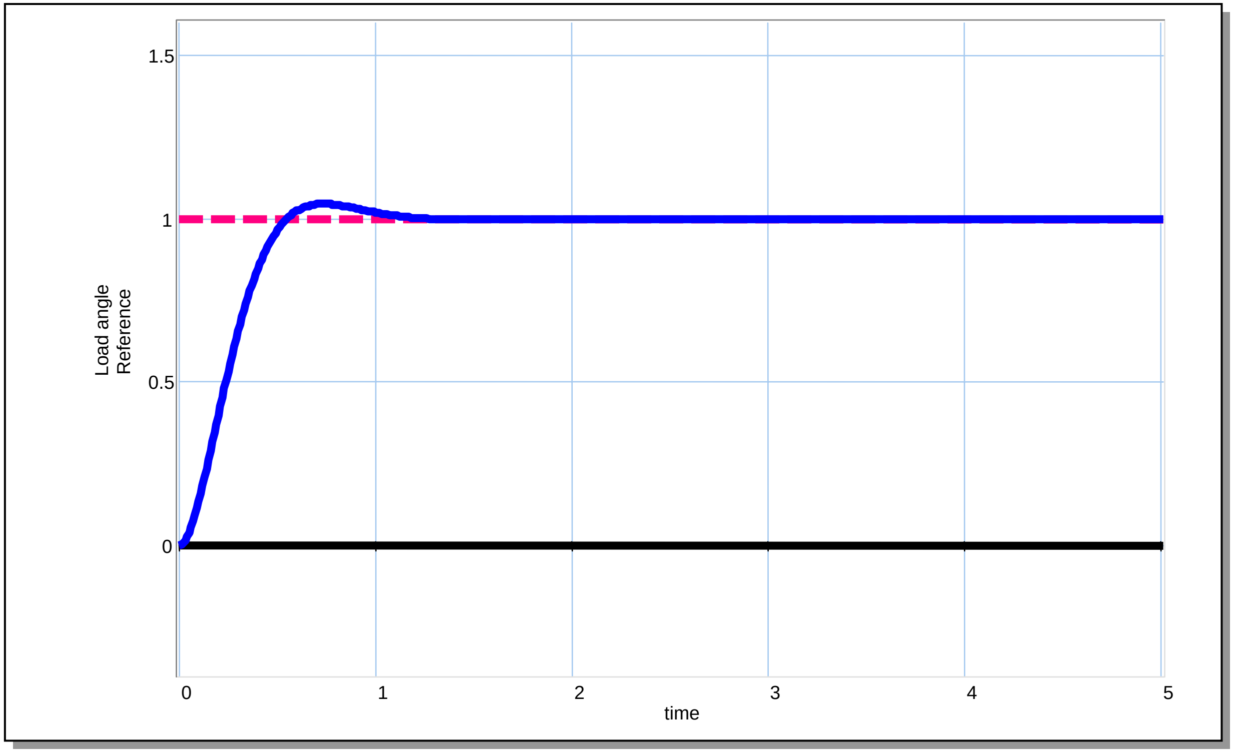


$K_p = 3$
$K_d = 0.6$



A2_Prop_plus_tacho_FB_exp_model.em

Alternative design

- Use state space representation and select ω_n (factor 5 smaller than resonance frequency) and desired z

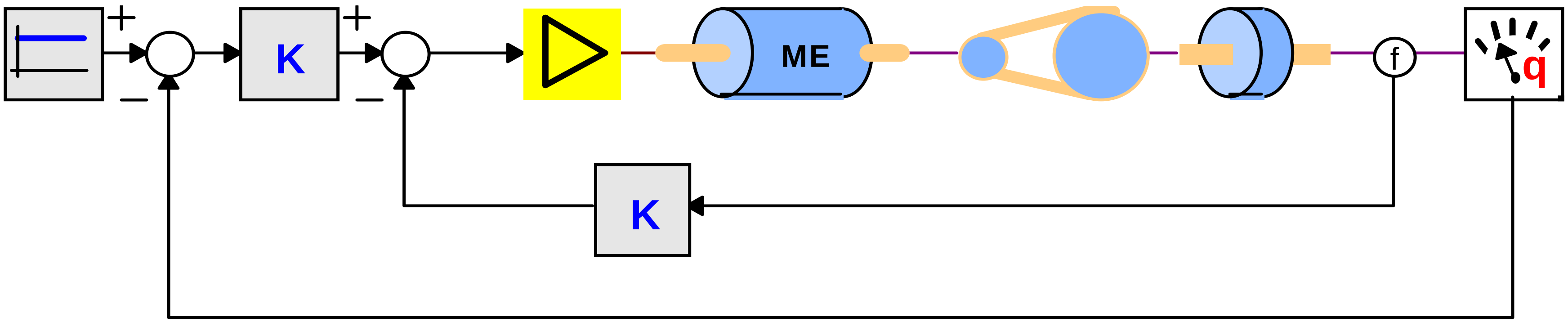
$$A' = \begin{pmatrix} 0 & 1 \\ -K'K_p & -a - K'K_d \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\omega_n^2 & -2z\omega_n \end{pmatrix}$$

$$A' = \begin{pmatrix} 0 & 1 \\ -12K_p & -1.2 - 12K_d \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -36 & -8.4 \end{pmatrix}$$

$$K_p = 3$$

$$K_d = 0.6$$

In “real” system



A3_Prop_plus_tacho_FB_real_model.em

Response of ‘real’ system

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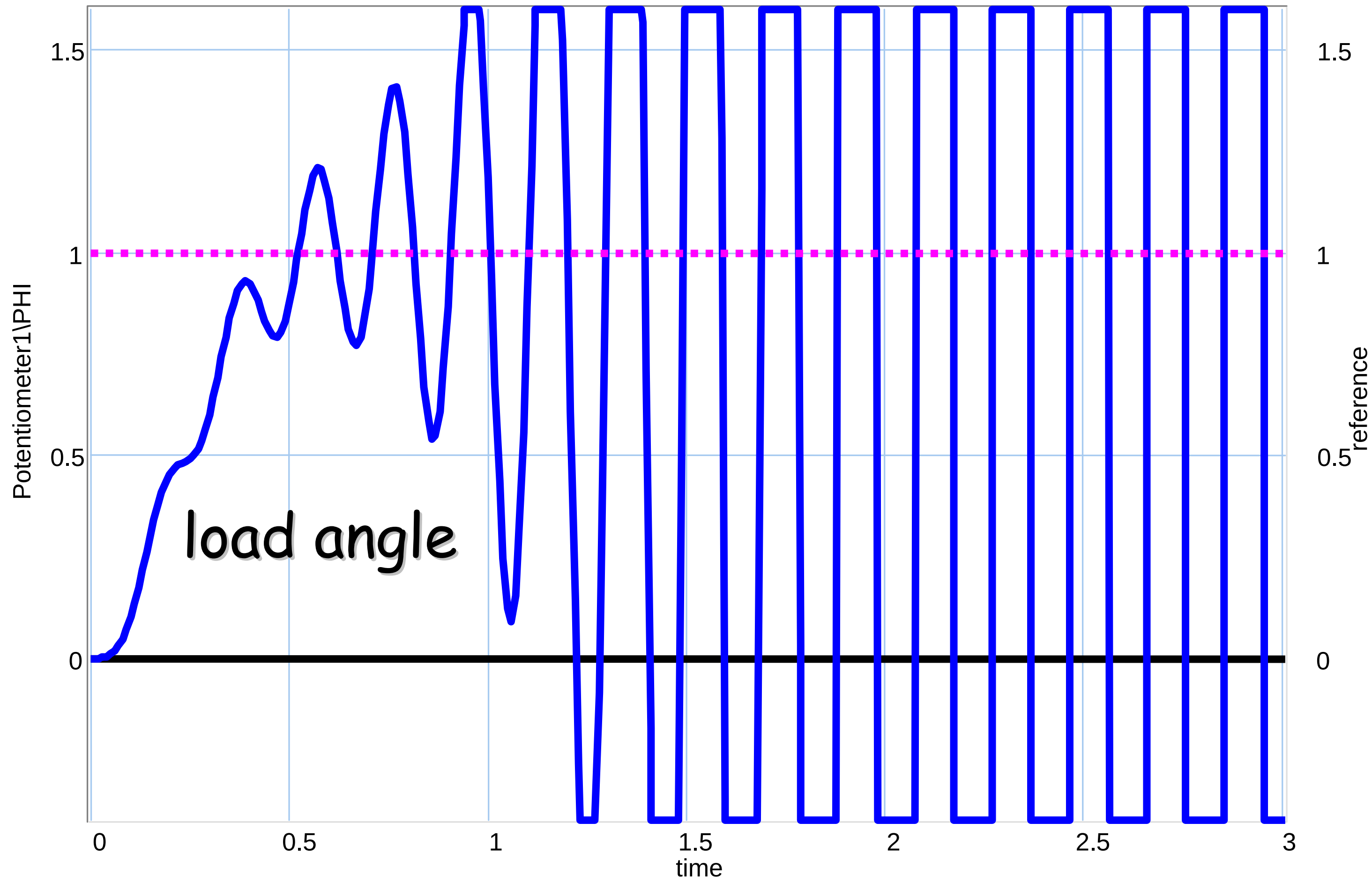
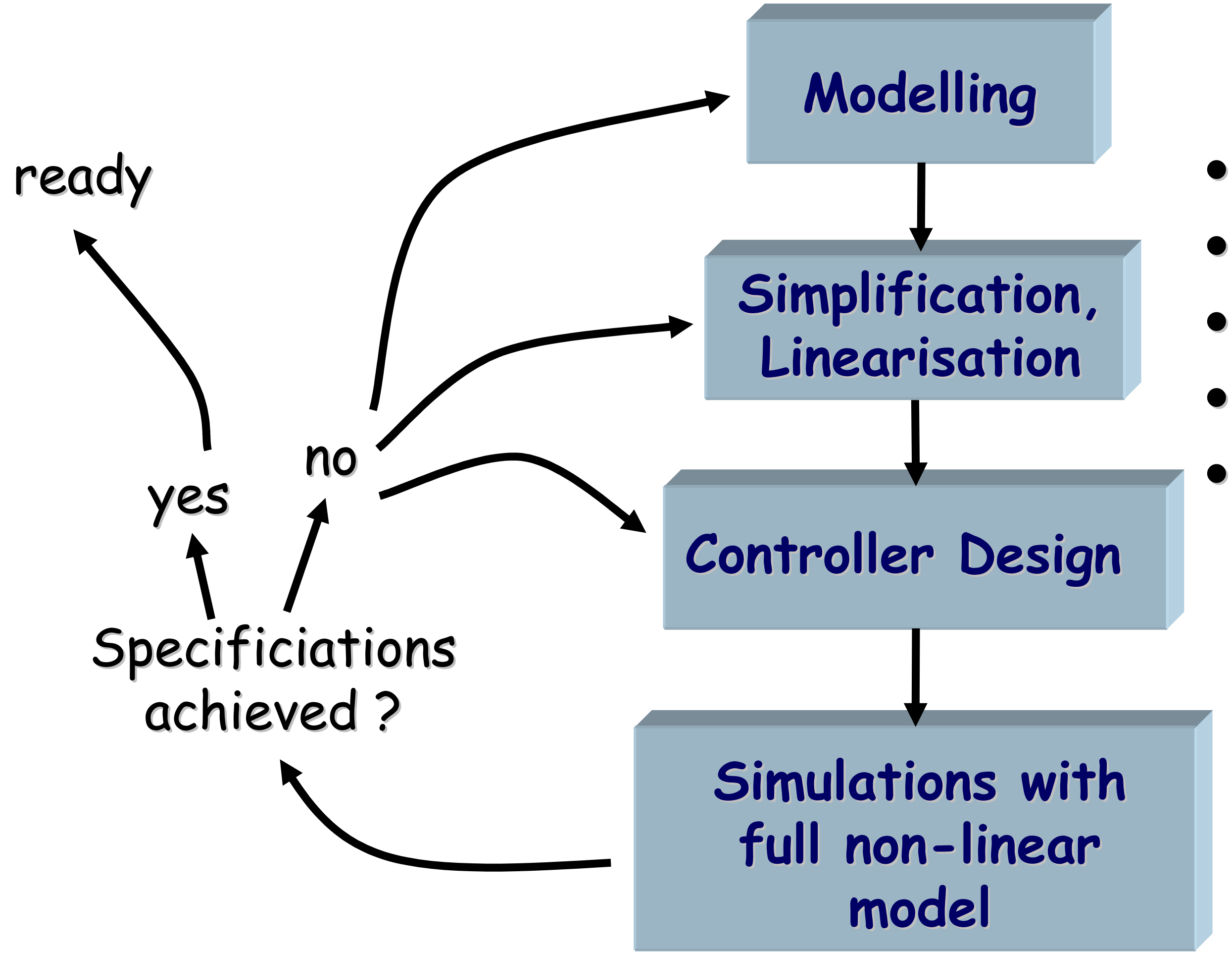


Design issues (from lecture 1)



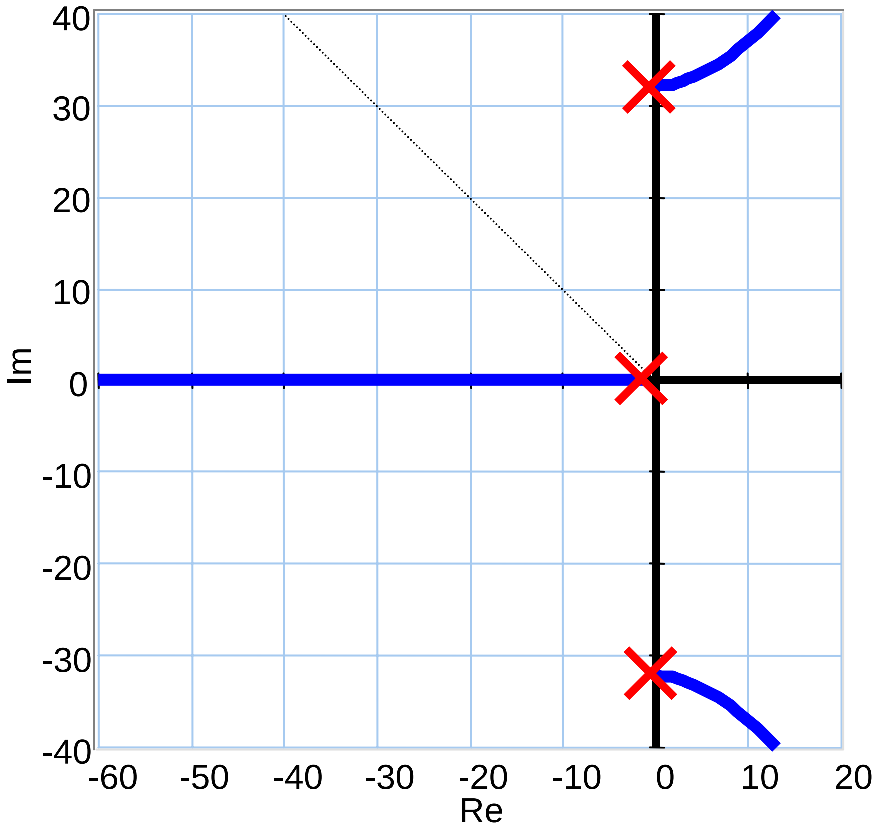
- speed of response
- bandwidth
- stability
- overshoot
- sensitivity for disturbances and parameter variatons

Tacho feedback in “real” system

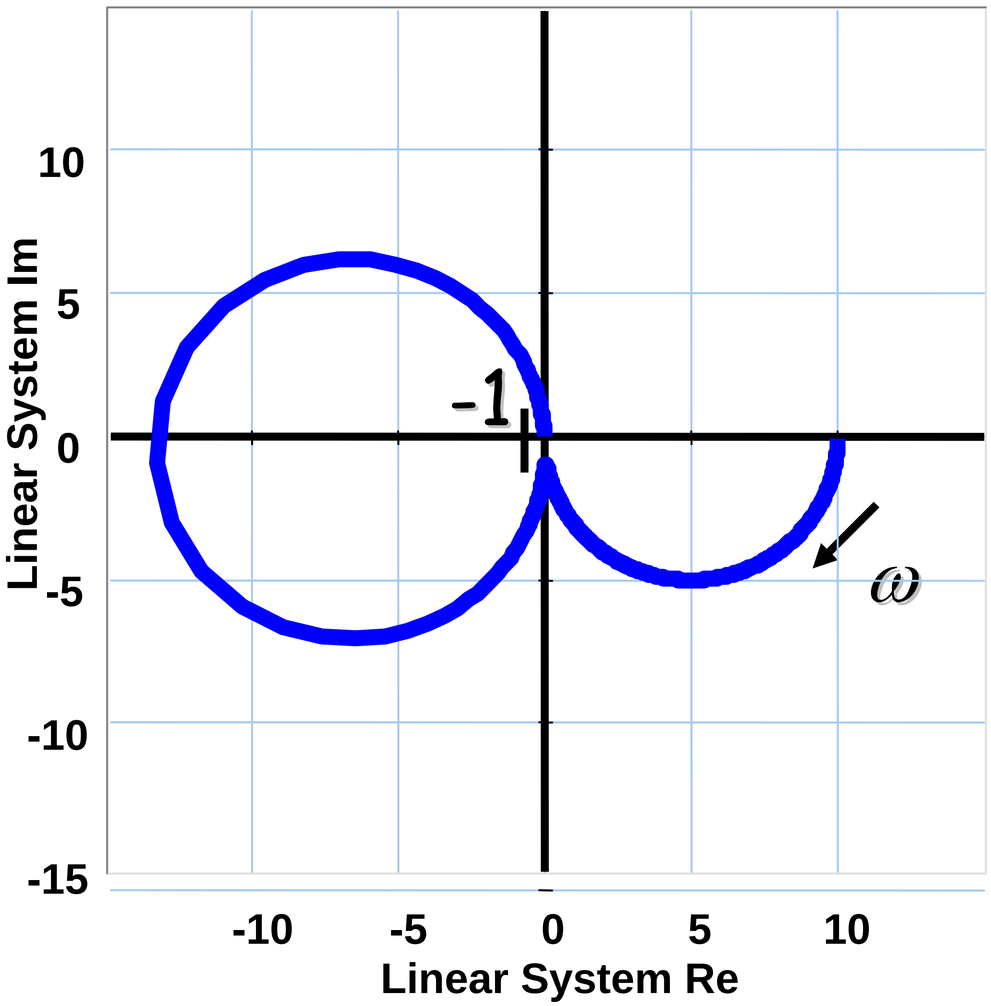
A_Model_for_identification.em

(tacho -feedback)

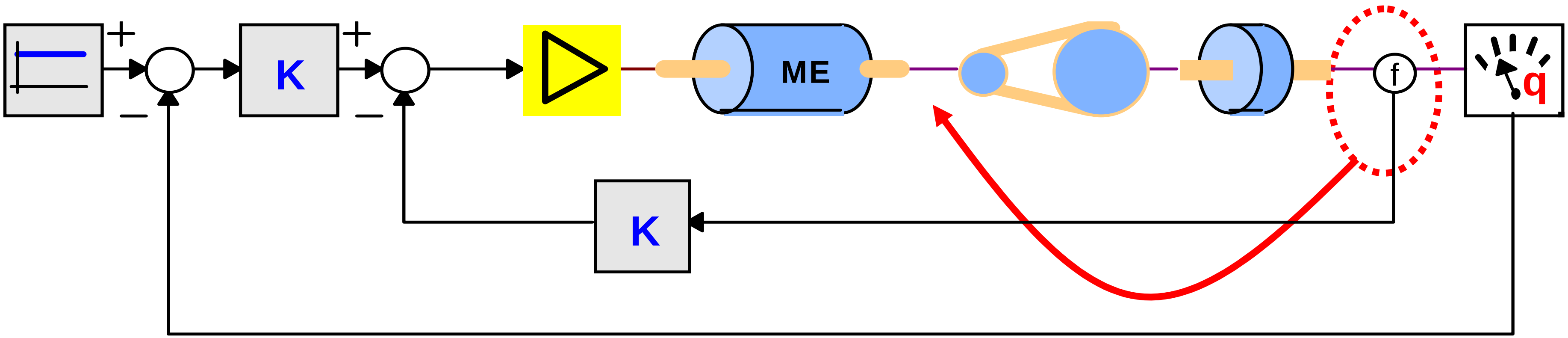
Due to (disregarded) complex poles, tacho feedback of no use here



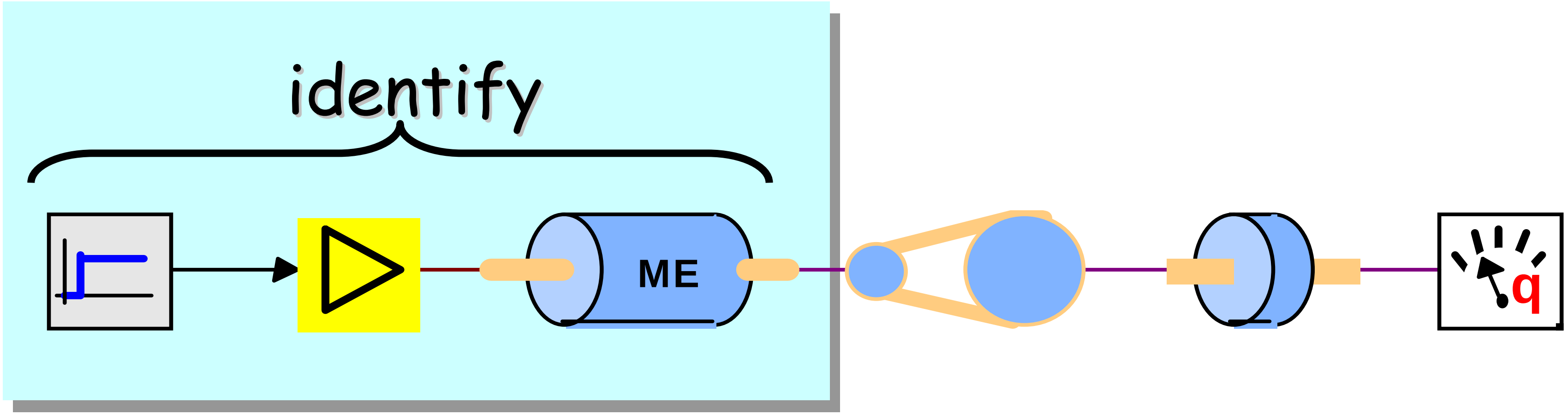
Nyquist



Alternative tacho feedback



New linearisation

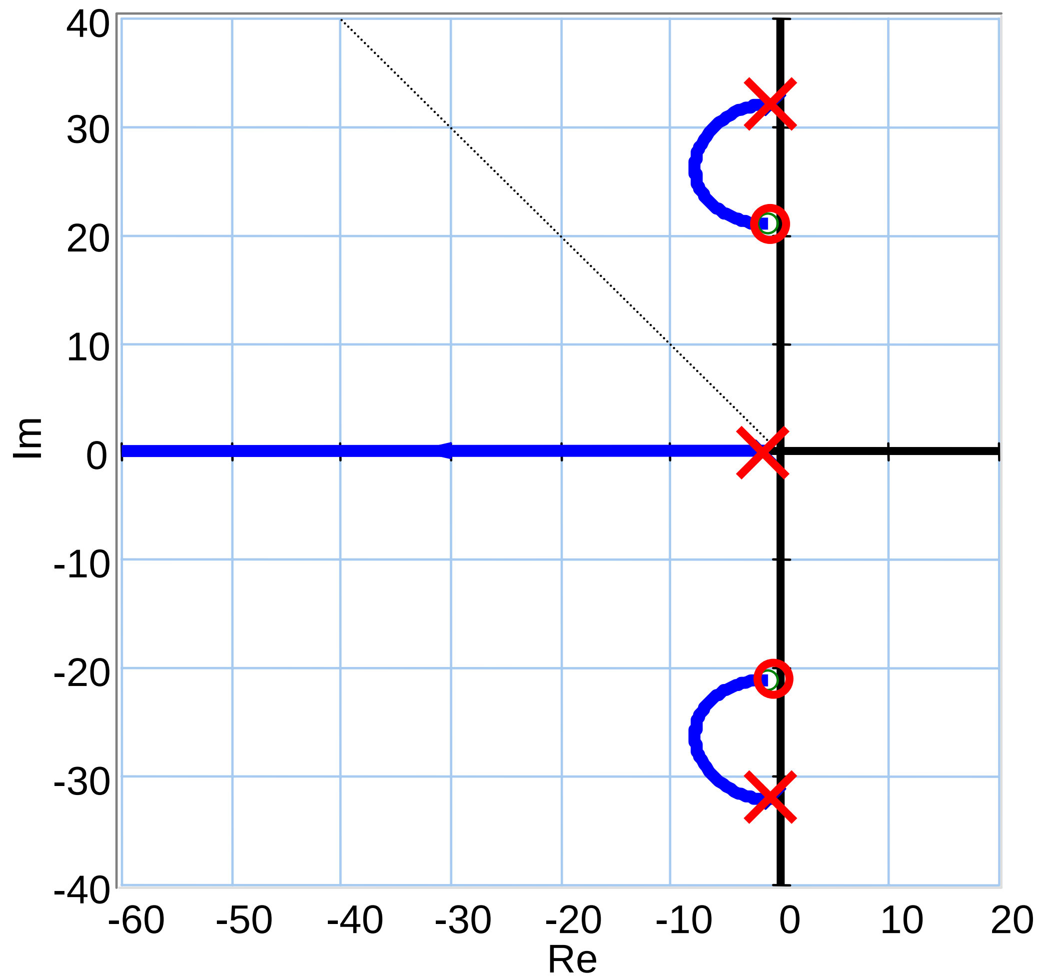


A_Model_for_identification.em

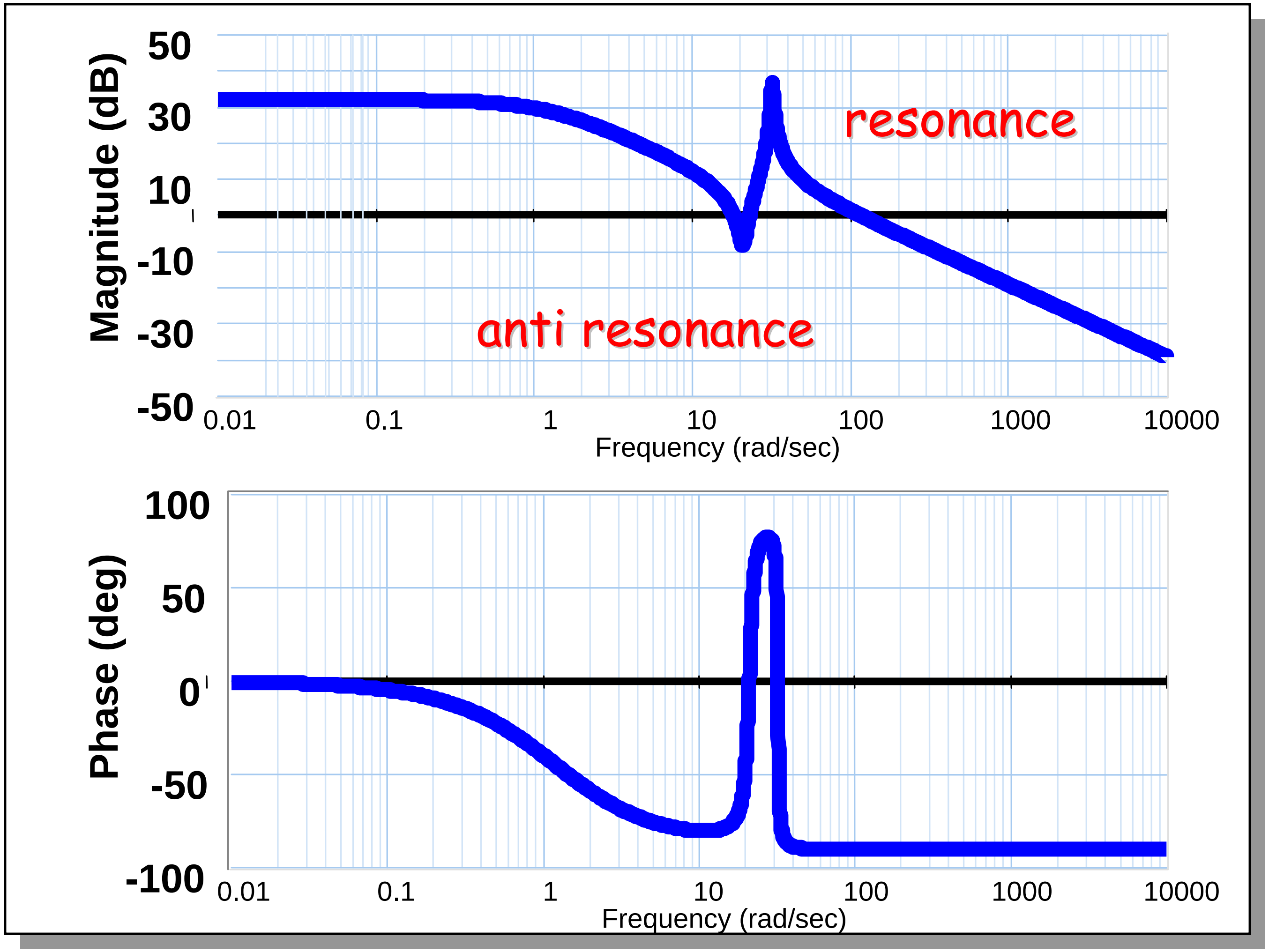
This helps !

Complex poles now compensated by complex zeros

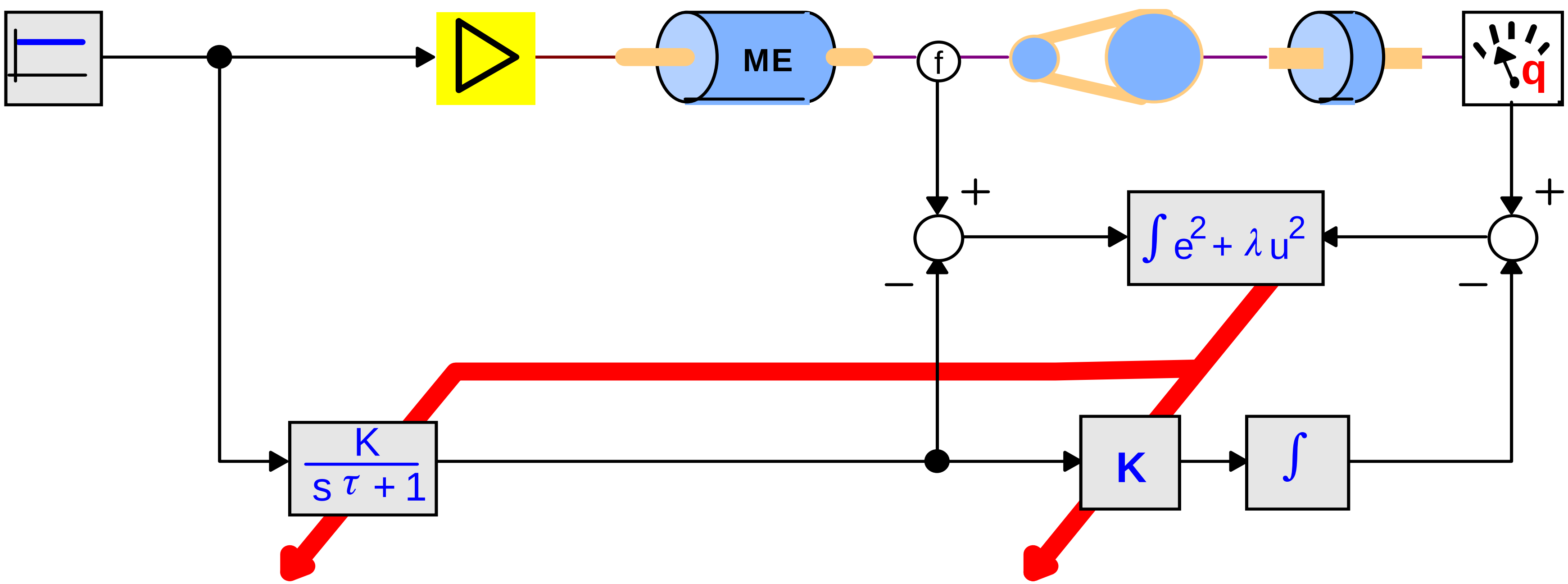
On real axis tacho feedback does what it is expected to do !



Bode

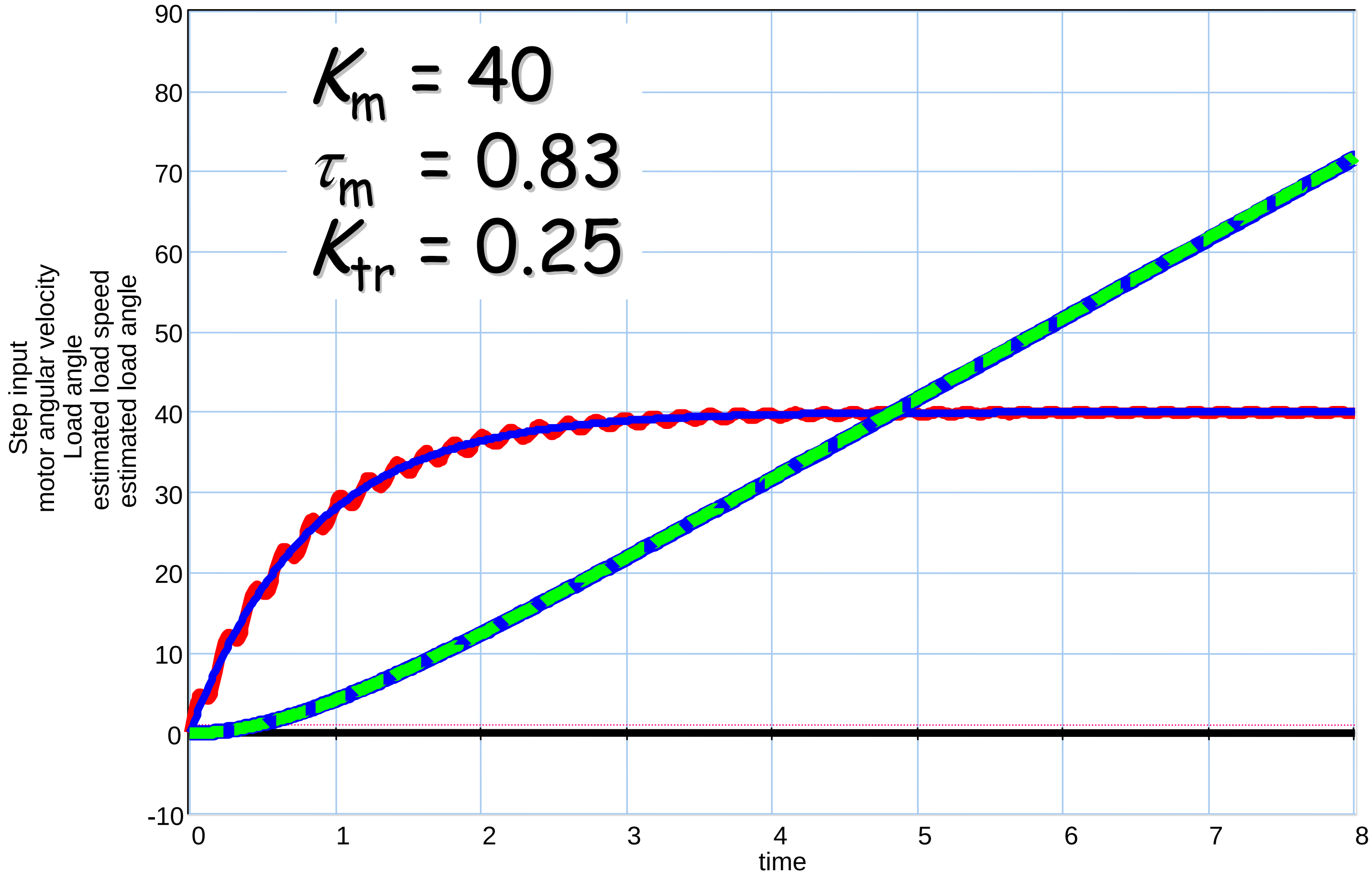

50
30
10
-10
-30
-50
Magnitude (dB)
resonance
anti resonance
0.01
0.1
1
10
100
1000
10000
Frequency (rad/sec)
100
50
0
-50
-100
Phase (deg)
0.01
0.1
1
10
100
1000
10000
Frequency (rad/sec)

Experiment



A4_Model_for_(exp)_identification_motor_tacho_FB.em

Identification result



Redesign of controller

We found before:

$K_p = 3$
$K_d = 0.6$

or

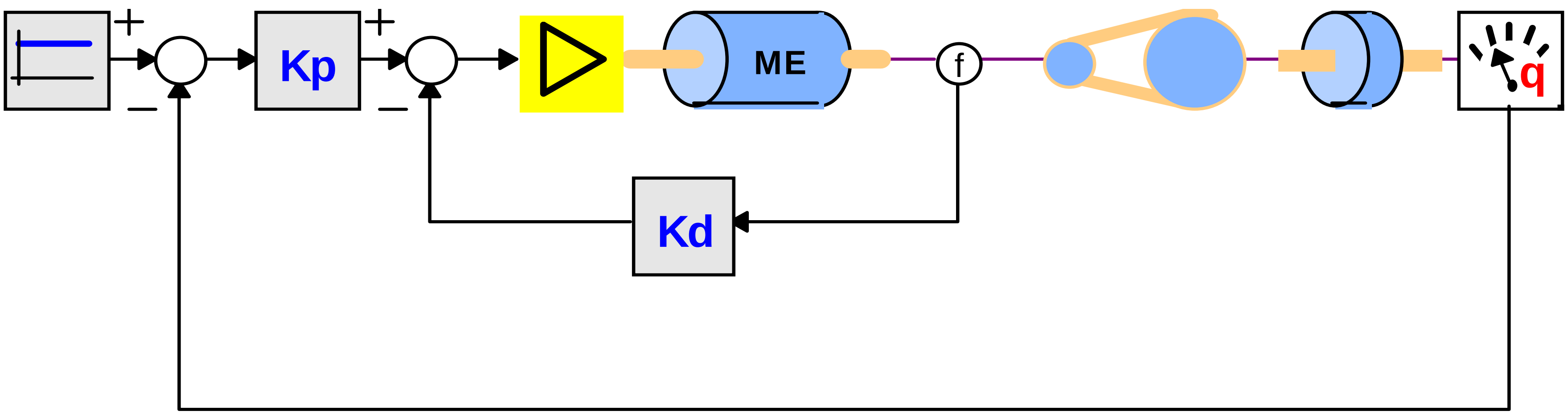
$K_p = 4$
$K_d = 0.8$

Because gain from input to motor is 4 times higher,

$K_{d,m} = 0.6/4 = 0.15$ (0.2)

$K_p = 3$ (4)

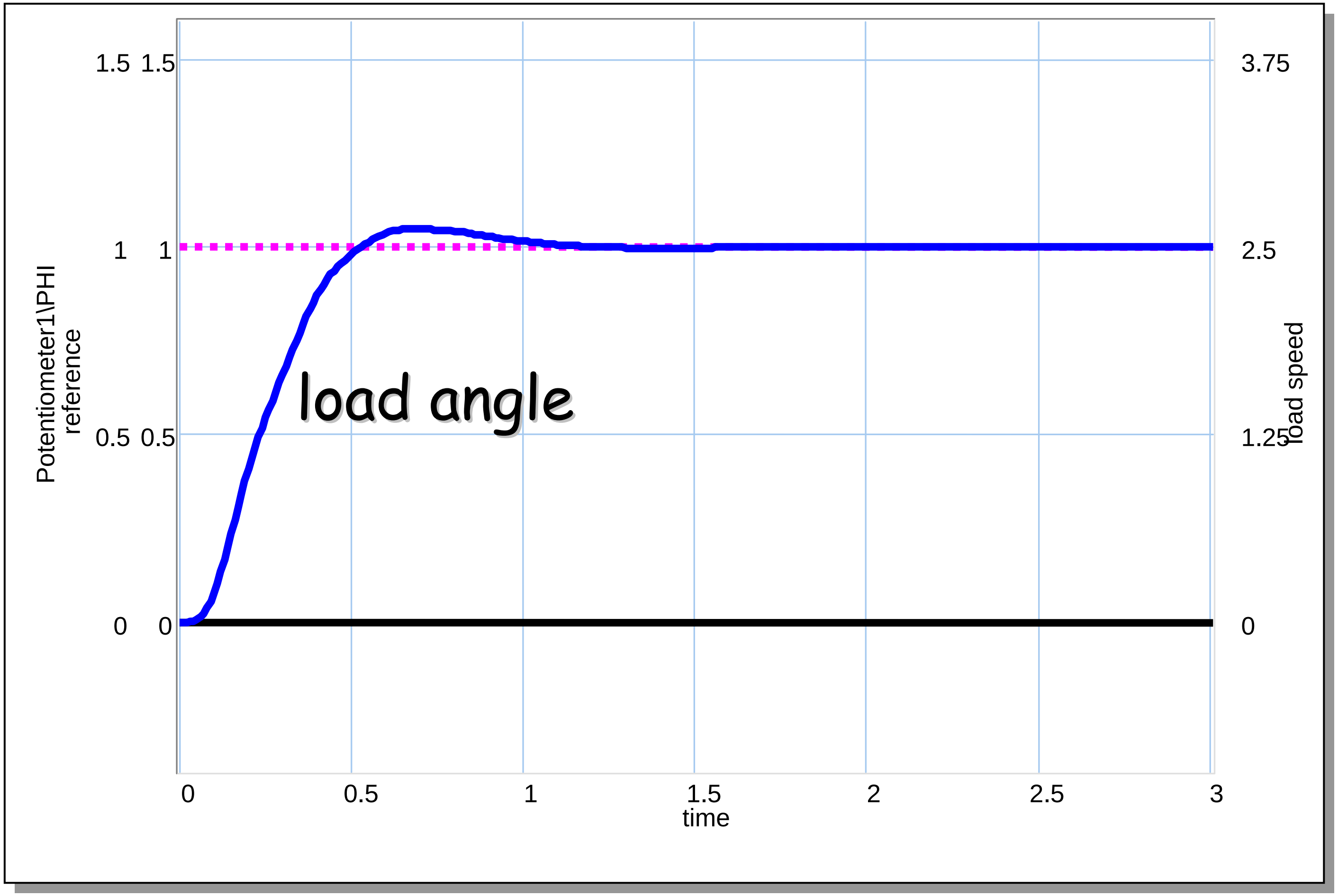
Result in ‘real’ system



C_Prop_plus_Tacho_feedback.em

Stepresponse

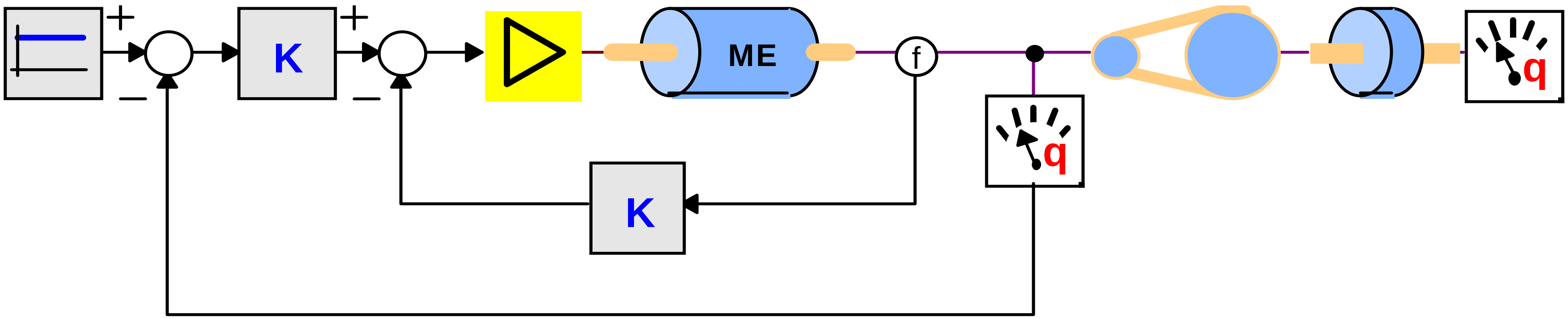
$K_p = 3$
$K_d = 0.6/4$
$= 0.15$



Tacho feedback

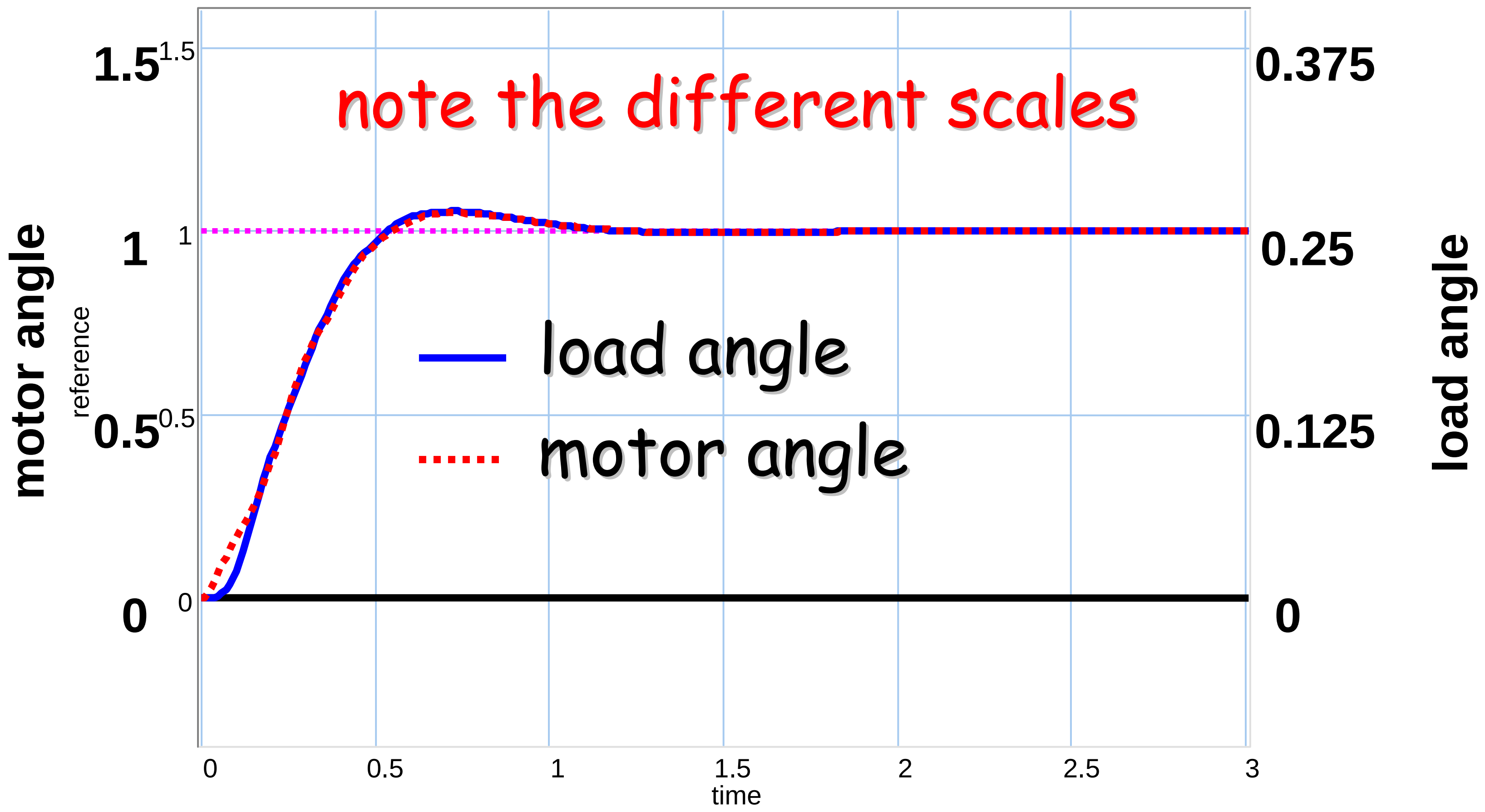
- Tacho feedback should always be based on the motor speed
- Tacho feedback of the load leads in a system with resonant poles easily to an unstable system

Motor feedback only



C1_Prop_plus_Tacho_feedback_motor_only.em

Responses


note the different scales
load angle
motor angle
motor angle
reference
load angle
1.5
1.5
1
1
0.5
0.5
0
0
0.375
0.25
0.125
0
0
0.5
1
1.5
2
2.5
3
time

Lead network

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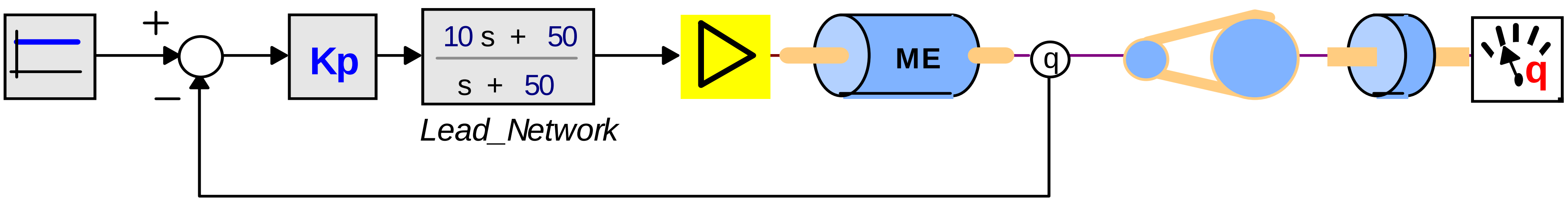
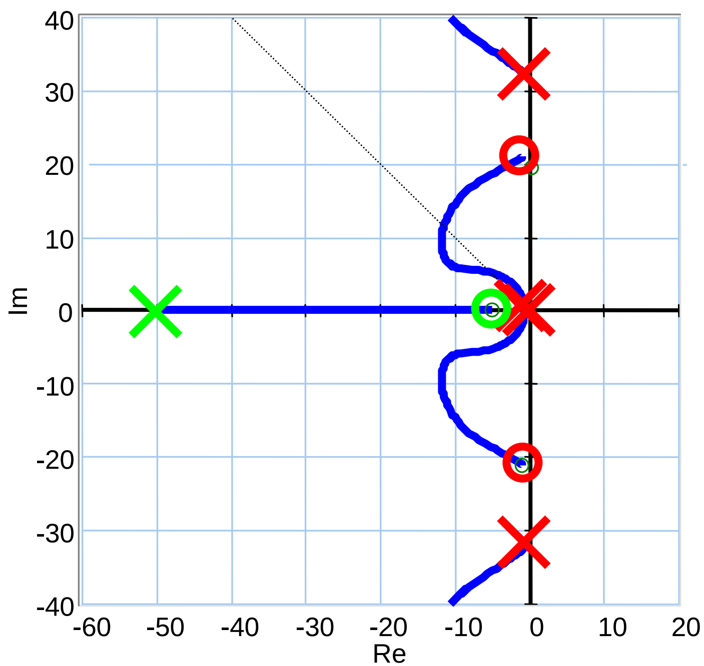


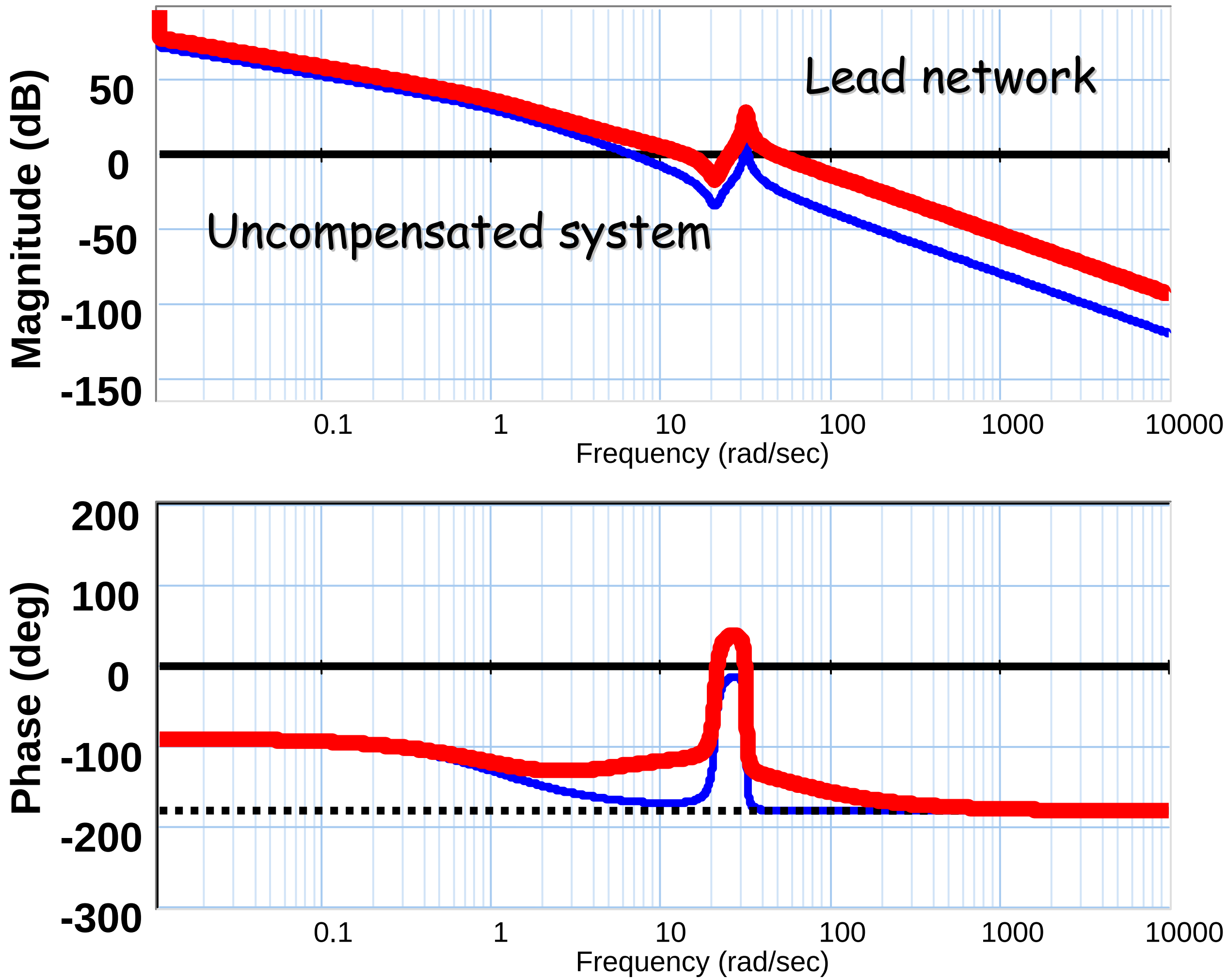
Lead network:

K = 1.9
zero in -5
pole in -50

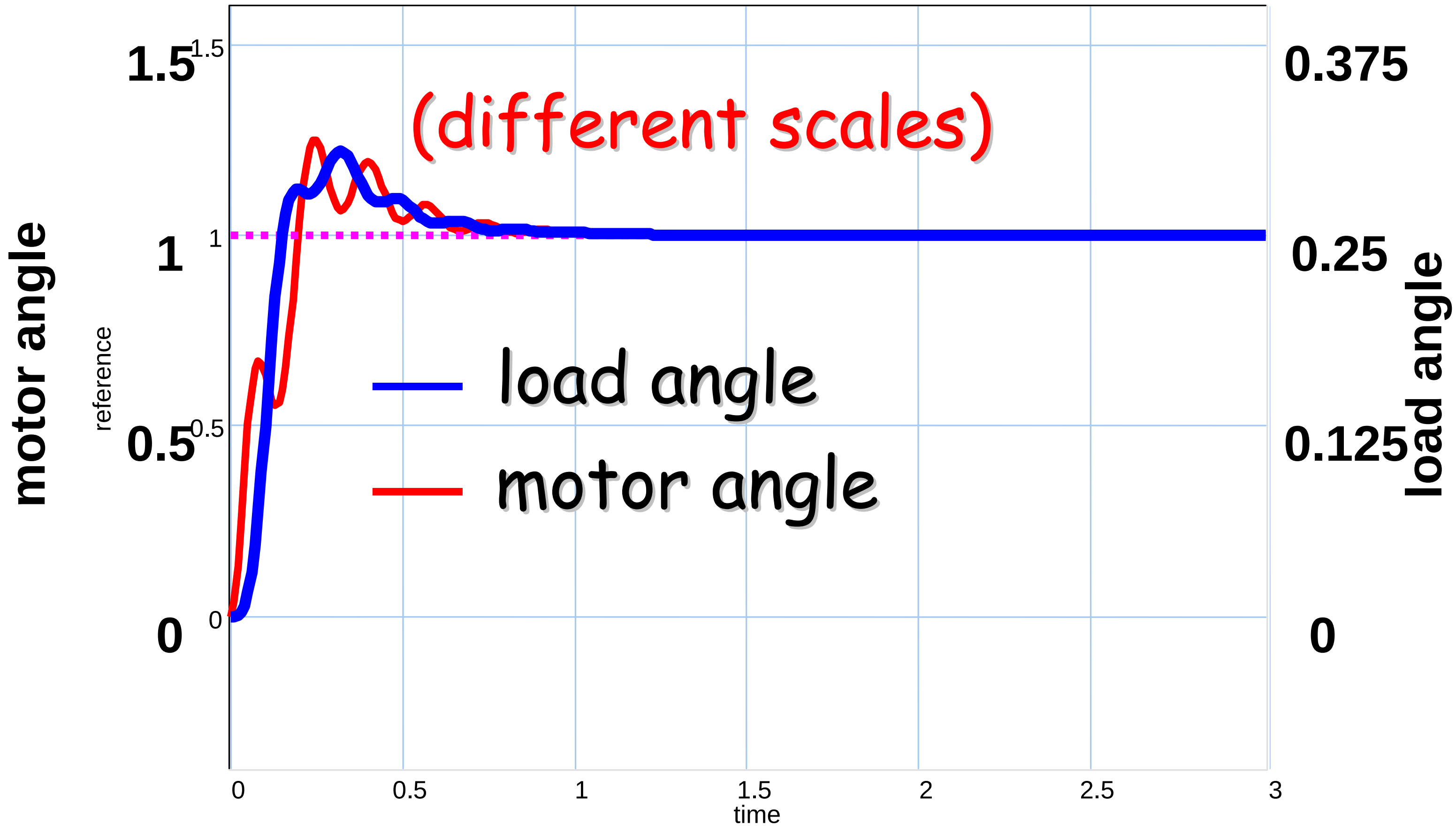
C2_lead_network_motor_only_no prefilter.em



Bode


Magnitude (dB)
50
0
-50
-100
-150
Lead network
Uncompensated system
0.1
1
10
100
1000
10000
Frequency (rad/sec)
Phase (deg)
200
100
0
-100
-200
-300
0.1
1
10
100
1000
10000
Frequency (rad/sec)

Response


(different scales)
load angle
motor angle
motor angle
reference
load angle
1.5
1
0.5
0
0.375
0.25
0.125
0
time
0
0.5
1
1.5
2
2.5
3

Bode Closed-loop system

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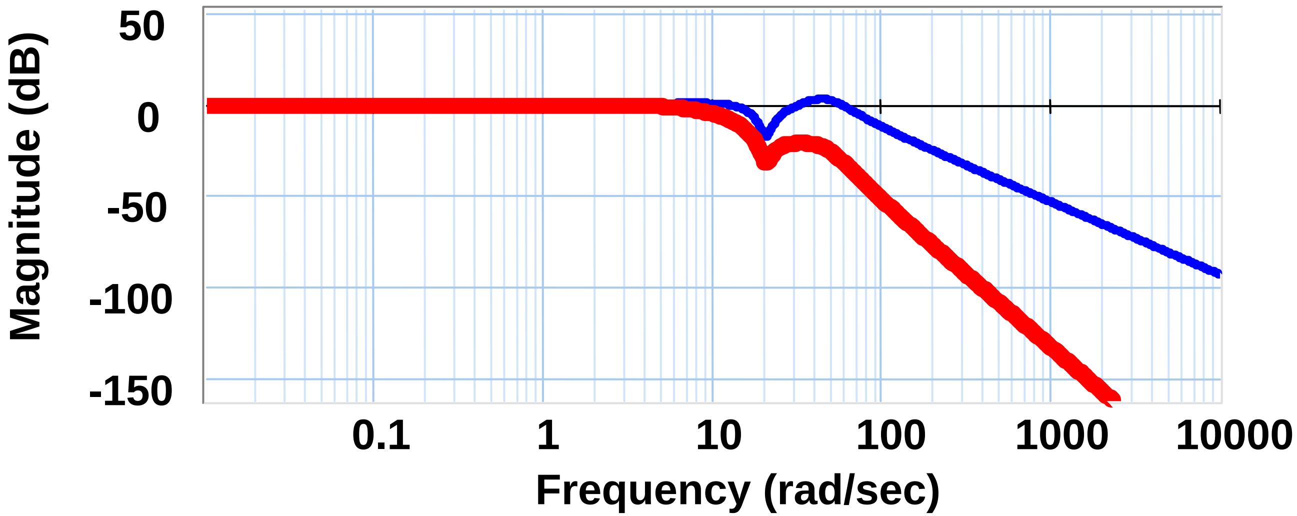
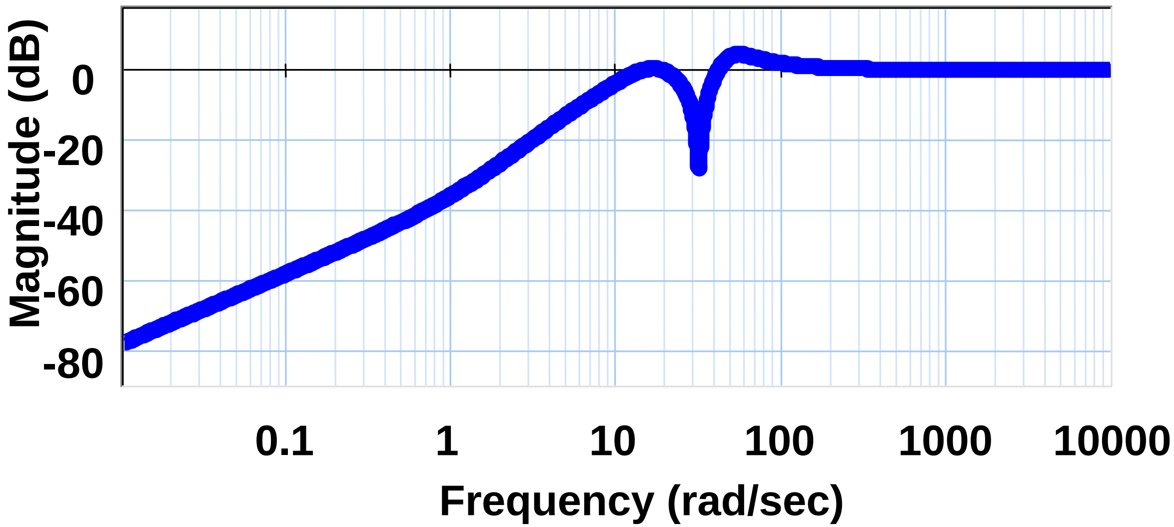
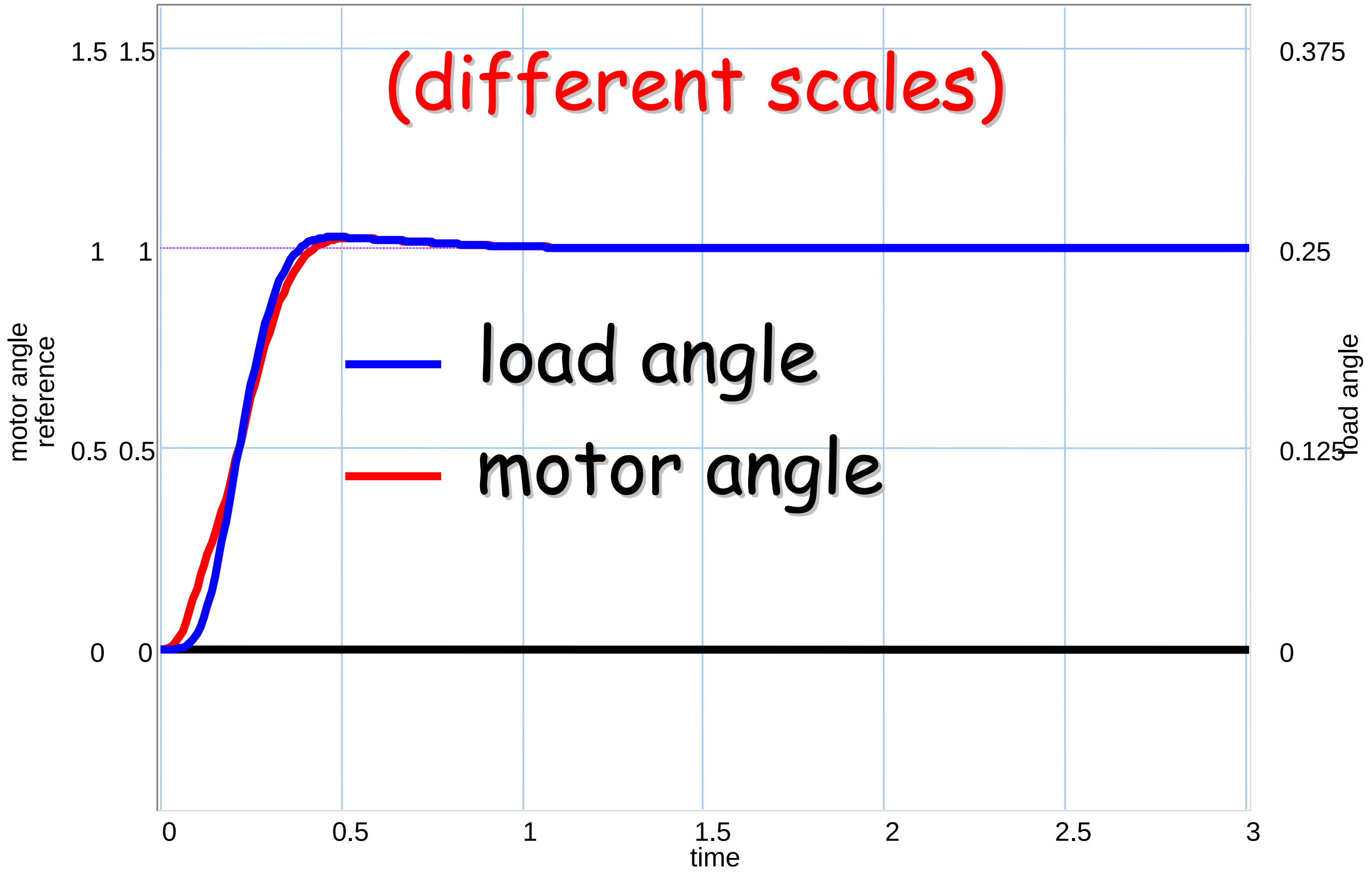


with prefilter in -10 ± 2j

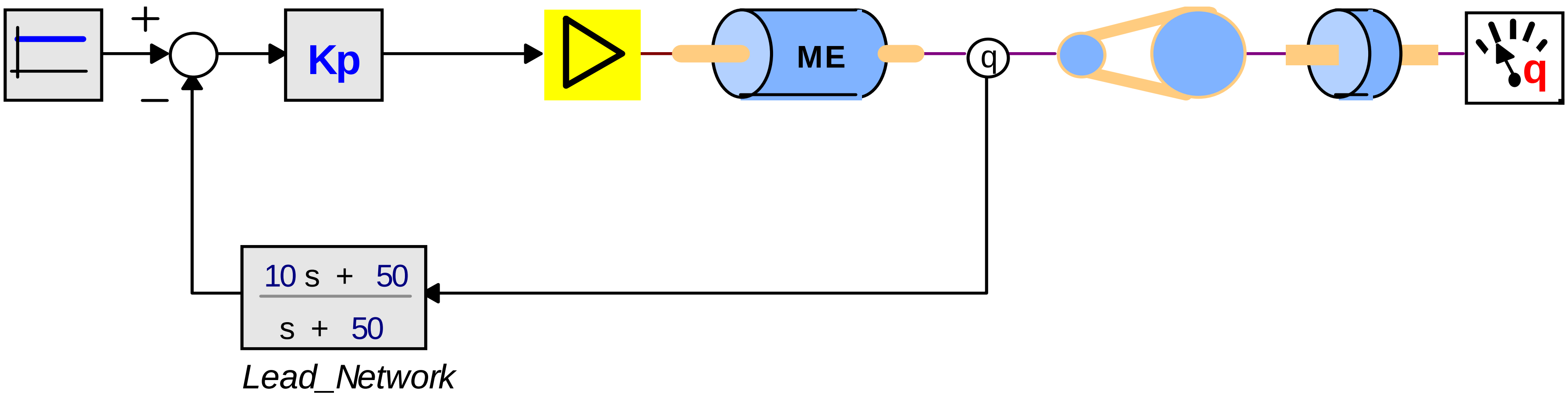
Sensitivity



Response with prefilter

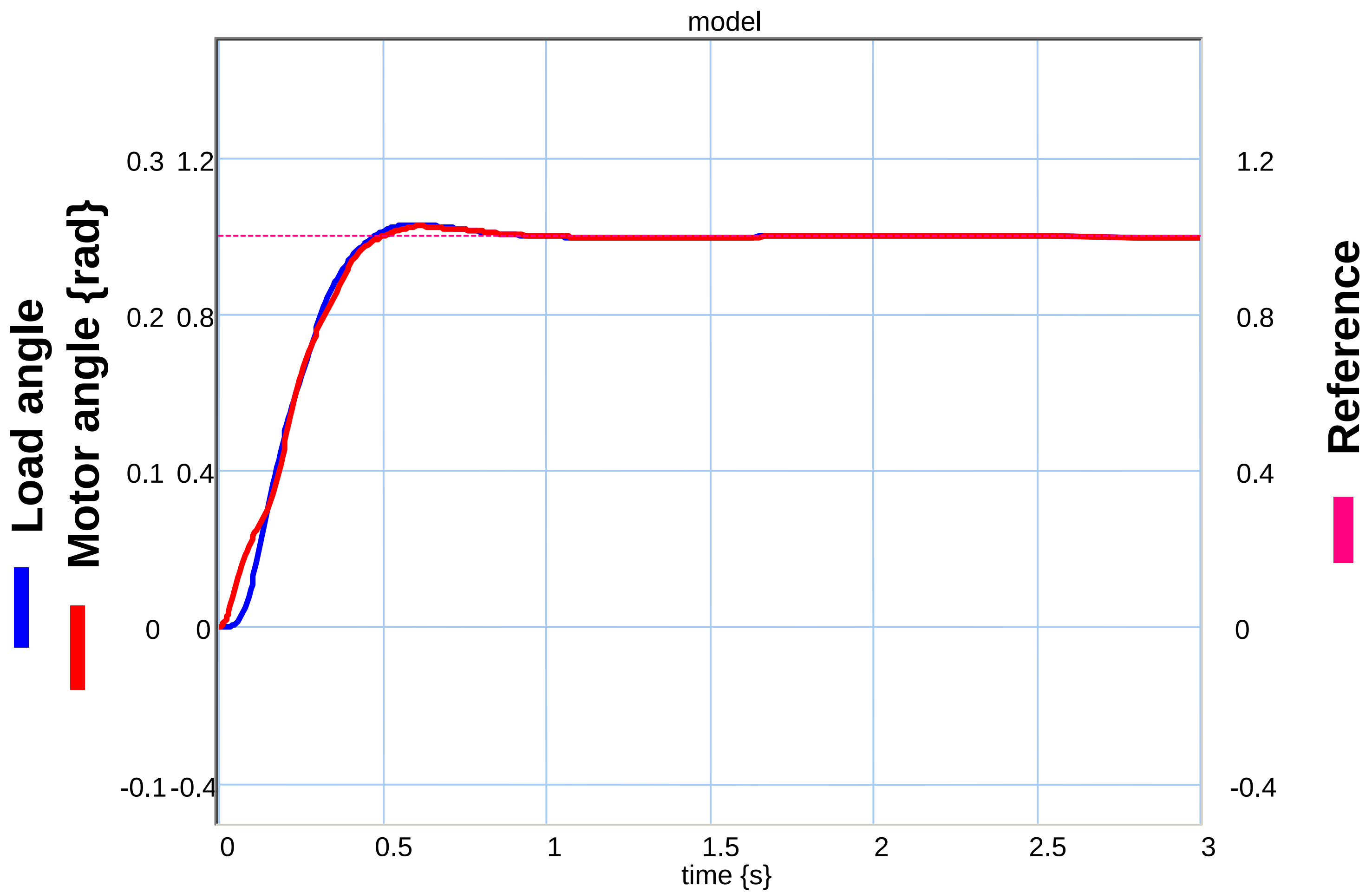


Lead network in feedback

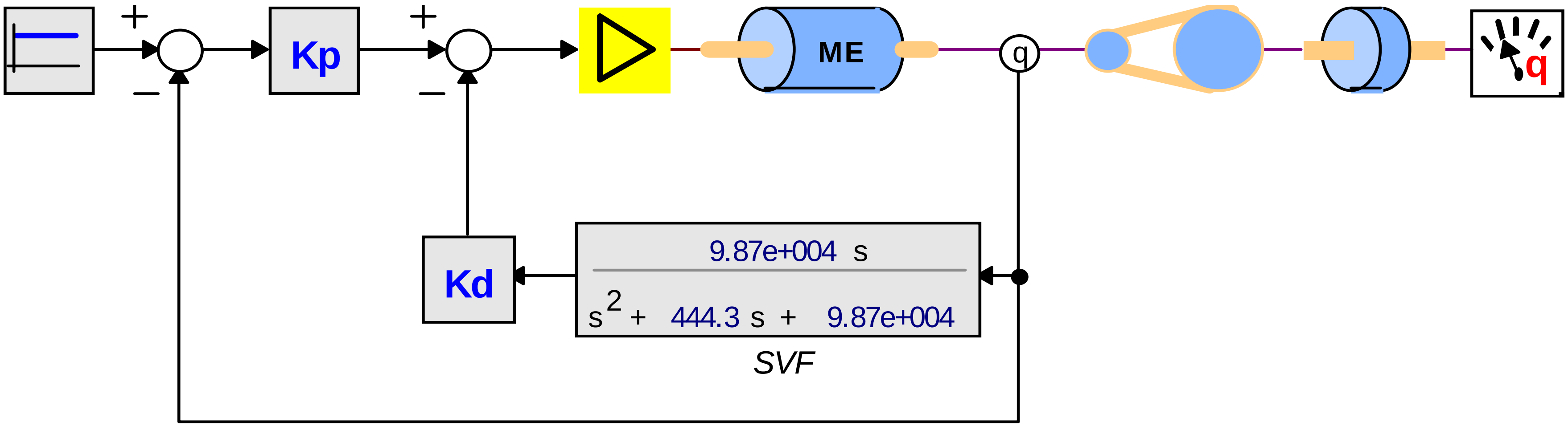


C2_lead_network_in_FB_motor_only.em

Responses


model
Load angle
Motor angle {rad}
Reference
0.3 1.2
0.2 0.8
0.1 0.4
0 0
-0.1 -0.4
1.2
0.8
0.4
0
-0.4
0
0.5
1
1.5
2
2.5
3
time {s}

Motor angle feedback & derivative of motor angle

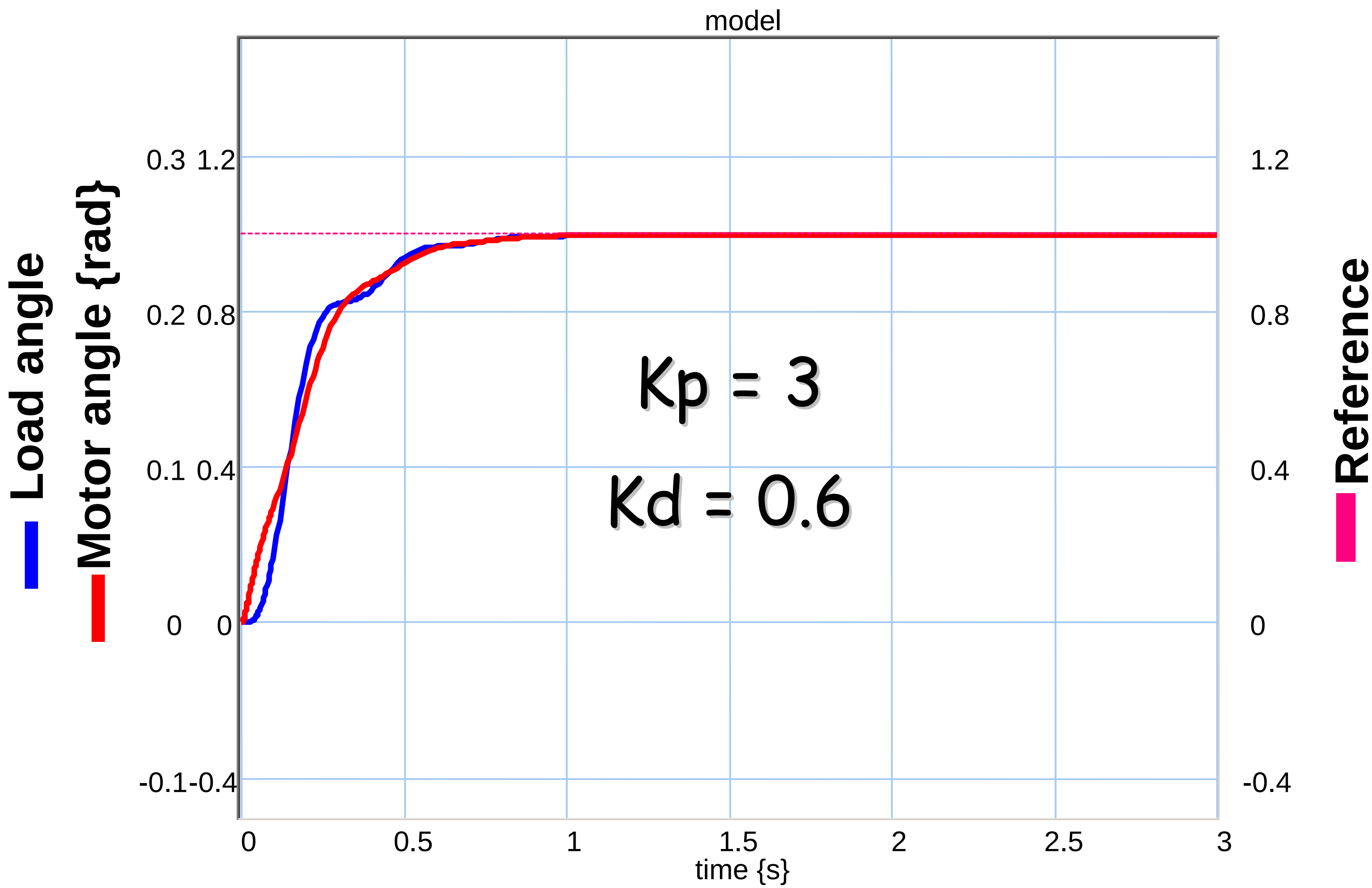


$$\text{SVF: } \frac{s\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2}$$

E1_fb_motor_only_SVF.em

$\omega_n =$ 10 times ω resonant poles

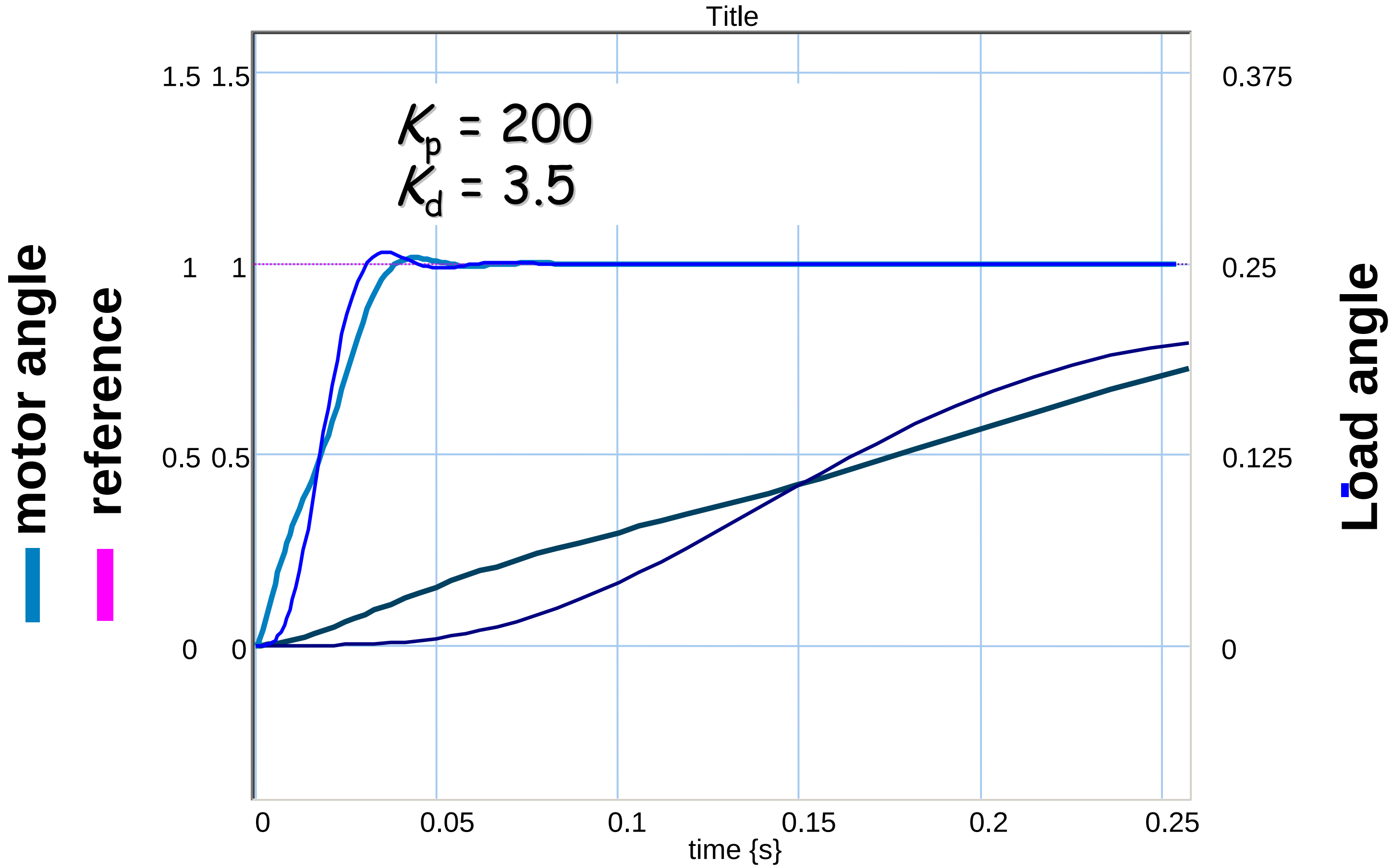
Responses


model
Load angle
Motor angle {rad}
Reference
0.3 1.2
0.2 0.8
0.1 0.4
0 0
-0.1 -0.4
1.2
0.8
0.4
0
-0.4
0
0.5
1
1.5
2
2.5
3
time {s}
Kp = 3
Kd = 0.6

Further improvements

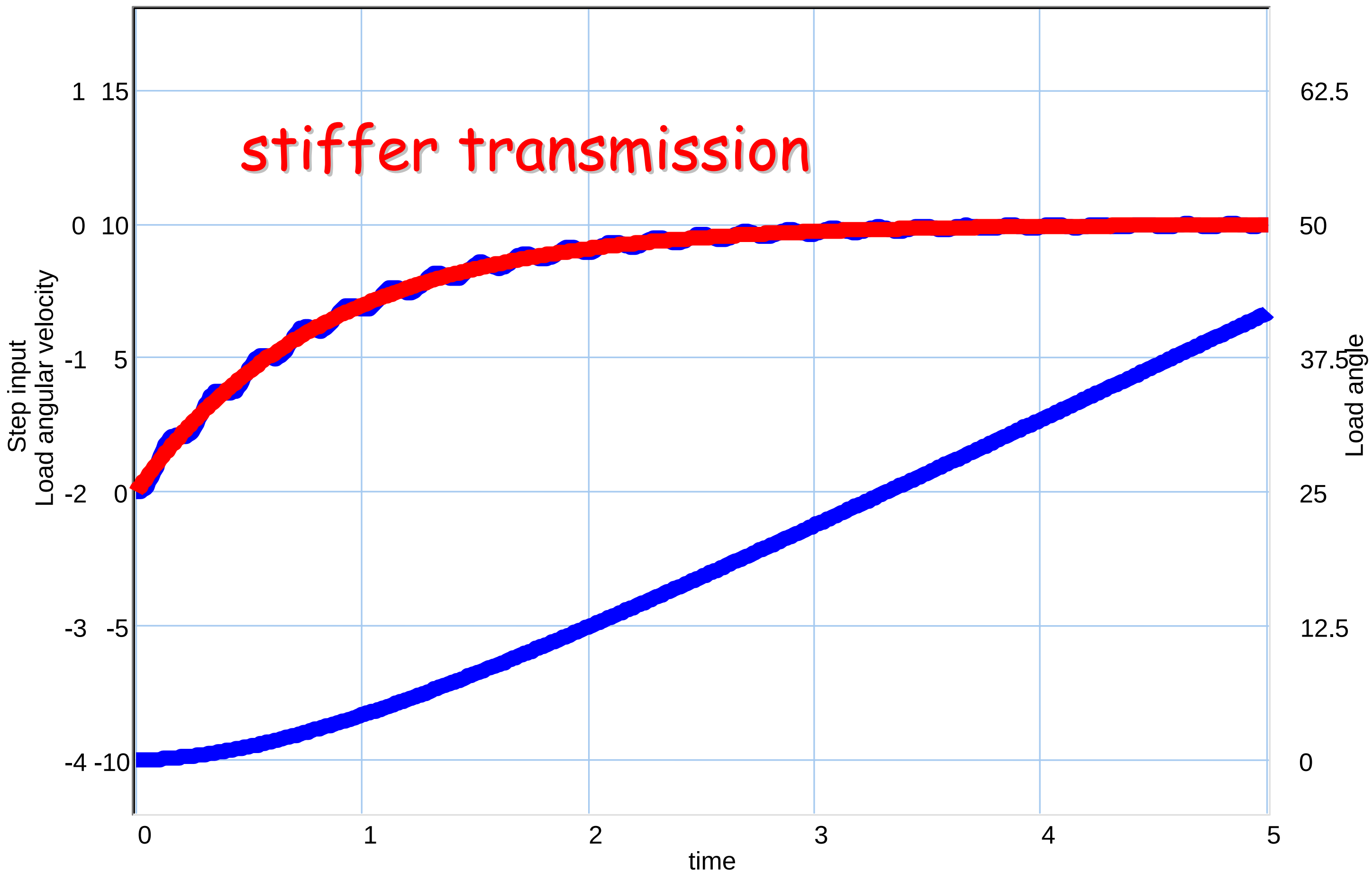
- Further improvements only possible by removing the limiting factor:
  - complex poles, due to limited stiffness of axis
  - a stiffer axis will move these poles to higher frequencies and
  - enable much better performance:
  - change k_{axis} from 1.45 into 100

Response with a stiffer axis

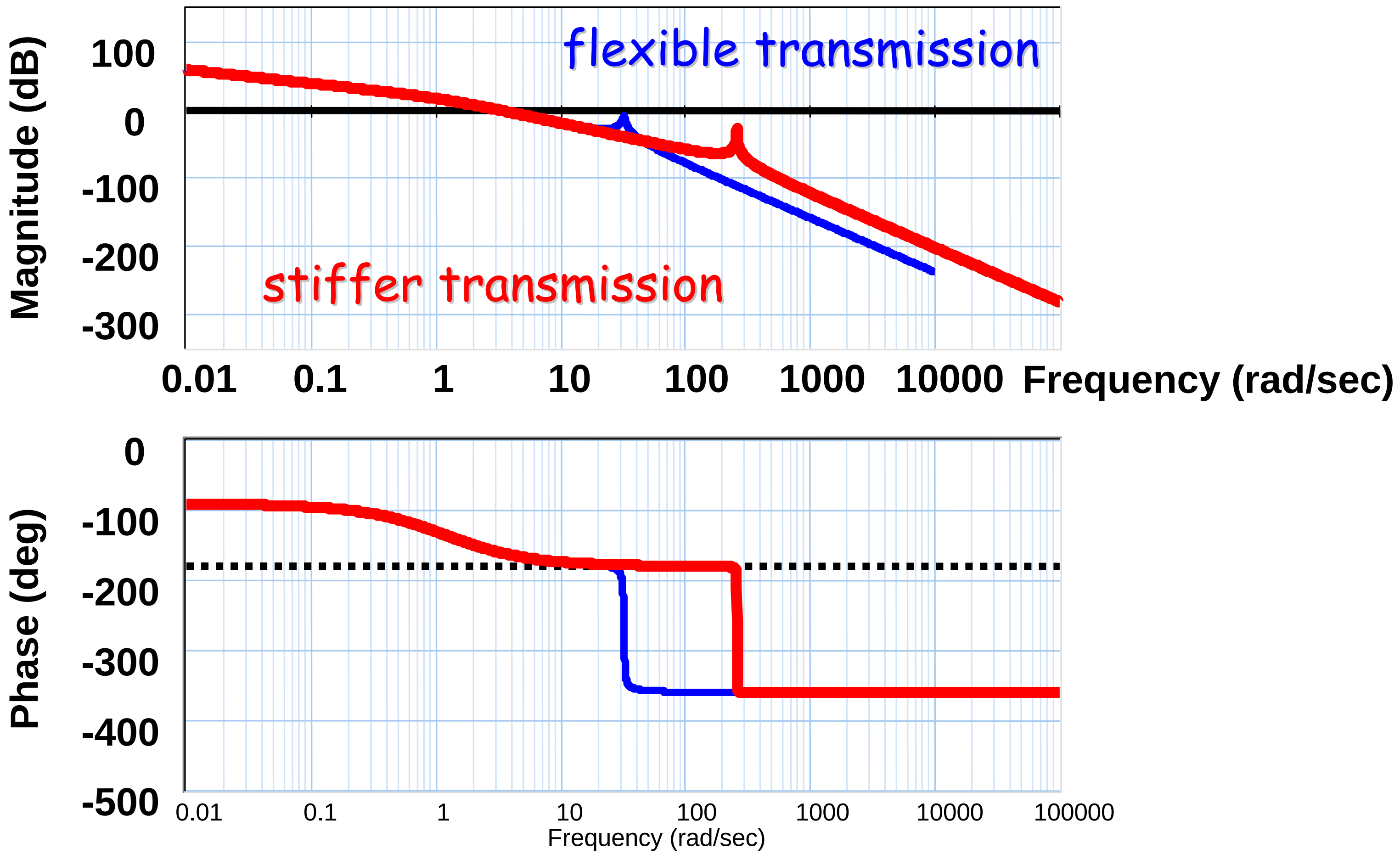


C_Prop_plus_Tacho_feedback_stiff_axis

Open loop comparison

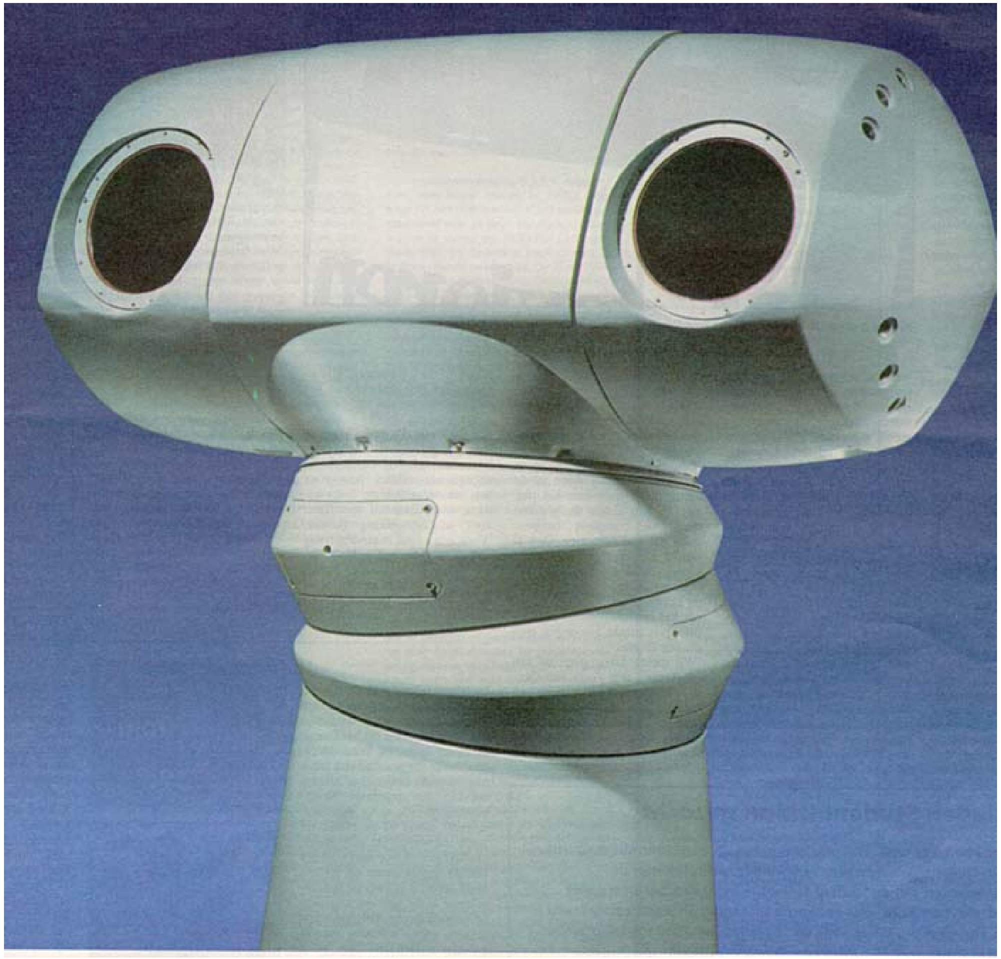


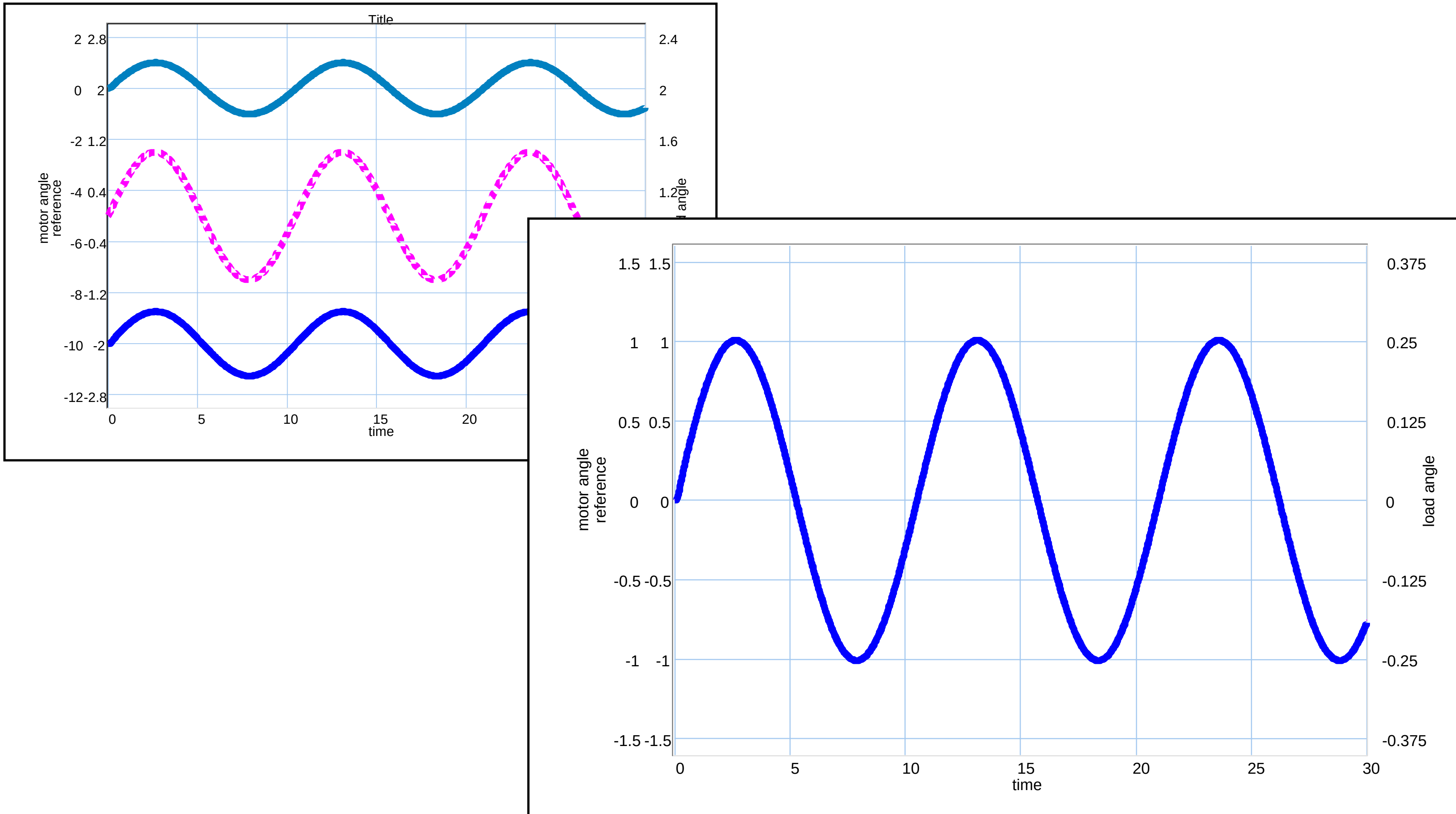
Bode plots


Magnitude (dB)
100
0
-100
-200
-300
flexible transmission
stiffer transmission
0.01
0.1
1
10
100
1000
10000
Frequency (rad/sec)
Phase (deg)
0
-100
-200
-300
-400
-500
0.01
0.1
1
10
100
1000
10000
100000
Frequency (rad/sec)

Tracking device

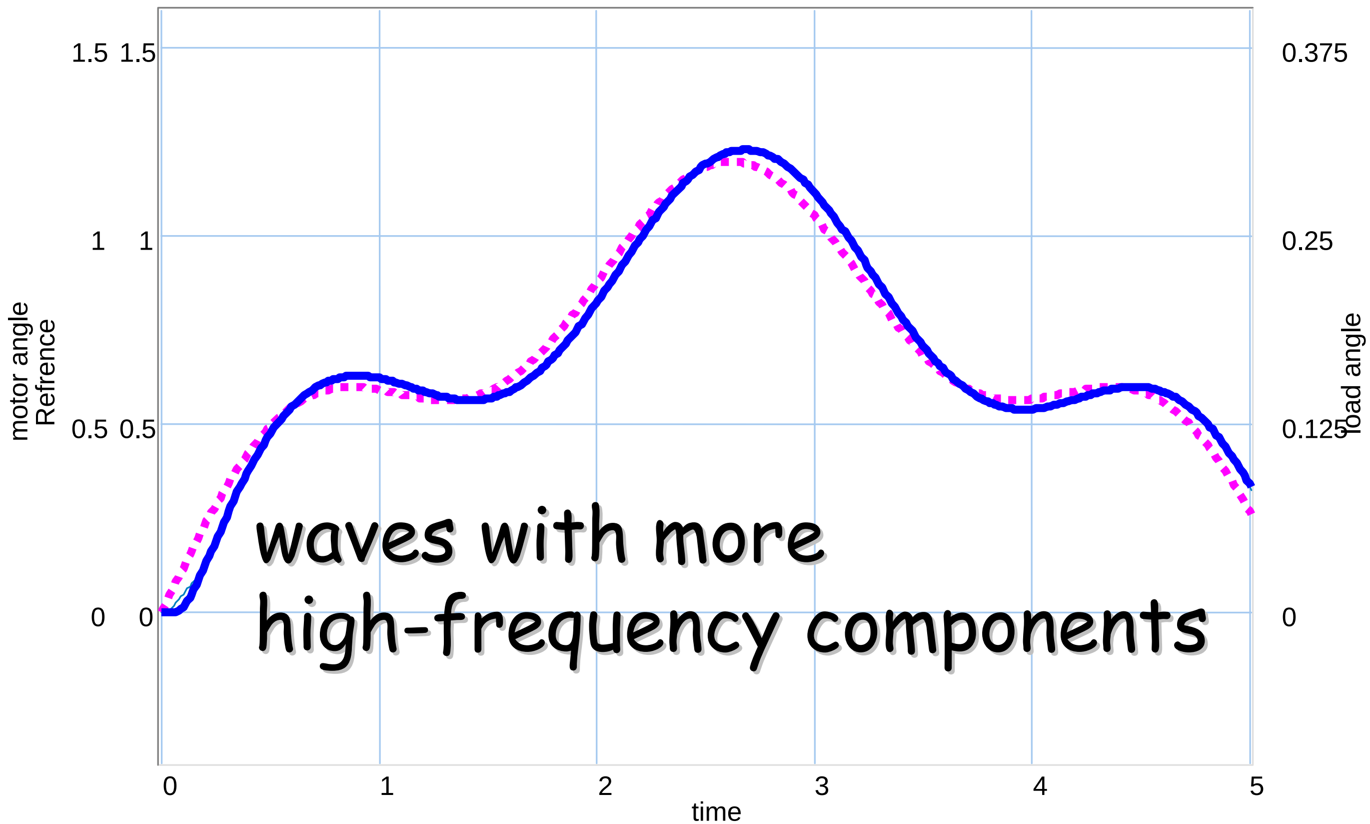
frequencies
sea waves
0.1 Hz
0.6 rad/s



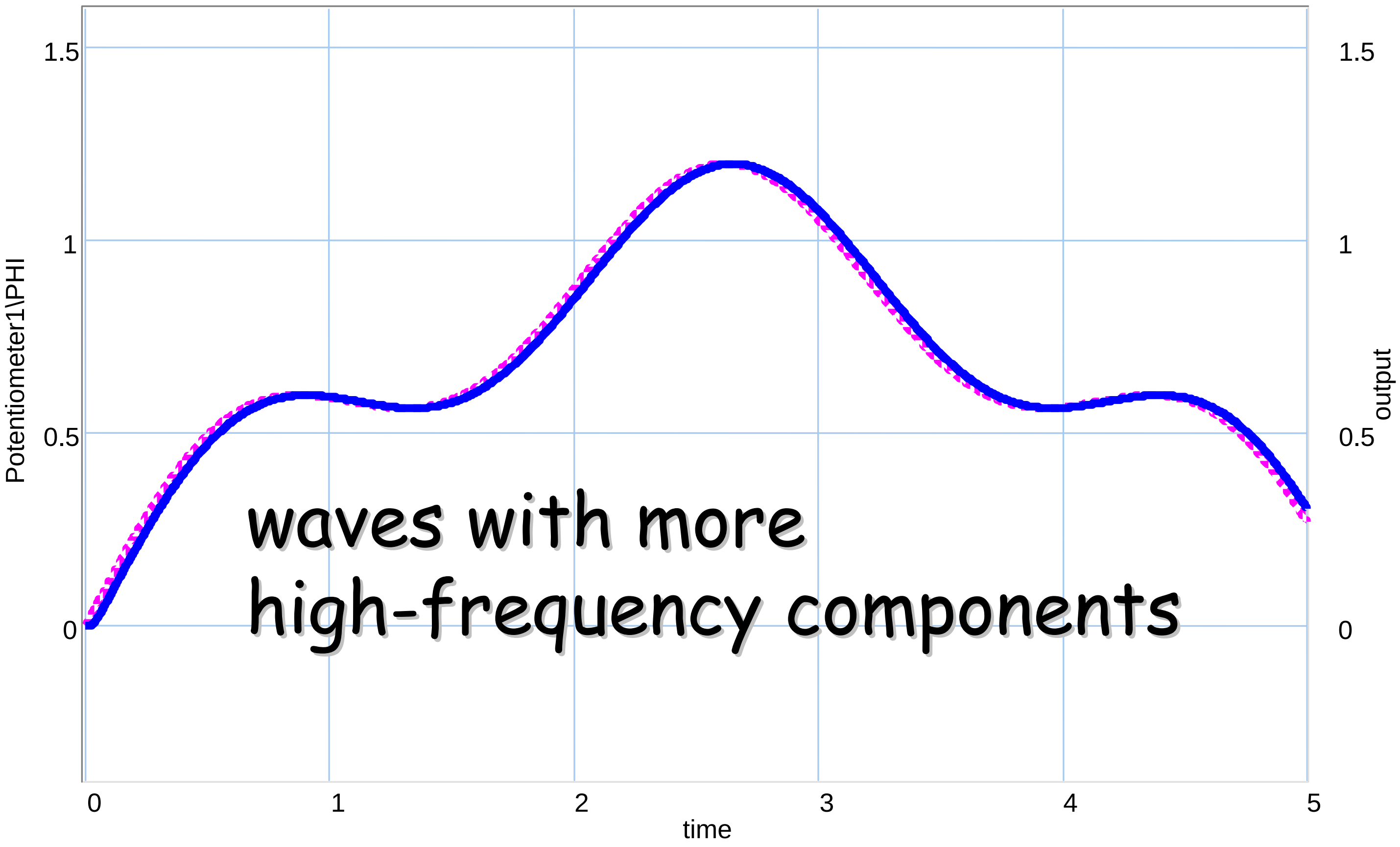

Title
motor angle
reference
time
motor angle
reference
load angle
time

Bandwidth too small

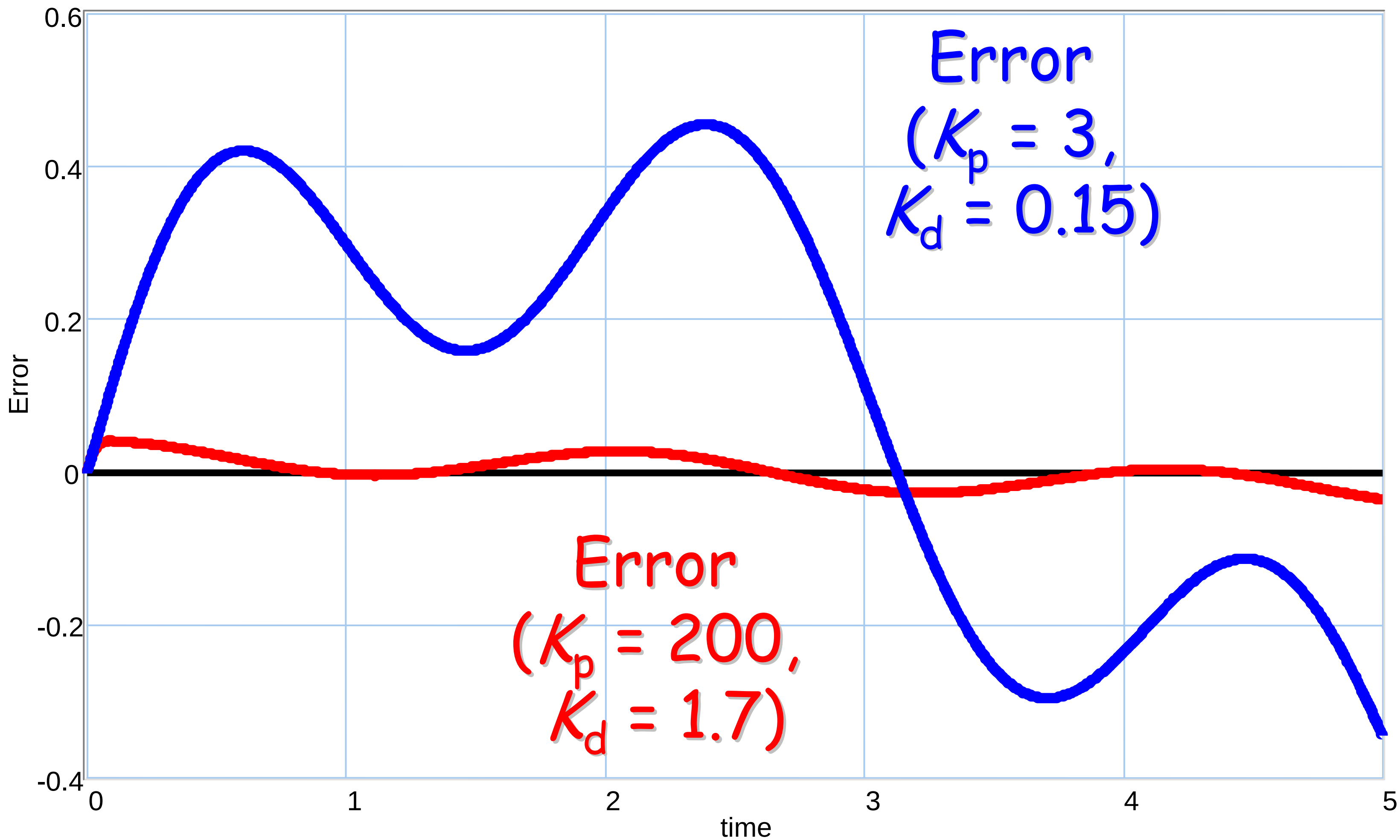
flexible transmission



Stiffer transmission



Comparison


0.6
0.4
0.2
0
-0.2
-0.4
Error
0
1
2
3
4
5
time
Error
(K_p = 3,
K_d = 0.15)
Error
(K_p = 200,
K_d = 1.7)

Closed-loop Bode plots

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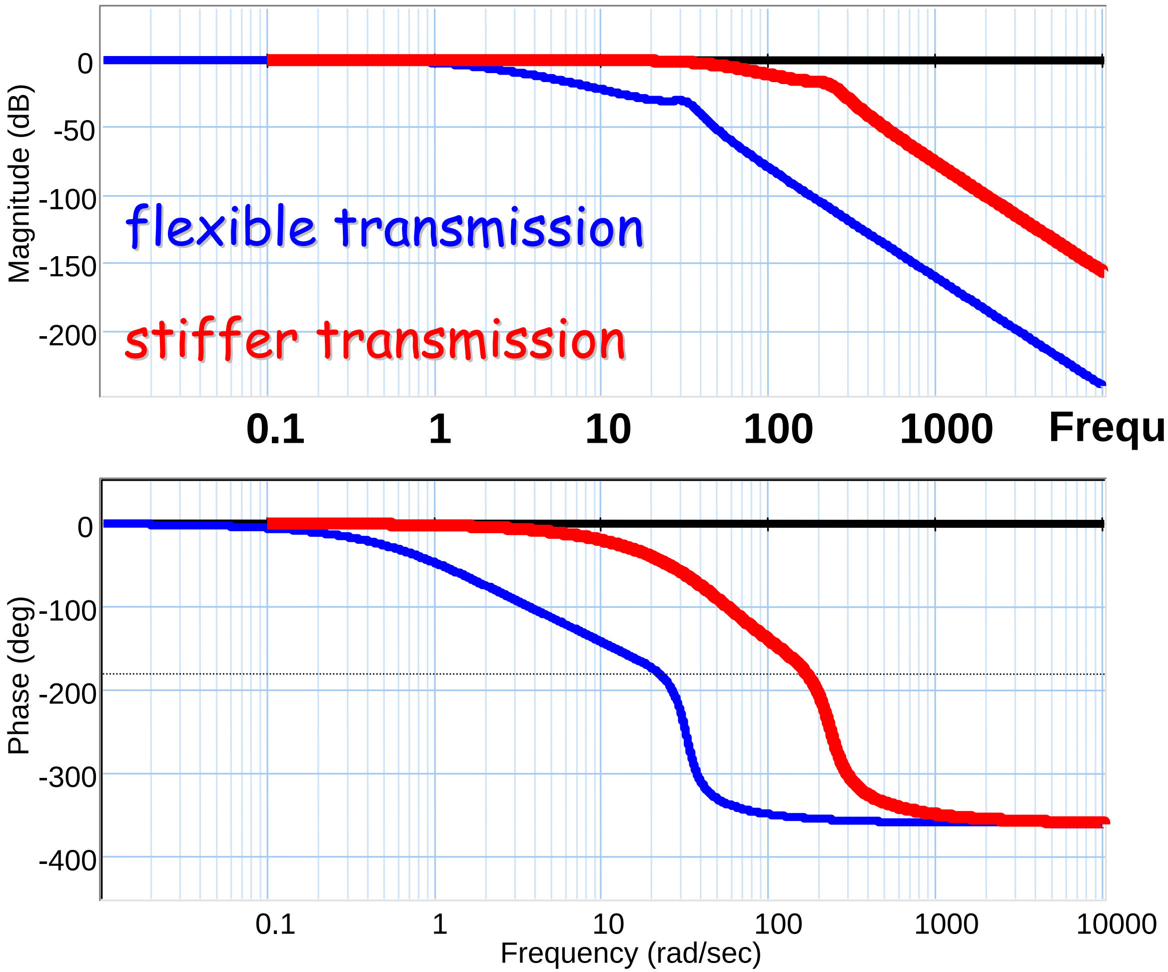

Bandwith:

1.2 rad/s

43 rad/s

Conclusions

- A realistic system can be controlled with the tools learned in this course
- What is left is the digital implementation of controllers:
  - Next two lectures