SIEMENS

Control Theory
控制理论

SINUMERIK 840D with
SIMODRIVE 611D

SIMOTION / SINAMICS

Gerhard Forster I DT MC R&D 2
Mechatronic Support

Simple Mechanical Model With a Load
带负载的简单机械模型

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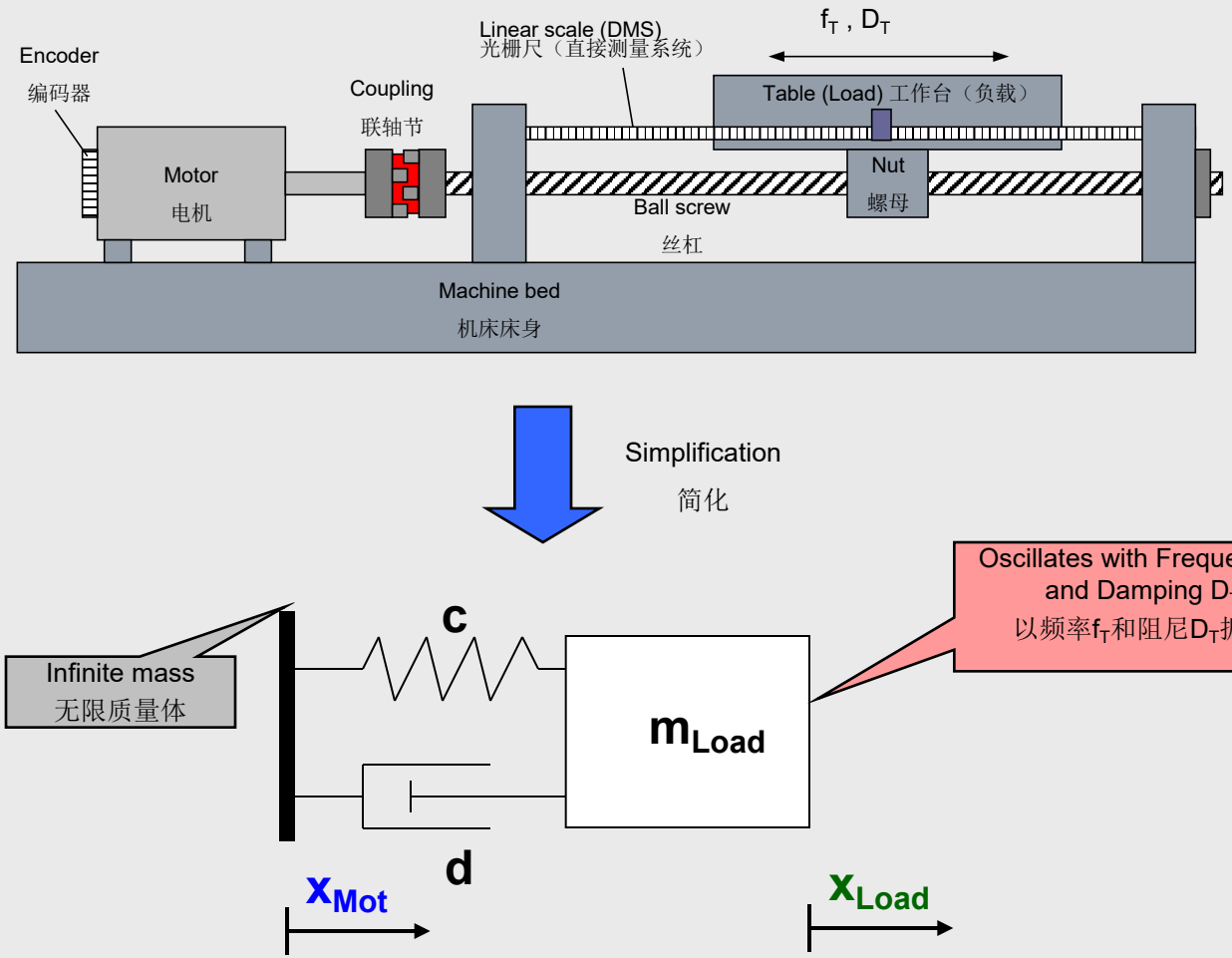

From the Mechanical Structure to the Block Diagram
从机械结构到方块图

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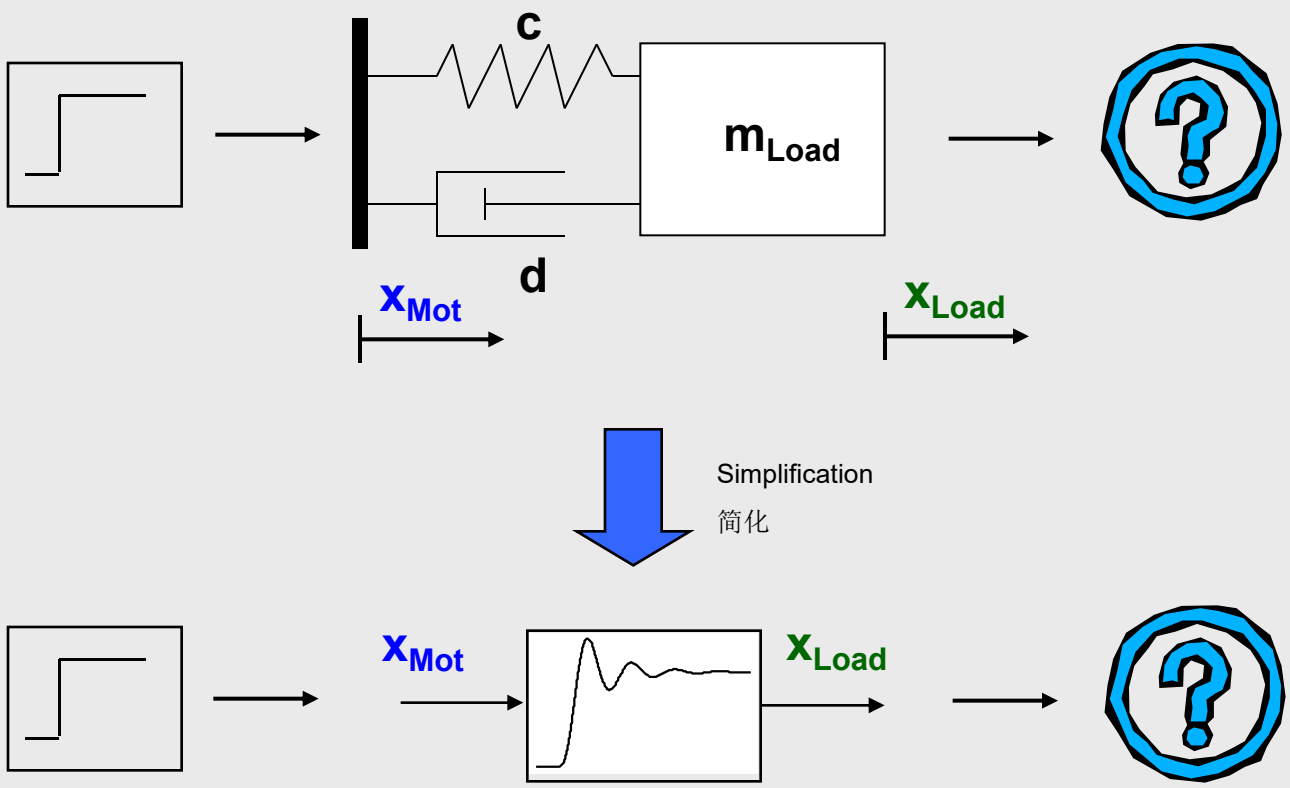

Fourier series of a square-wave signal
方波信号的富里叶级数

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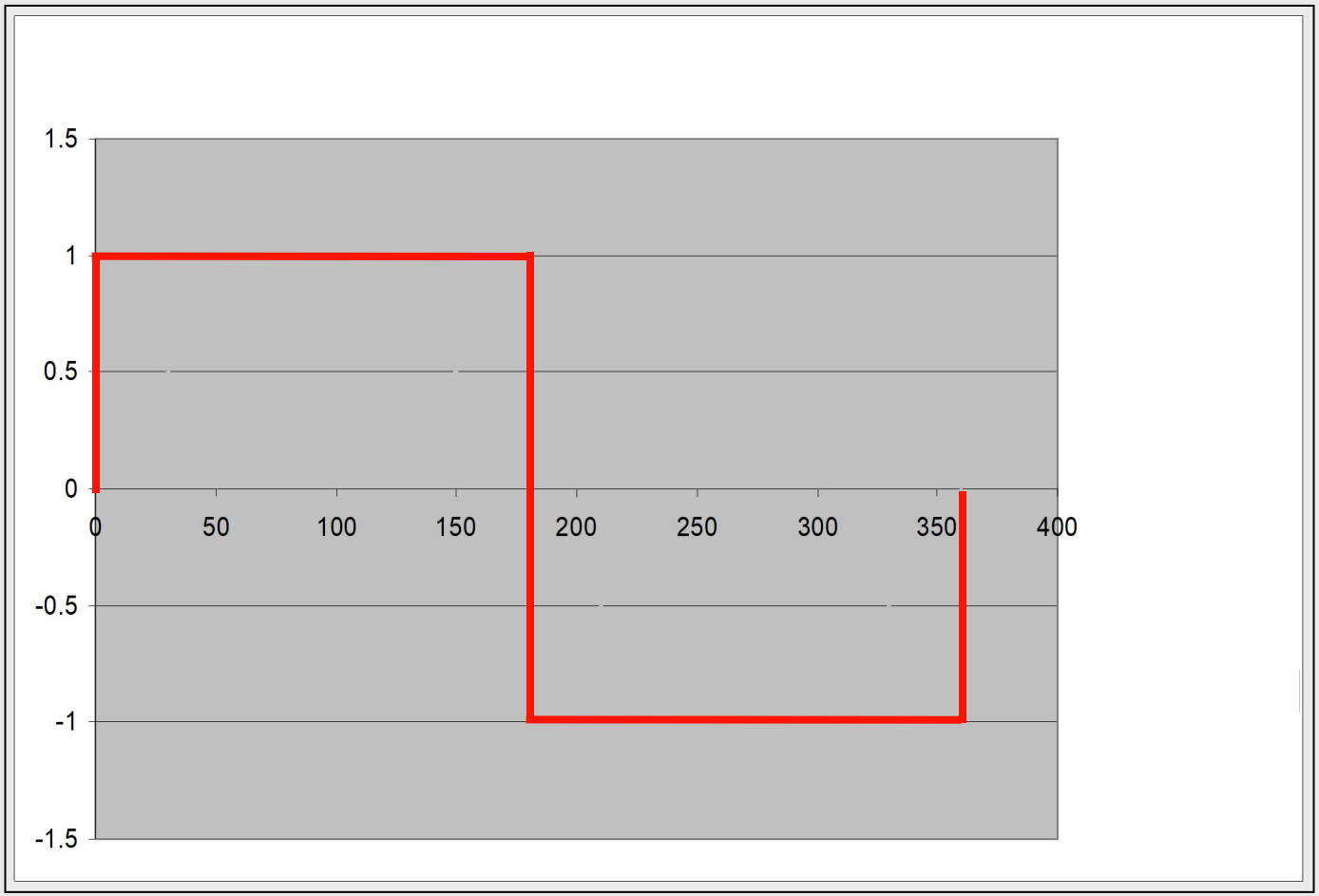
任何周期函数都可以用正弦函数和余弦函数构成的无穷级数来表示



Fourier series of a square-wave signal
方波信号的富里叶级数

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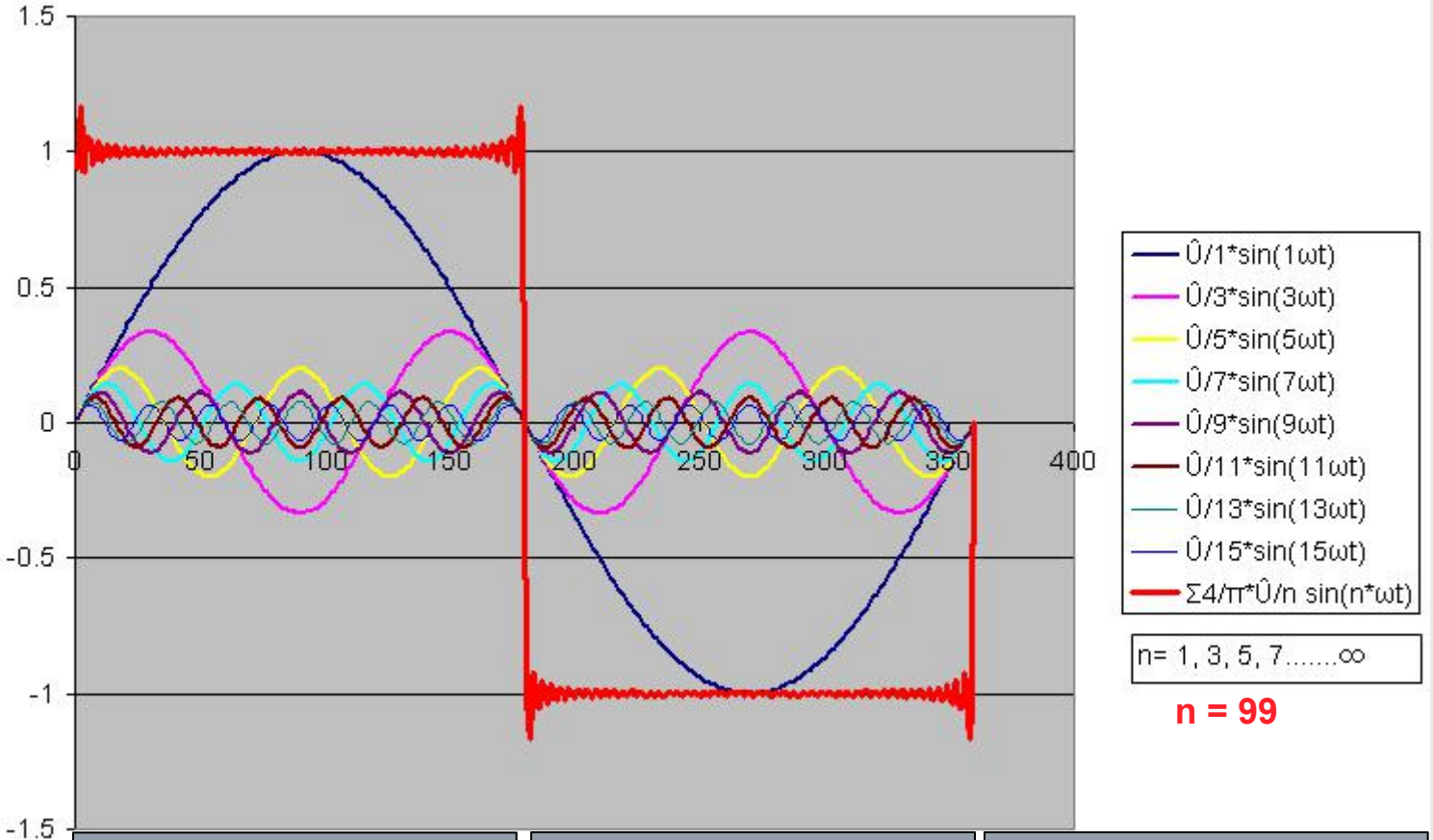
$$u(t) = \frac{4\hat{u}}{\pi}\left(sin(wt) + \frac{1}{3}sin(3wt) + \frac{1}{5}sin(5wt) + \ldots\right)$$



方波的富里叶级数 | 梯形波的富里叶级数 | 三角波的富里叶级数

Identification of the Characteristics of the Simplified Model
简单模型特性识别

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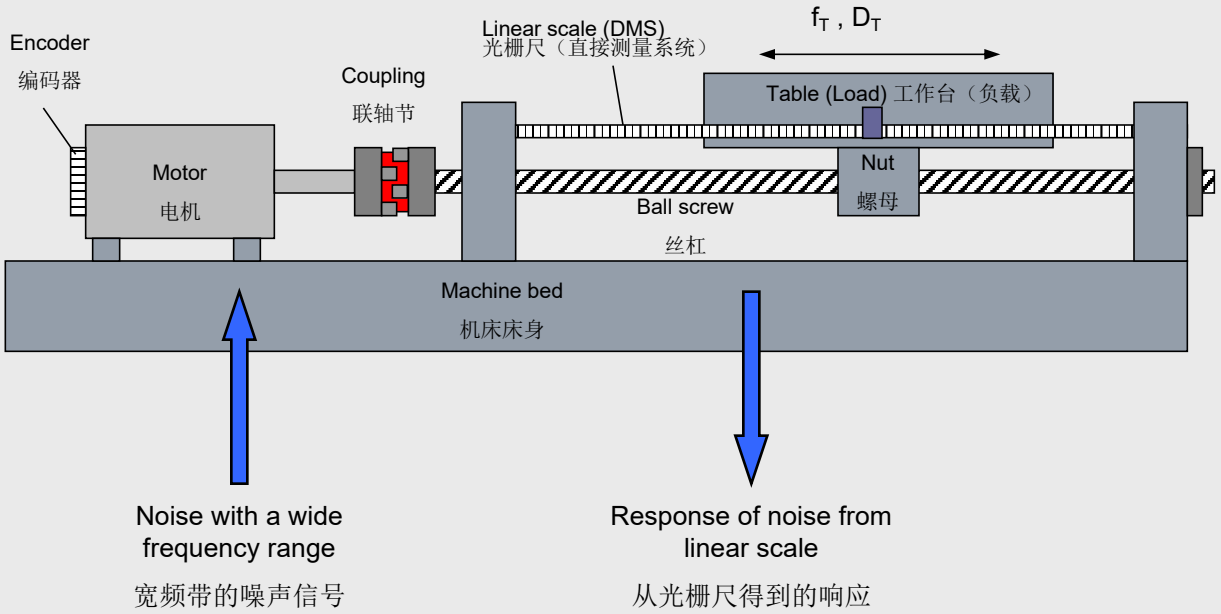

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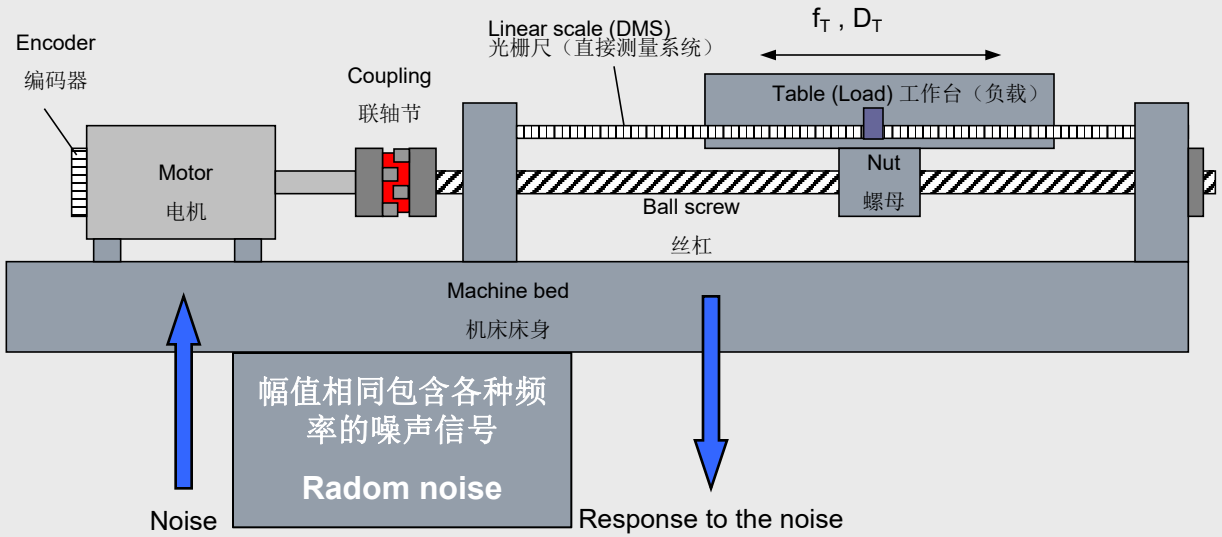

幅值相同包含各种频率的噪声信号

Radom noise

Noise
噪声信号

Response to the noise
噪声信号的响应

Numerical Control 840D
840D 控制器

$$Transfer\ \ function\ \Big|_{s=j\omega} = Frequency\ response = \frac{\mathrm{Re}\,sponse\ to\ noise}{noise}$$

Presentation of the result in a Bode diagram

以伯德图描述结果

Identification of the Characteristics of the Simplified Model
简单模型特性识别

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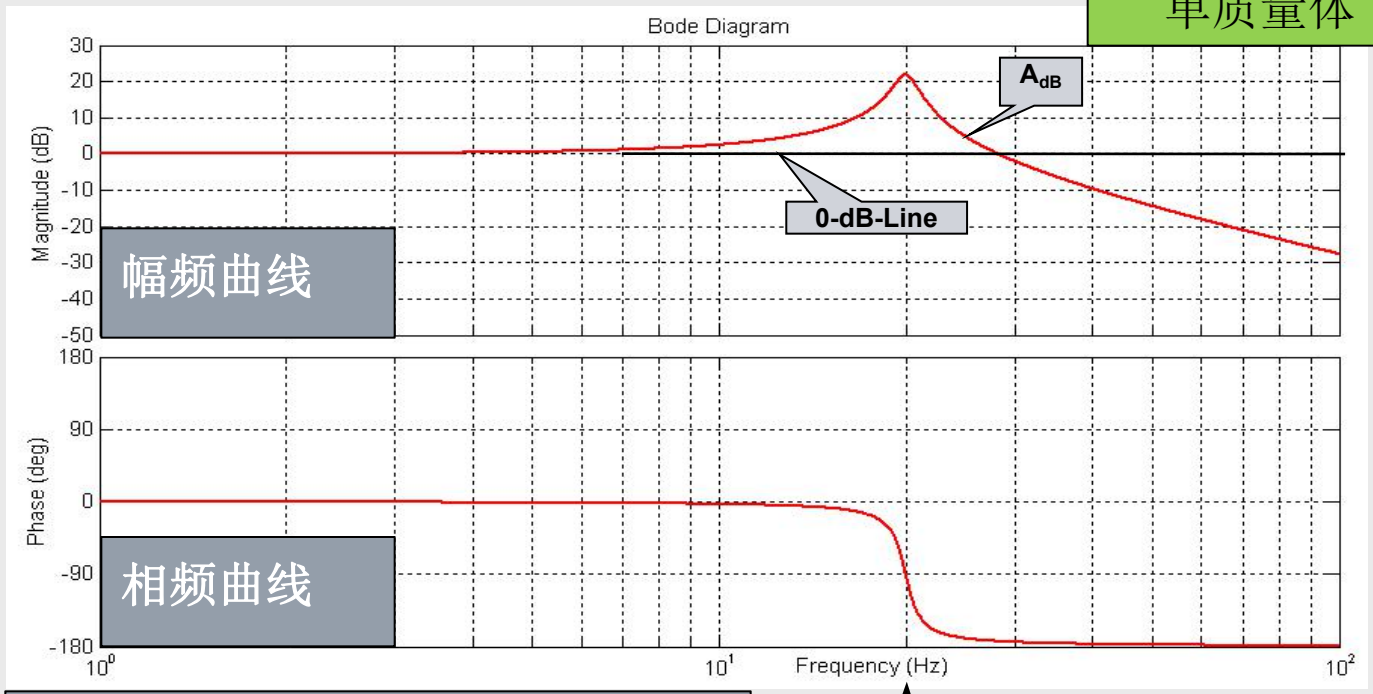
单质量体

$$\frac{x_{Load}}{x_{Mot}}$$



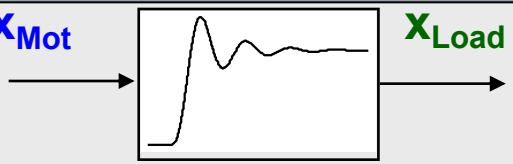
机械频率响应

转子锁定频率：

电机转子很小的转动，机械很大的位移

Locked rotor frequency ≈ 20 Hz

转子锁定频率≈ 20 Hz



$$A[dB] = 20Log\frac{|xLoad|}{|xMotor|}$$

问题：为什么优化时要求0dB曲线带宽越宽越好？

Linear Amplitude Factor = f(dB)
线形幅值系数

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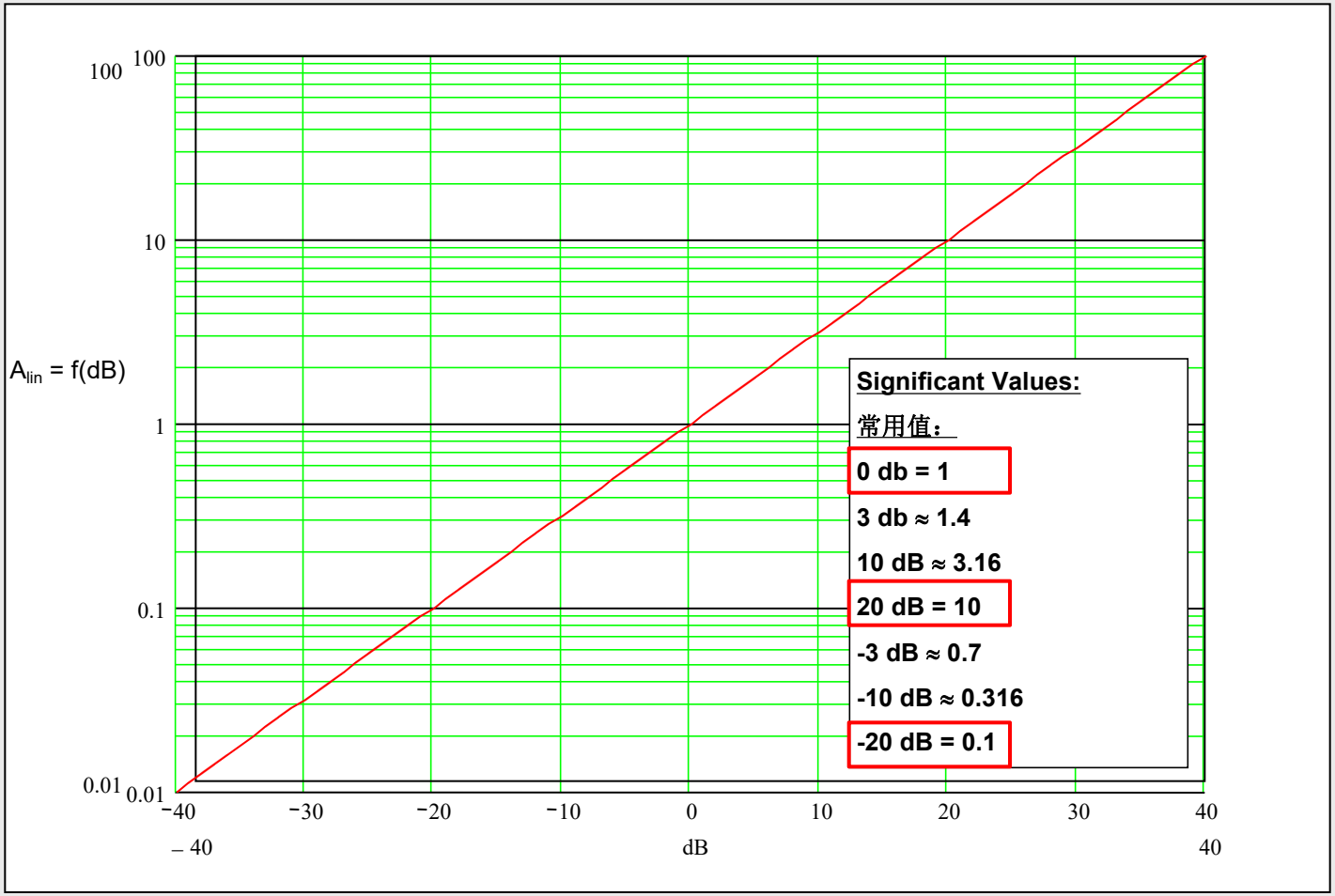

Relation Between Frequency Response and Time Response
频域响应和时域响应的关系

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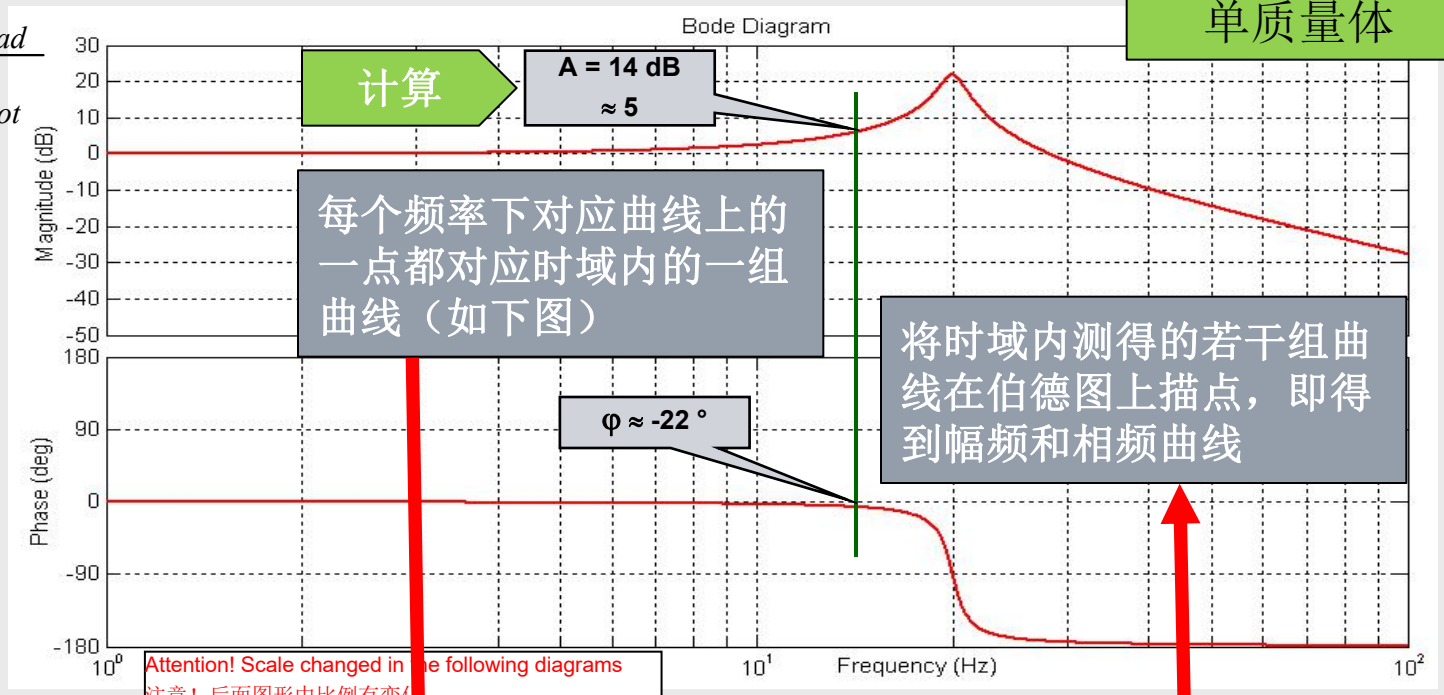
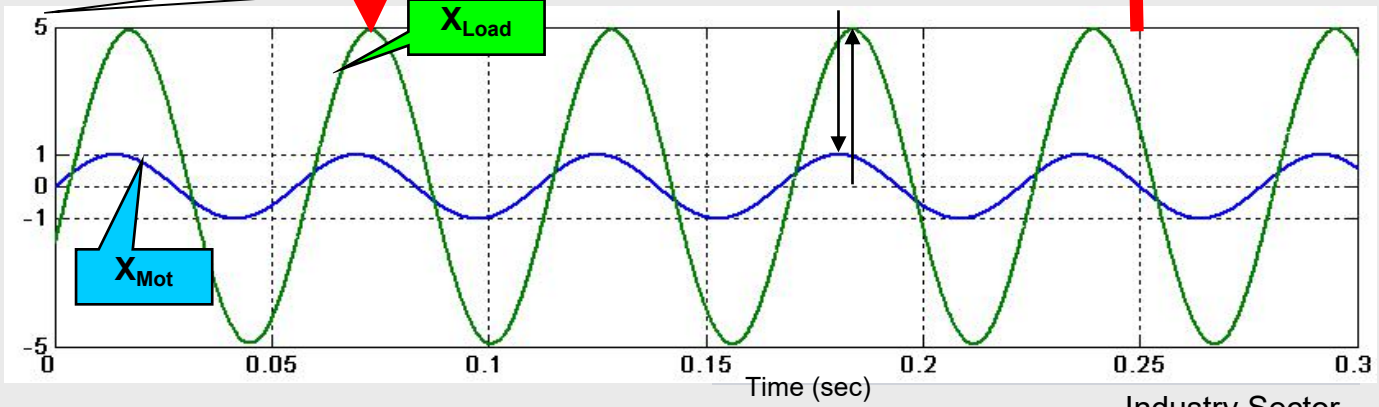
$\frac{x_{Load}}{x_{Mot}}$

单质量体





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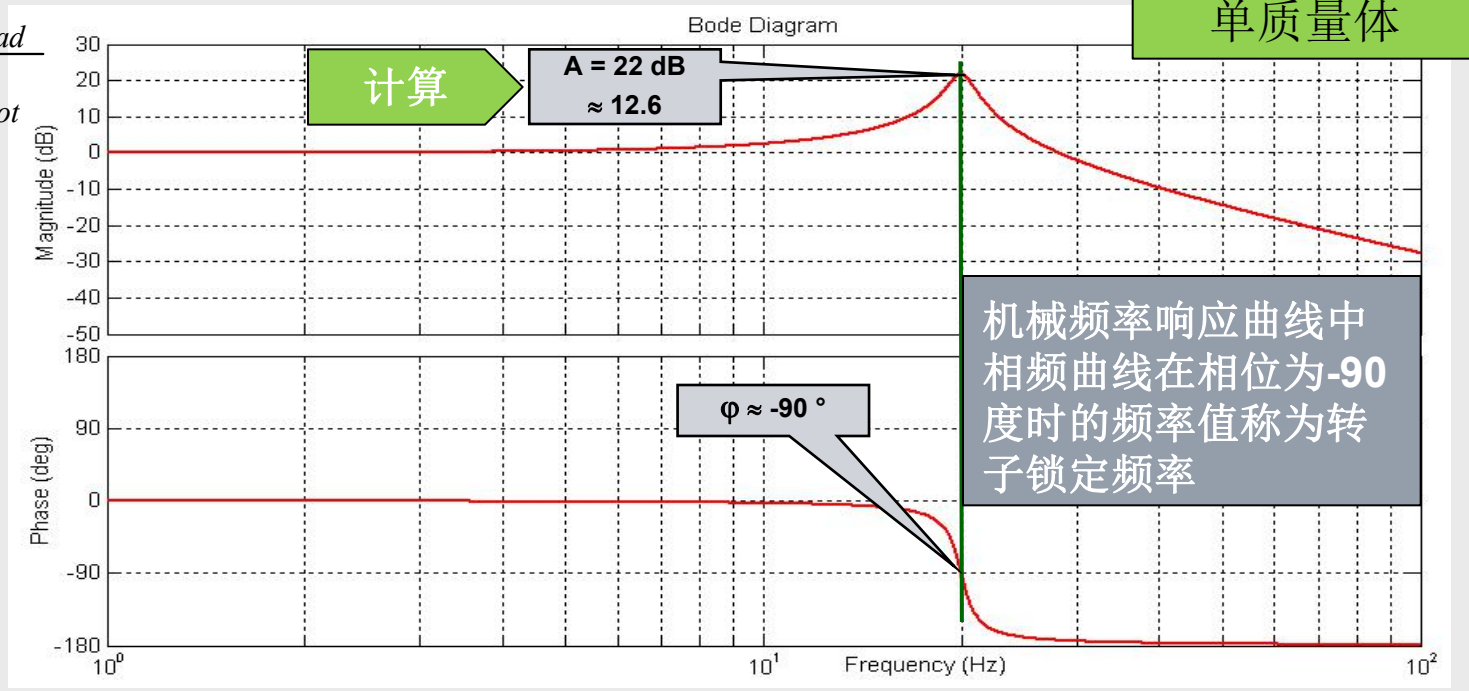

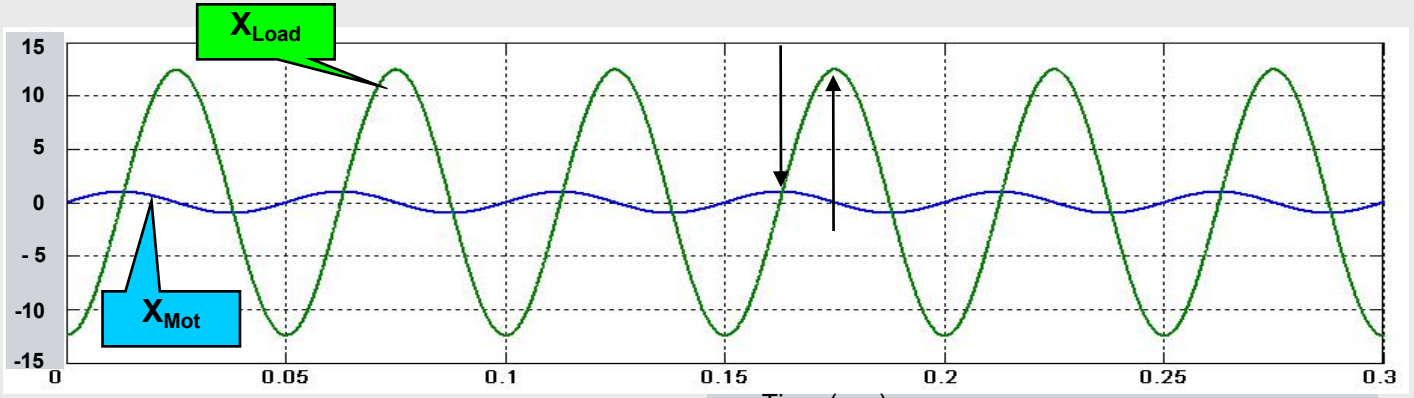

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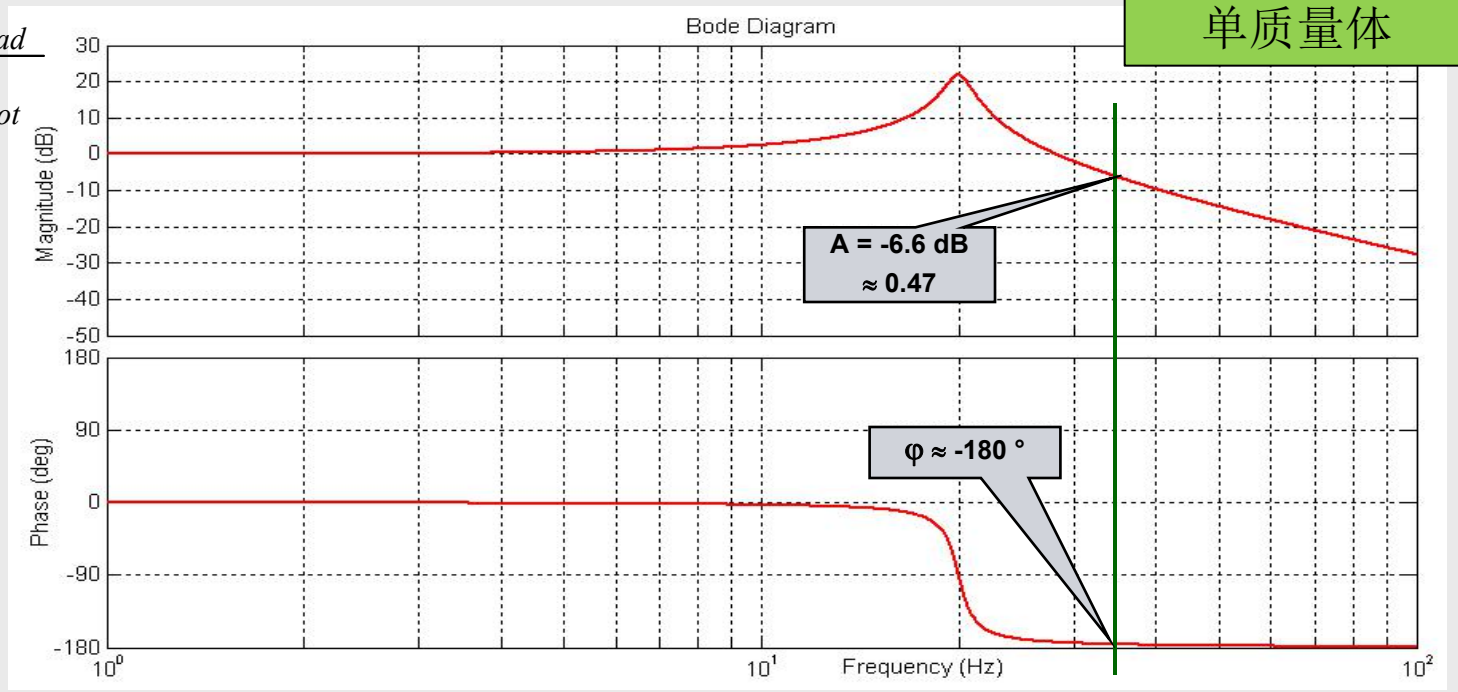

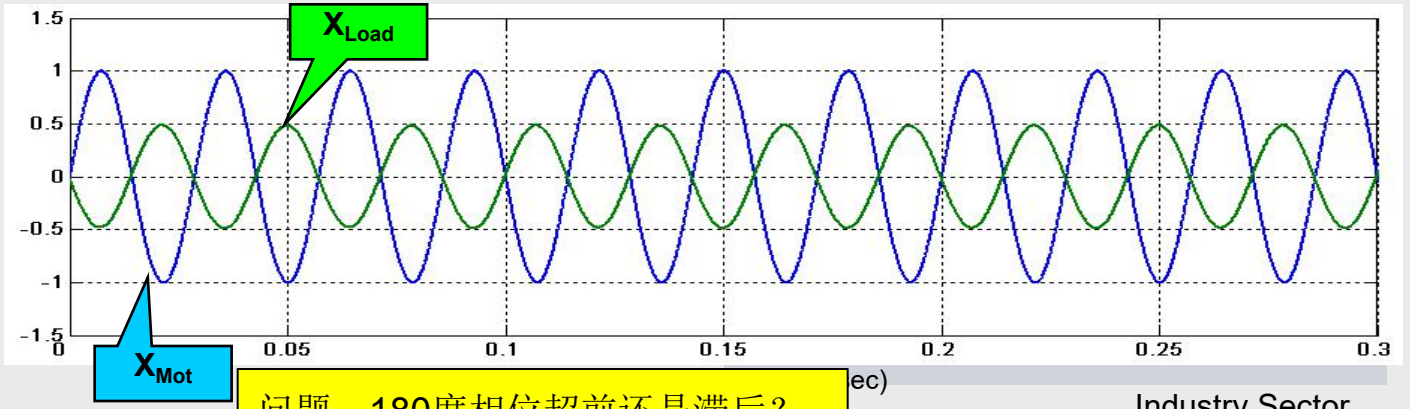

问题：180度相位超前还是滞后？

Damping, Frequency und Step Response
阻尼，频率和阶跃响应

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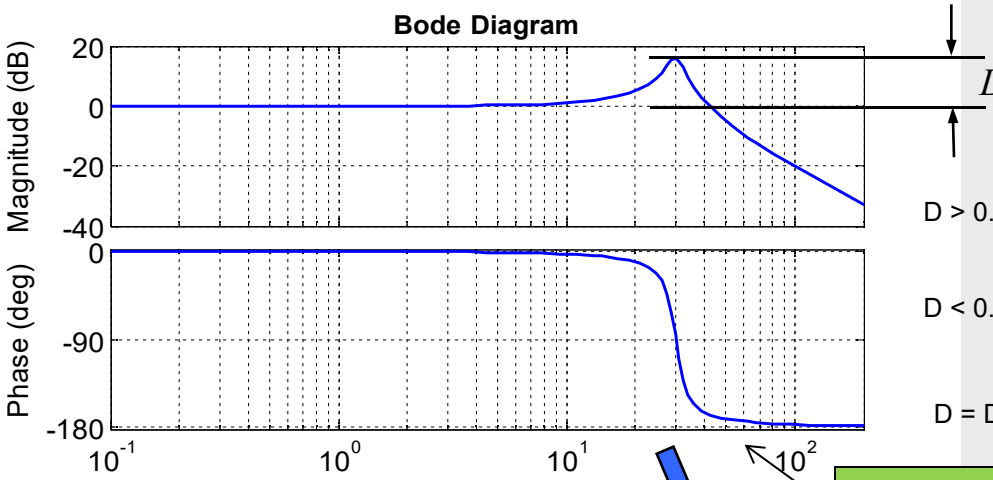


$$D \approx 10^{\frac{-A_{dB}}{20}} \cdot 0.5$$

D > 0.15 (=15%): well damped
良好的阻尼

D < 0.10 (=10%): bad damped
较差的阻尼

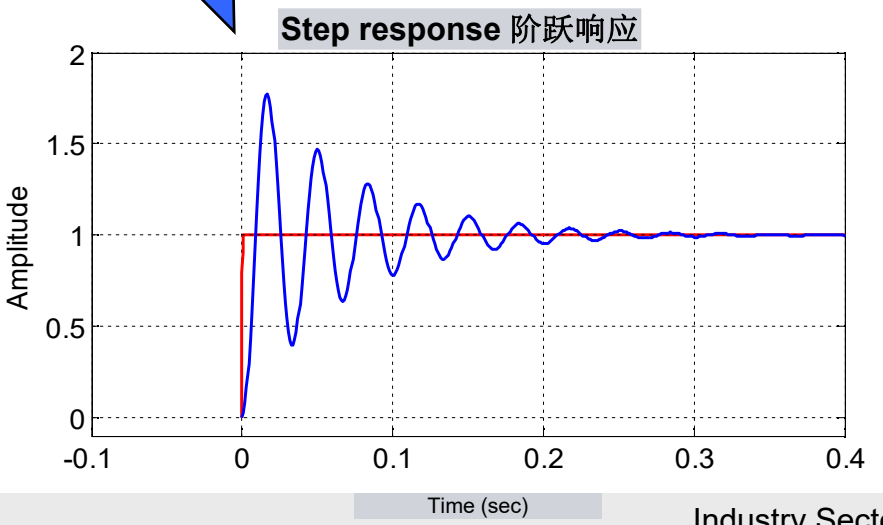
D = Damping 阻尼

注意阻尼加大时,幅频相频曲线的变化

频域和时域的测试之间是有关联的：

频域过0分贝的频率必然可以在时域的阶跃响应中有体现。

阻尼大对系统稳定有好处，但阻尼在机床上主要与摩擦相关，摩擦大导致过象限不好控制，另动静摩擦系数差别大导致“爬行”



Damping, Frequency und Step response
阻尼，频率和阶跃响应

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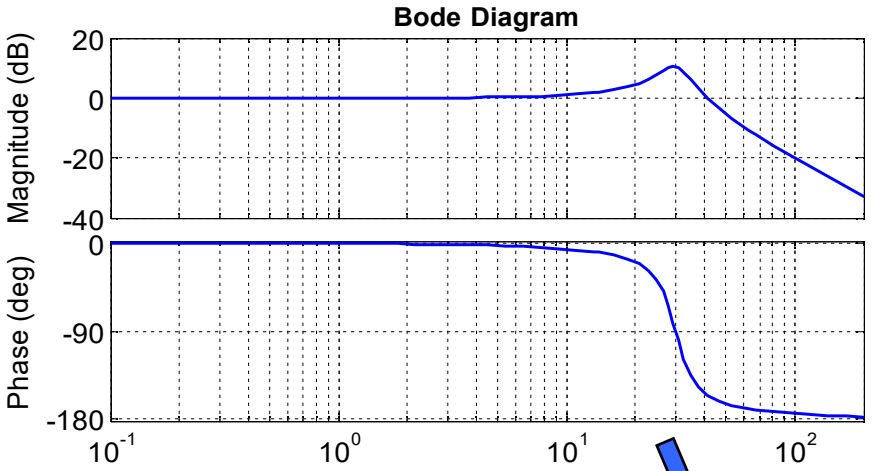

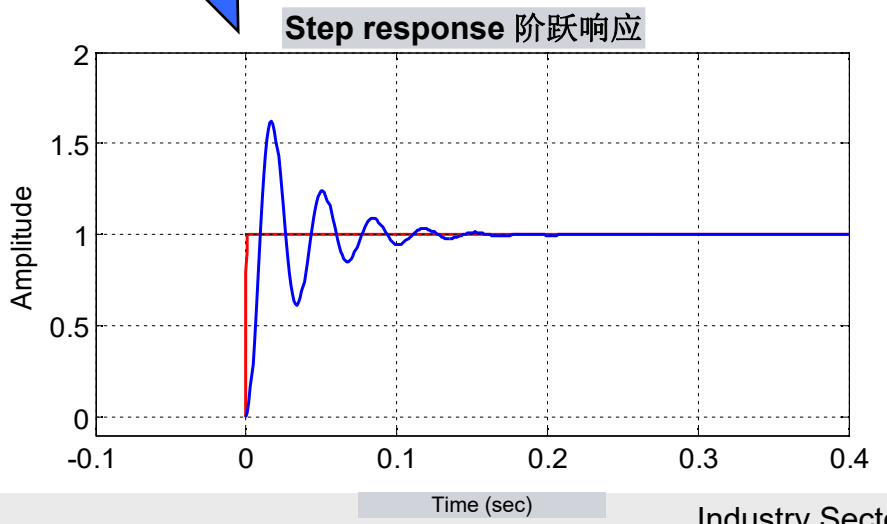

Damping, Frequency und Step response
阻尼，频率和阶跃响应

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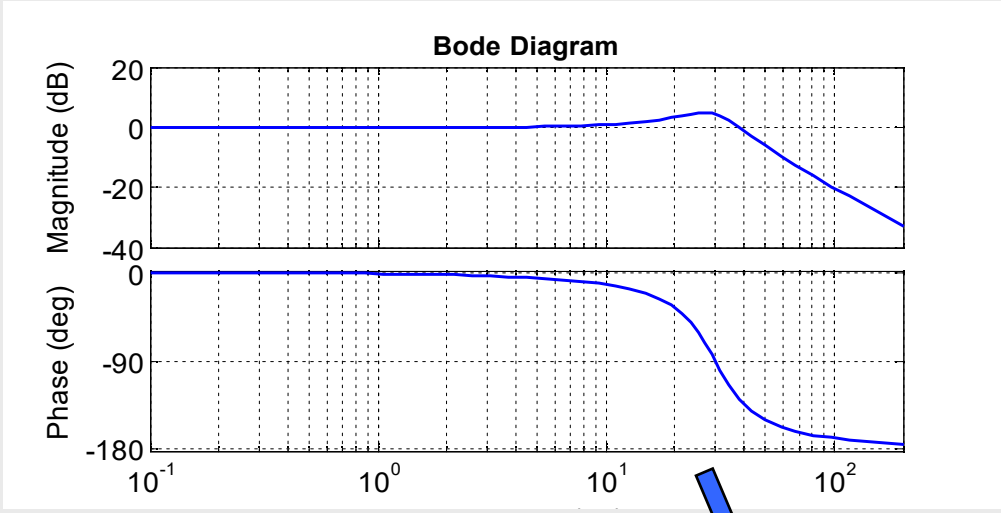

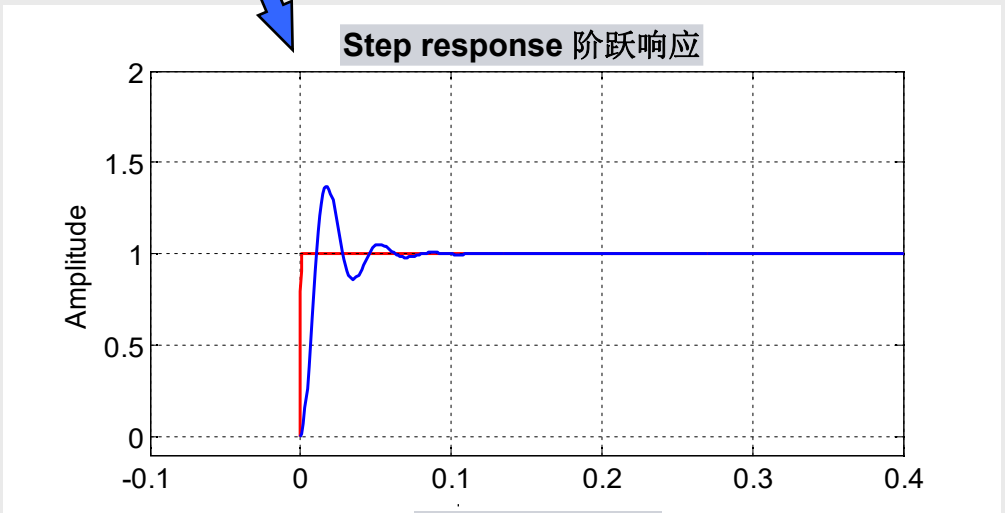

Damping, Frequency und Step response
阻尼，频率和阶跃响应

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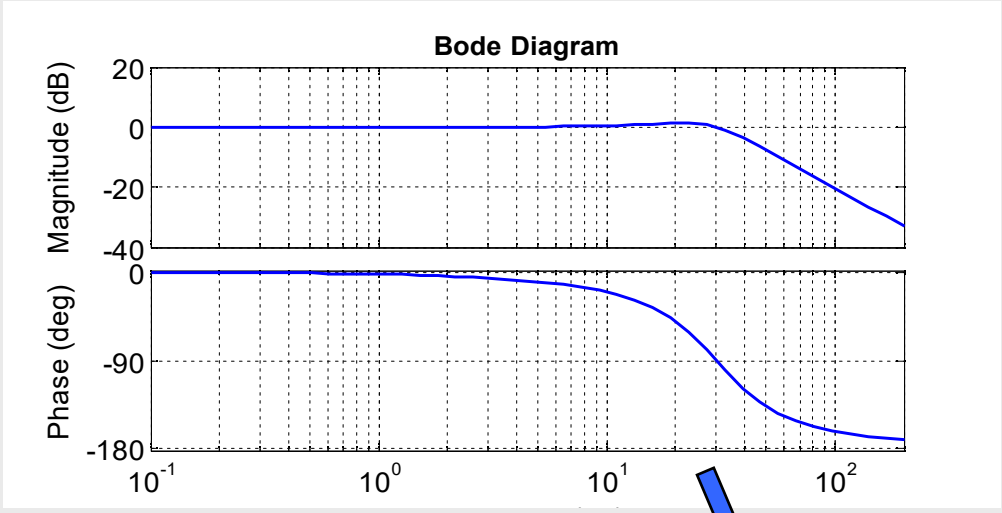

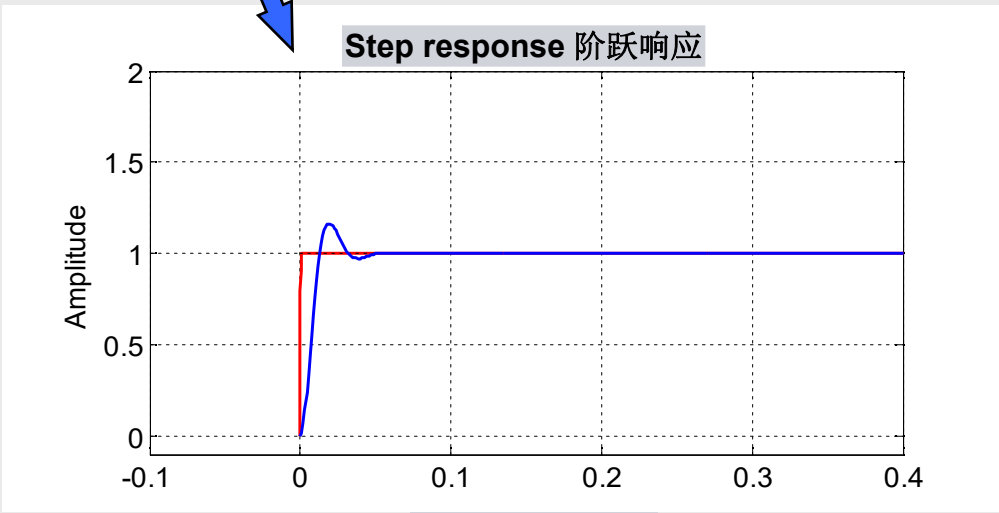

Positioning (x=500 mm) With Low Acceleration (a = 1 m/s²) Without Jerk Limitation (r = ∞)
无Jerk限制(r = ∞)的低加速度(a = 1 m/s²)定位

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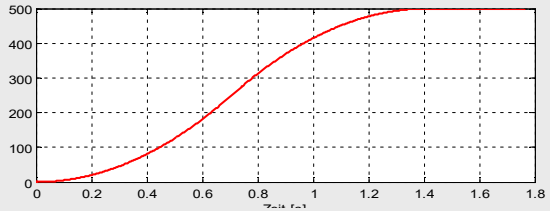
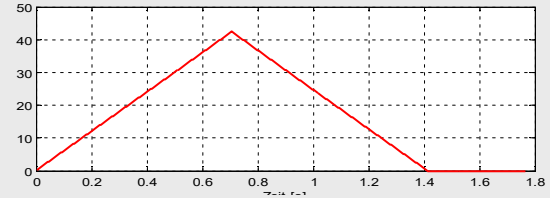
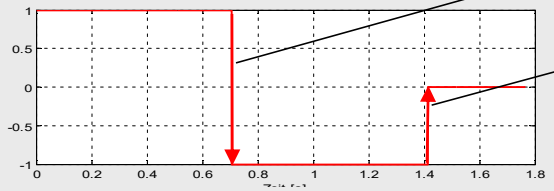
Position



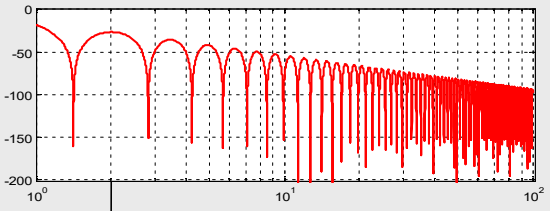
Velocity



Acceleration



Jerk Equivalent Filter

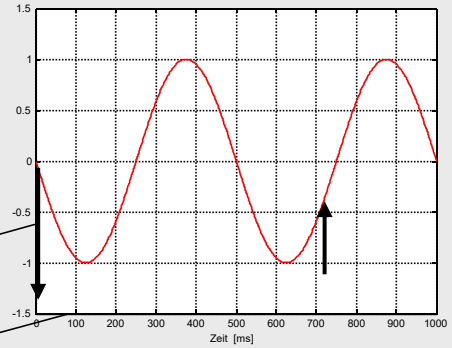


The positioning profile has no filter effect at 2Hz

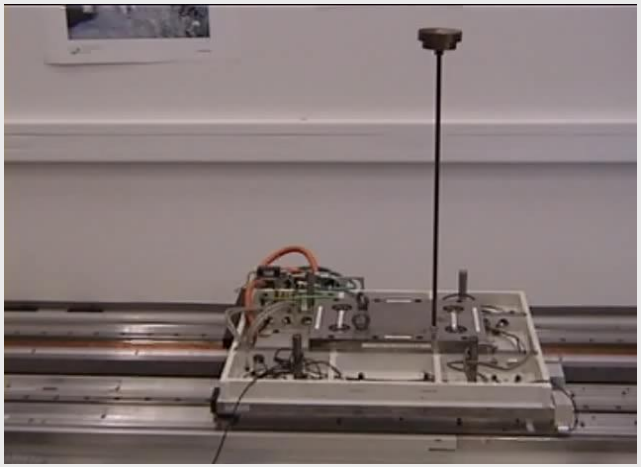
运动曲线对2Hz振荡没有滤波效果

Both Impulses are in the direction of the vibration and thus excite the oscillation of the stick

两个冲动与振动的方向相同，从而激励产生振荡



e.g. Resonant frequency at 2 Hz 如：共振频率2Hz



Positioning (x=500 mm) With a Higher Acceleration (a = 2 m/s²) Without Jerk Limitation (r = ∞)
无Jerk限制的高加速度定位

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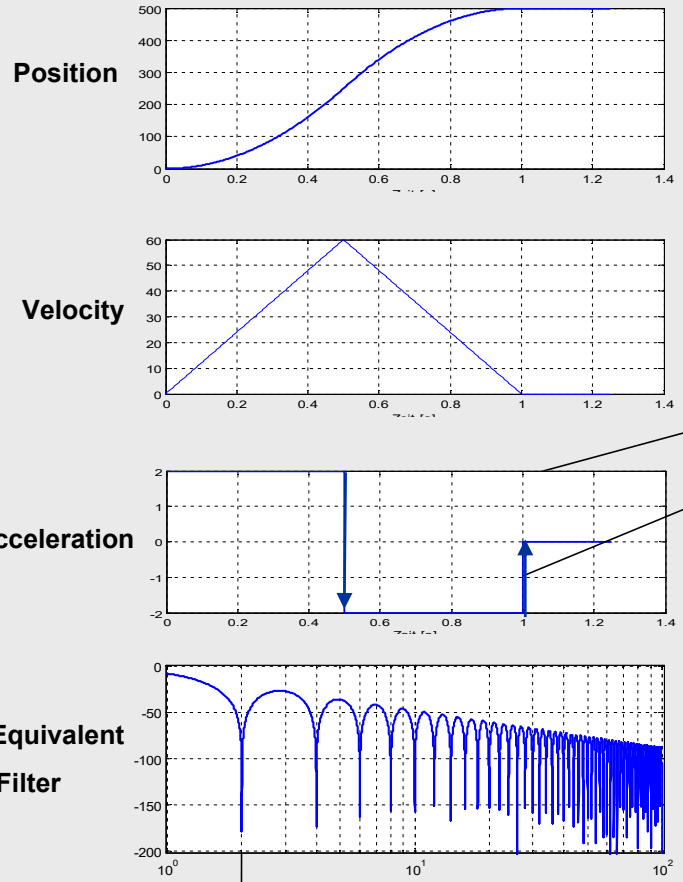
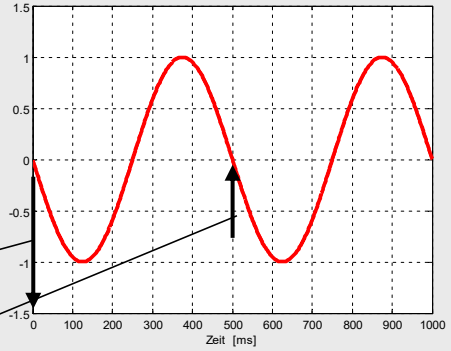


The positioning profile damps the oscillation at 2Hz very well

运动曲线对2Hz振荡有很好的衰减作用

The second Impulse is against the direction of the vibration and is canceled out

第二个冲动与振动方向相反，被抵消



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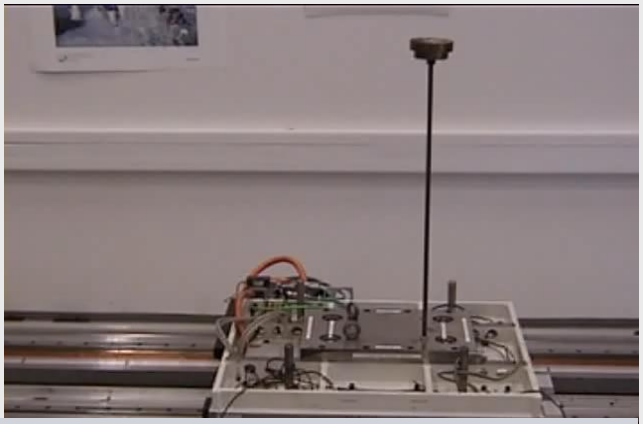

Positioning (x=500 mm) With Low and High Acceleration Without Jerk Limitation (r = ∞)
无Jerk限制的低加速度和高加速度定位对比

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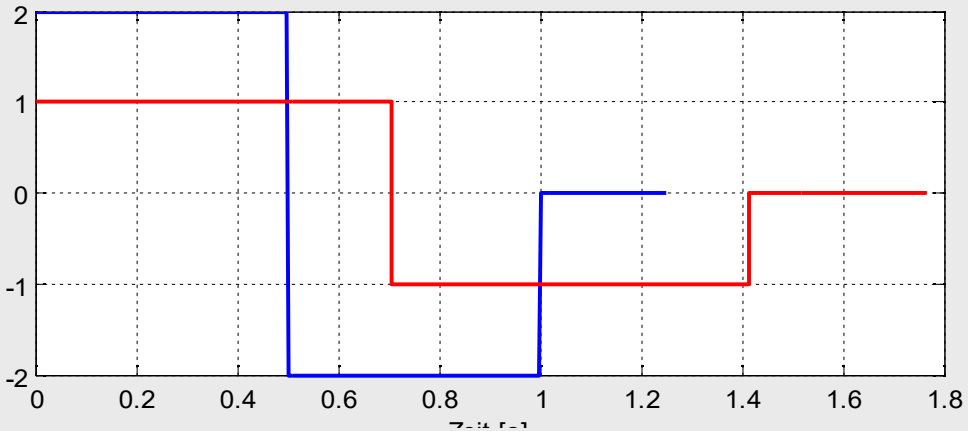
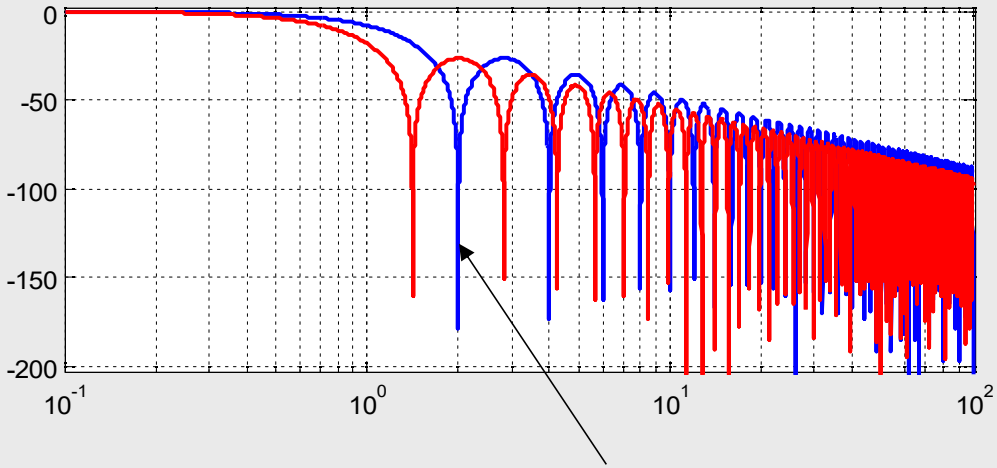
Acceleration
加速度



Jerk equivalent Filter
Jerk等效滤波



The jerk equivalent filter of the positioning profile with a = 1 m/s² (red) has at 2 Hz compared to a = 2 m/s² (blue) no filter effect!

a = 1 m/s² (red)定位曲线的等效Jerk滤波对比a = 2 m/s² (blue)定位曲线的等效Jerk滤波，在2Hz是没有滤波效果的

解释

Fourier series of a square-wave signal
正弦信号的富里叶级数

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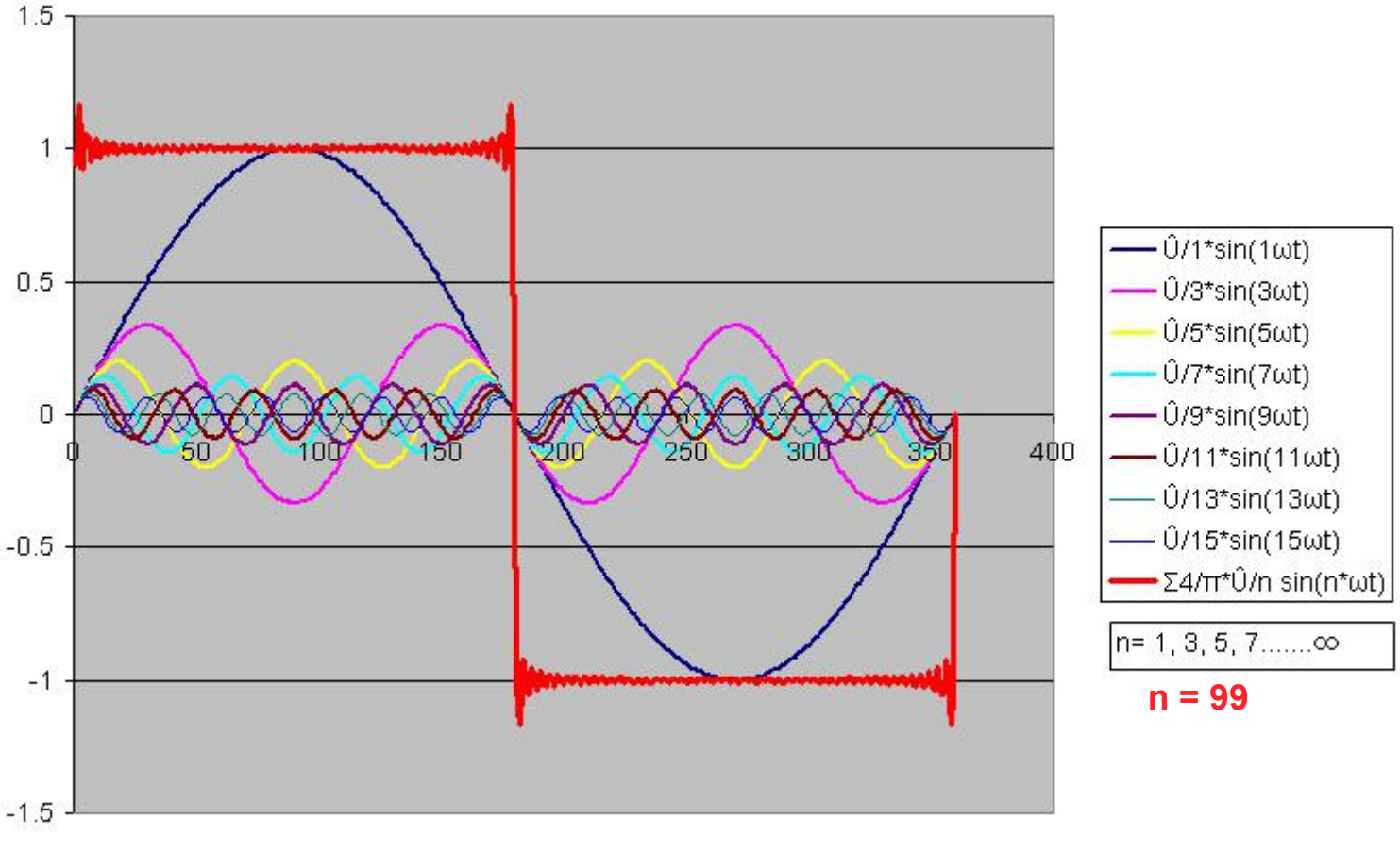
$$u(t) = \frac{4\hat{u}}{\pi}\left(sin(wt) + \frac{1}{3}sin(3wt) + \frac{1}{5}sin(5wt) + \ldots\right)$$



Fundamental Block Diagram of SINUMERIK 840D Servo and SIMODRIVE 611D (2)

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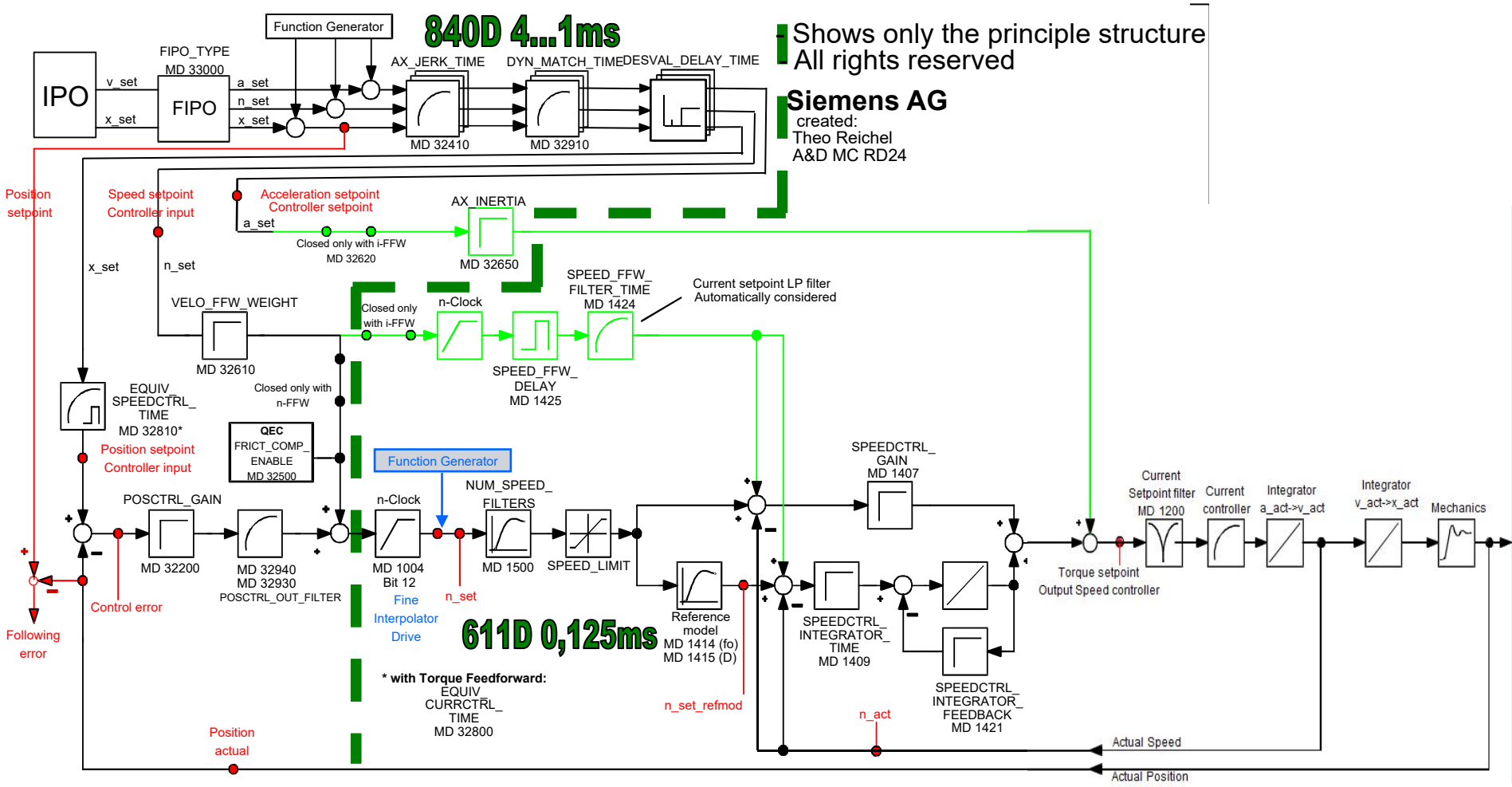

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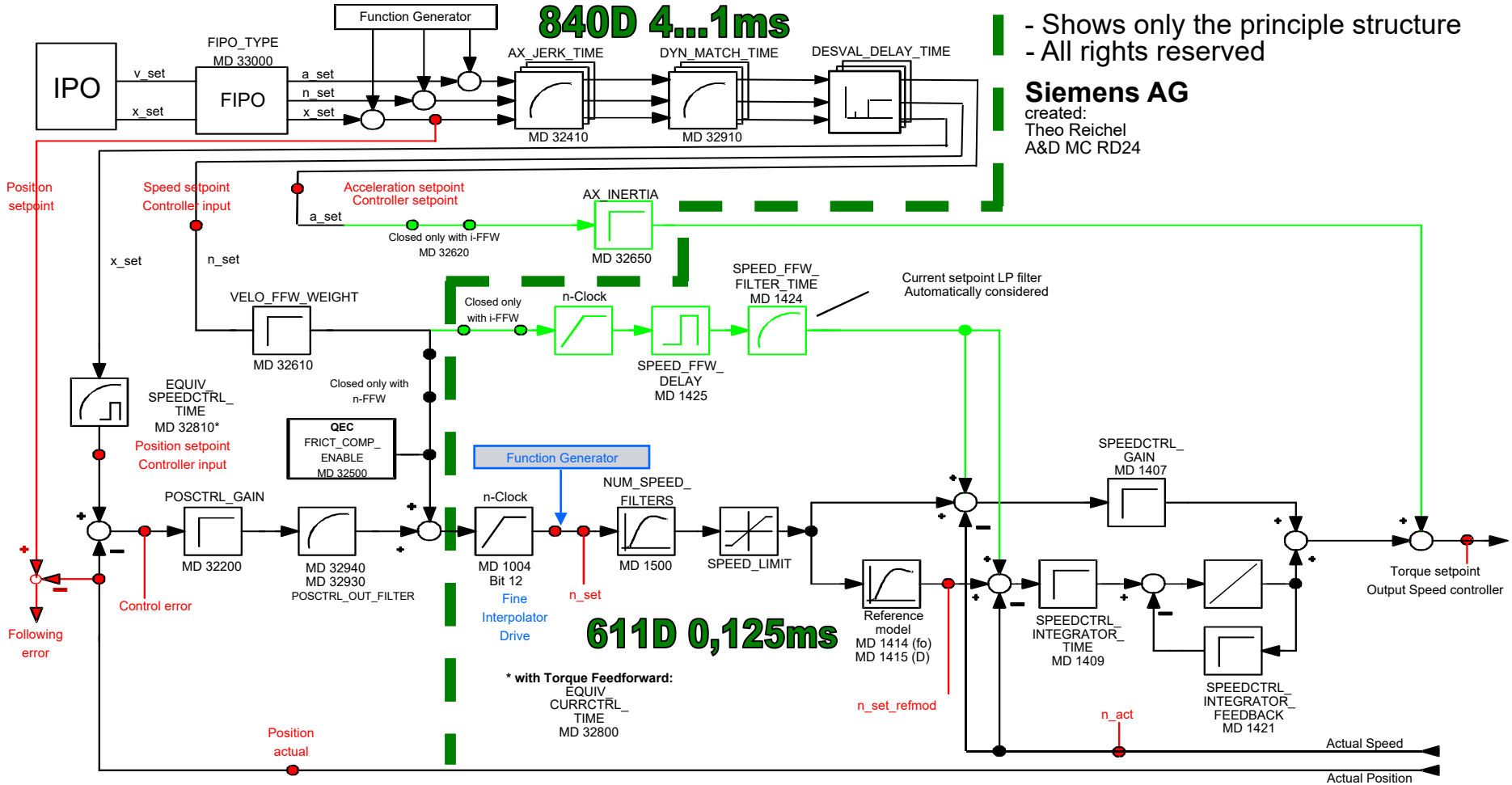

Fundamental Block diagram of SIMOTION V4.0 and SINAMICS S120 V02.03
SIMOTION 和 SINAMICS 的原理框图

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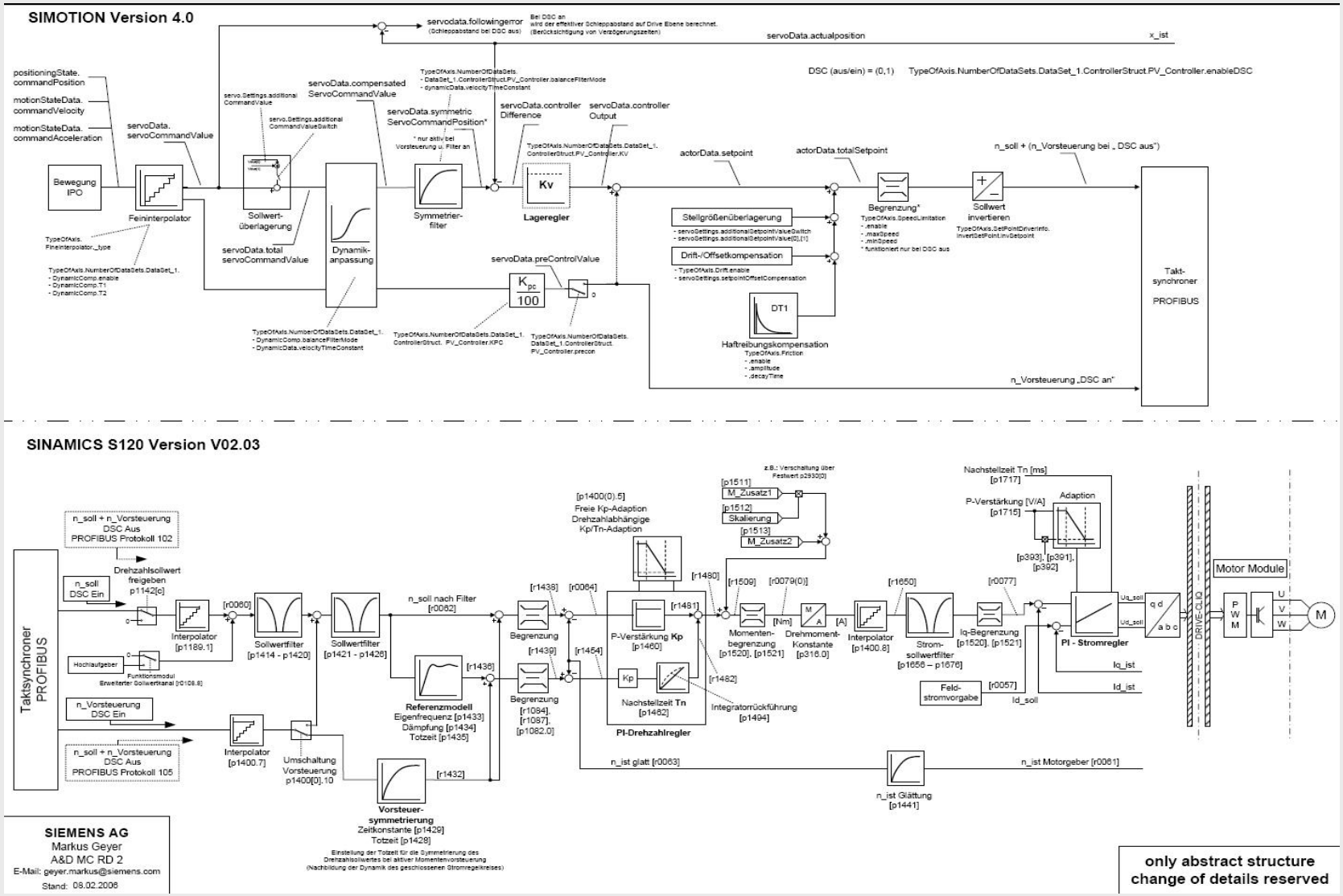

Overview of the Measurement Points Related to the Freq. Resp.
频率响应相关的测量点概览

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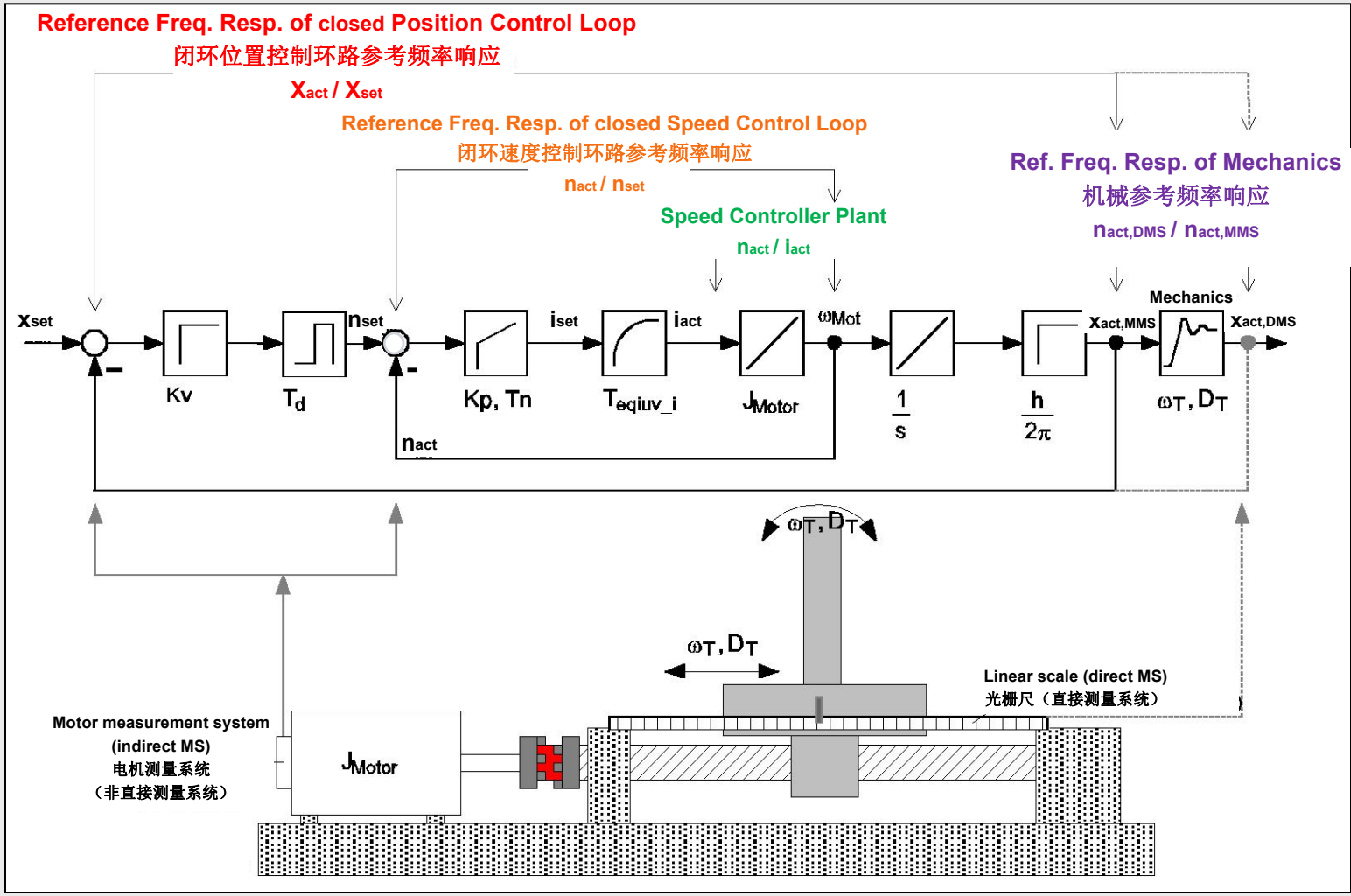

Freq. Resp. of the Speed Controller plant:
Speed Controller plant的频率响应

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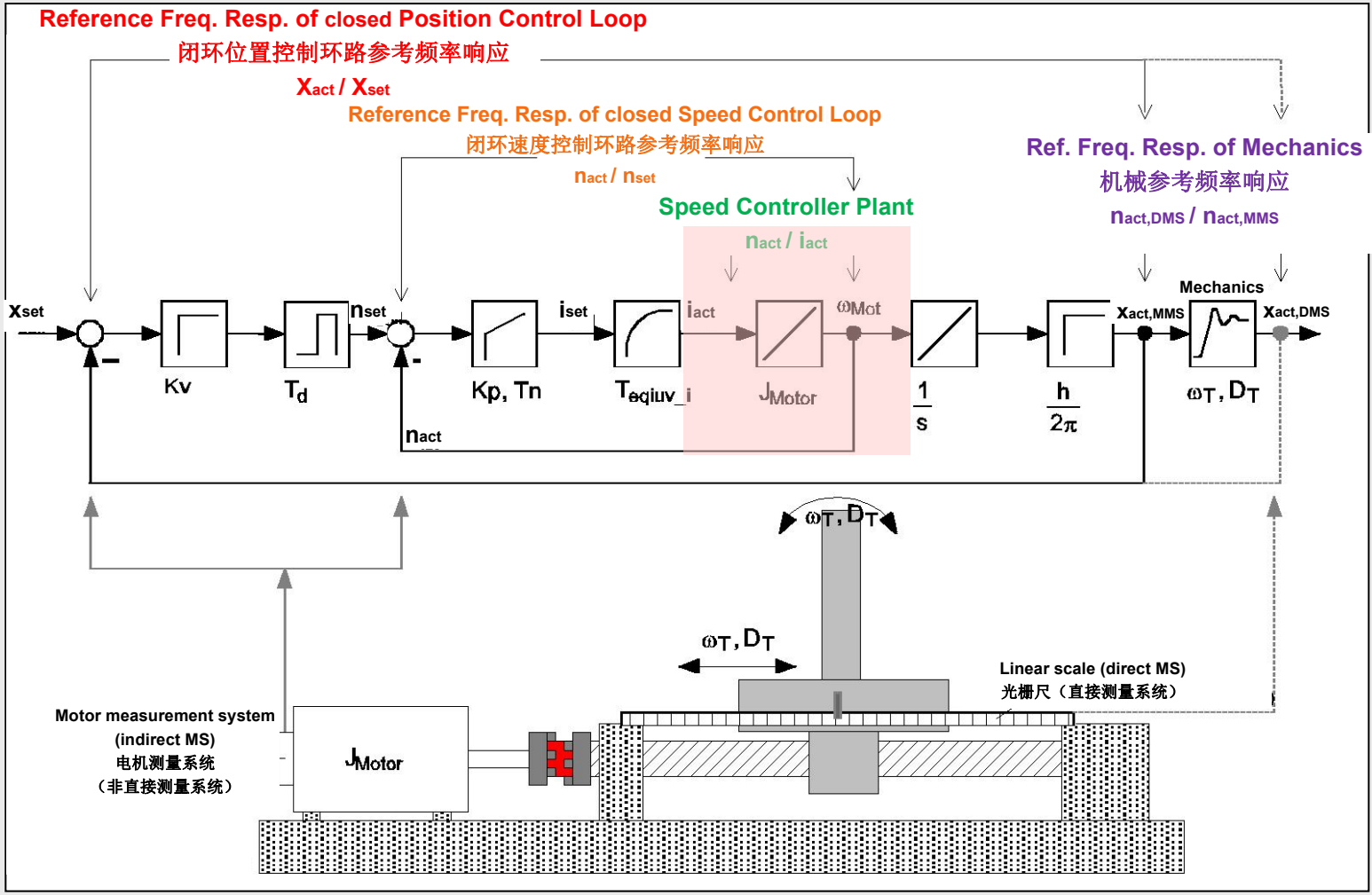
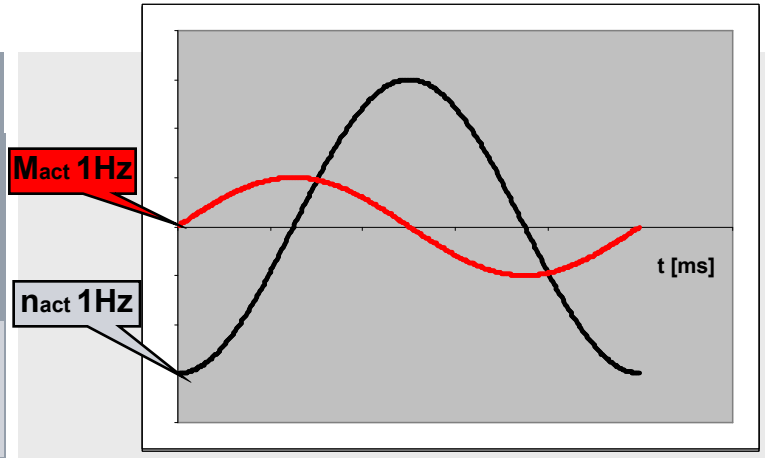
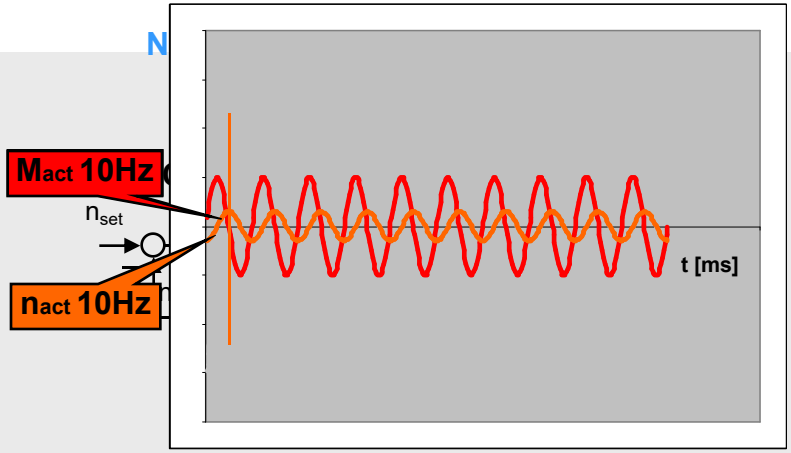
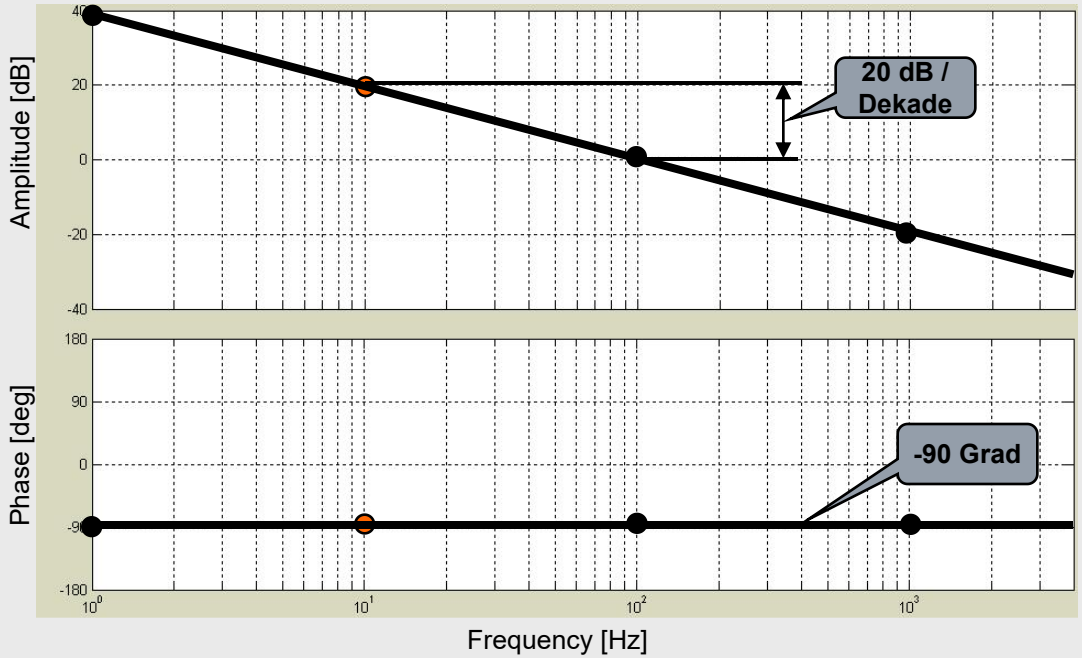






Bode-Diagram



$$\int \hat{A}\sin\omega t = -\frac{\hat{A}}{\omega}\cos\omega t$$

根据积分公式，频率提高10倍→幅值降低10倍

幅值降低10倍→在幅频图上降低20dB

→频率提高10倍幅值降低20dB

积分环节：

幅频曲线（20dB/10倍频）

相频曲线（-90度）

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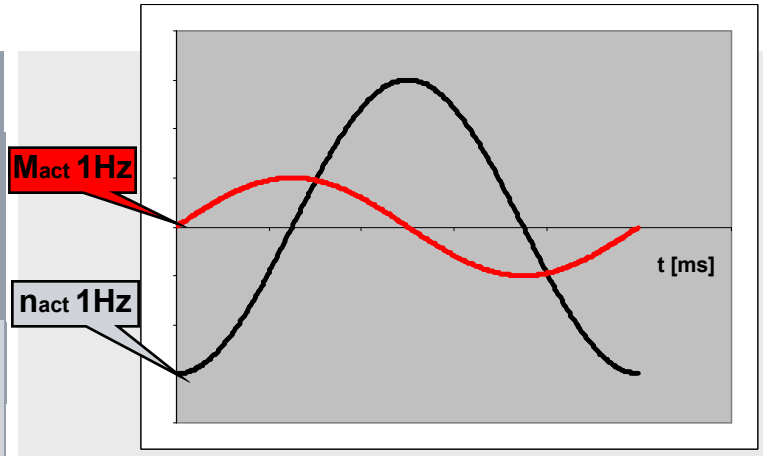
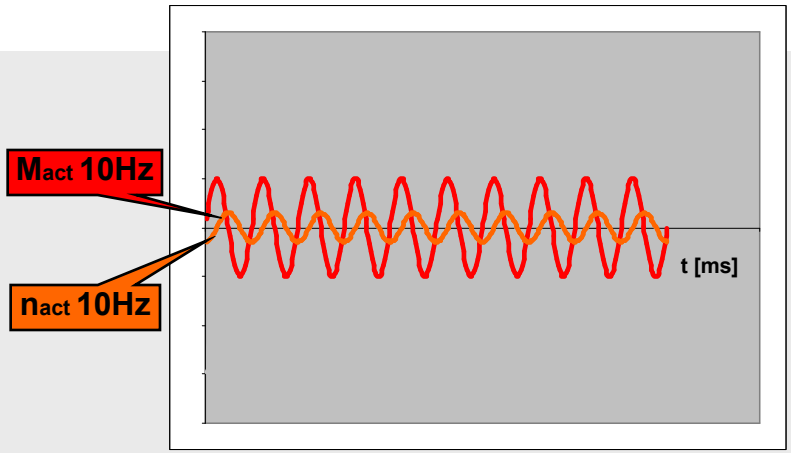
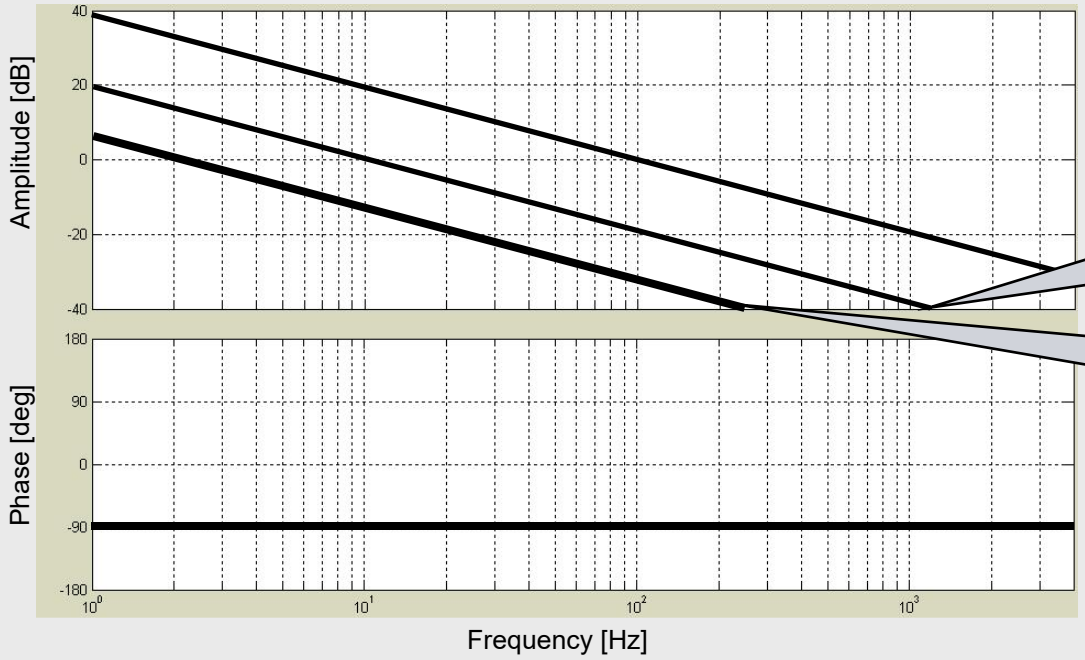




Bode-Diagram 伯德图



$$M = J * \alpha$$

Moment of inertia J 10 times greater
惯量大10倍

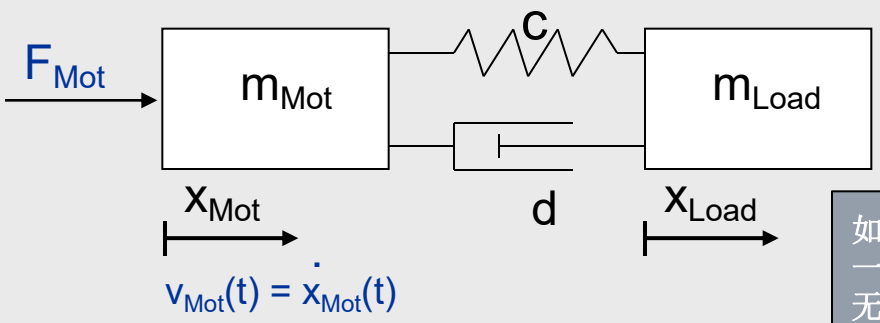
Moment of Inertia J even greater
惯量更大

F[N] = m[kg] * a[m/s²]

M[Nm] = J[kgm²] * α[rad/s²]

2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

SIEMENS



$v_{Mot}(t) = \dot{x}_{Mot}(t)$

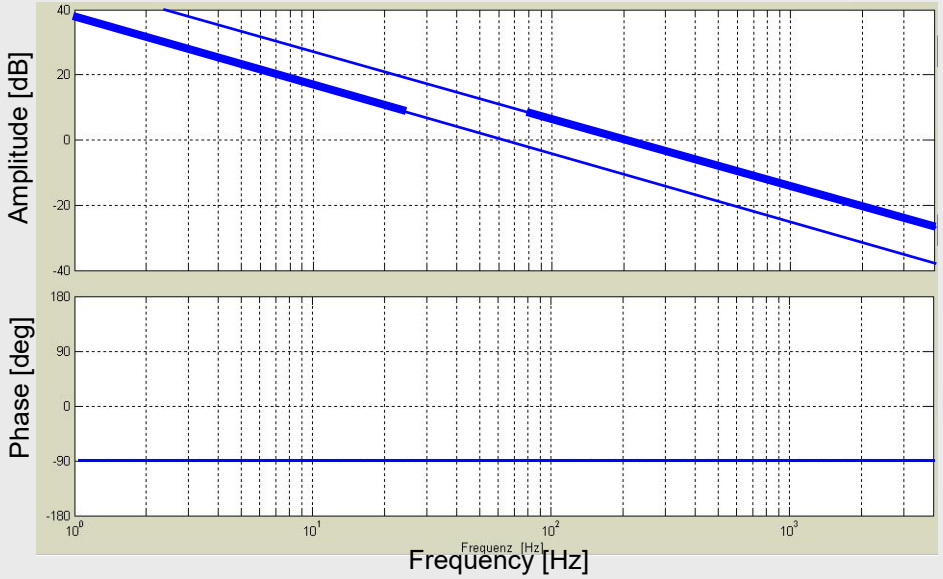
如果是双质量体，当频率高到一定程度，其中一个质量体将无法响应。这时在高频段就如同没有这个质量体。

看**Resonance**演示

Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数

$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

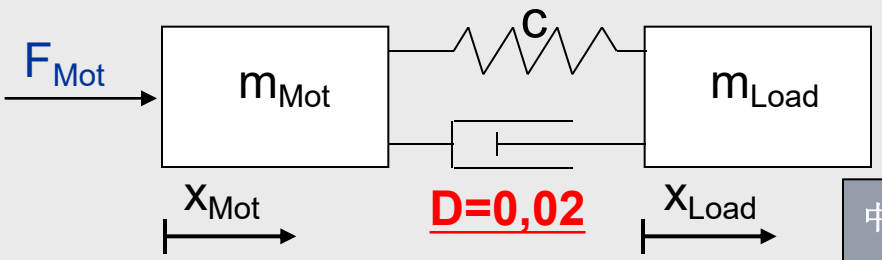
Bode-Diagram 伯德图



Industry Sector

2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

SIEMENS

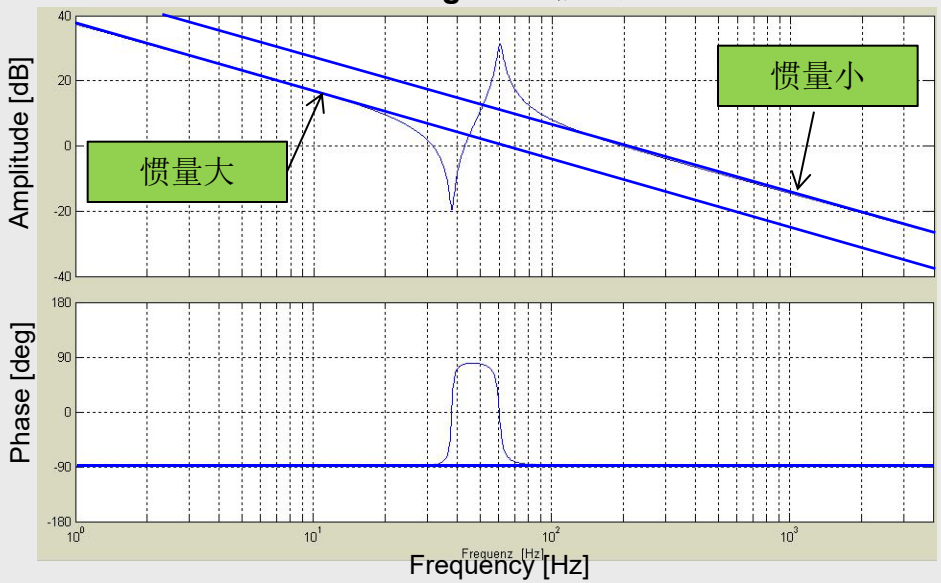


$v_{Mot}(t) = x_{Mot}(t)$

中间过渡段取决于阻尼环节

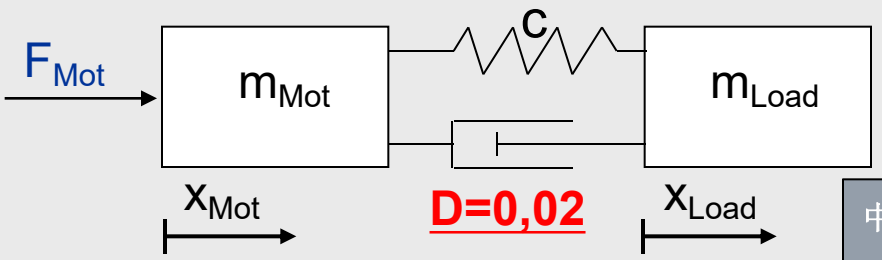
Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数
$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

Bode-Diagram 伯德图



2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

SIEMENS



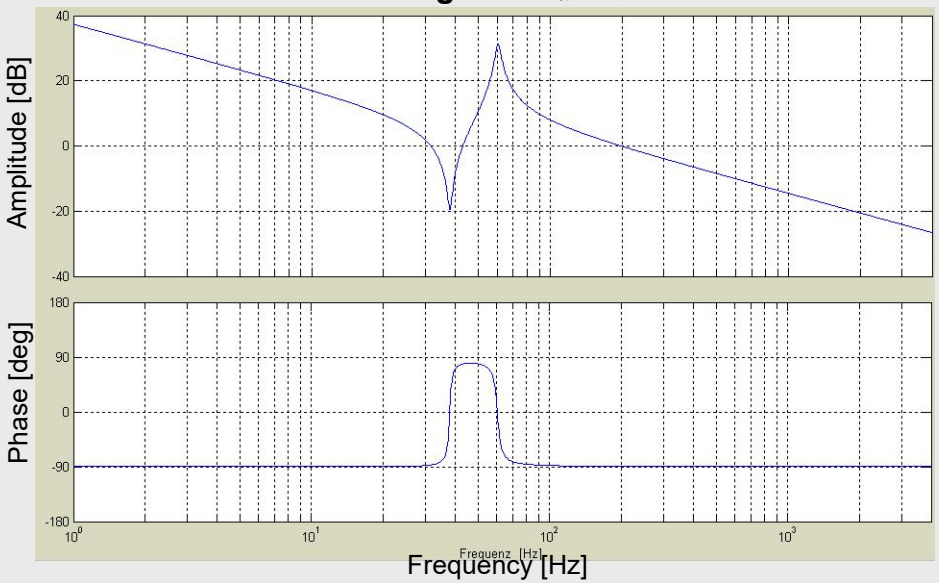
$v_{Mot}(t) = x_{Mot}(t)$

中间过渡段取决于阻尼环节

Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数

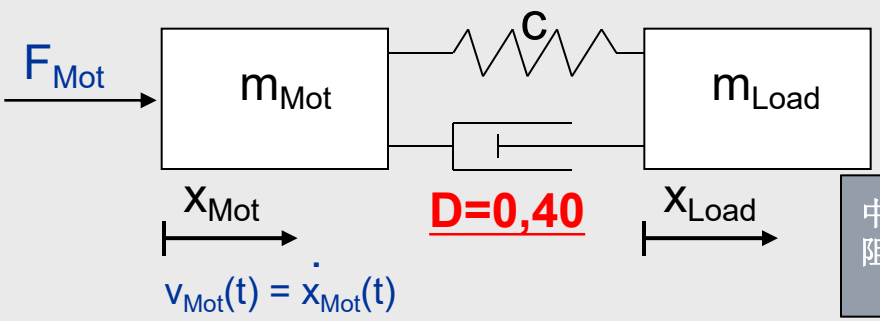
$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

Bode-Diagram 伯德图



2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

SIEMENS



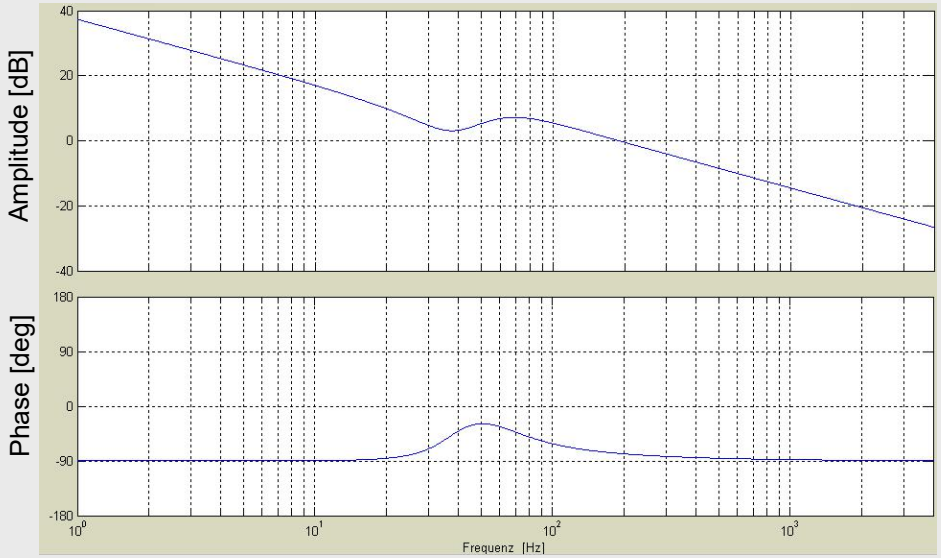
$v_{Mot}(t) = \dot{x}_{Mot}(t)$

中间过渡段取决于阻尼环节，阻尼大过渡段平稳

Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数

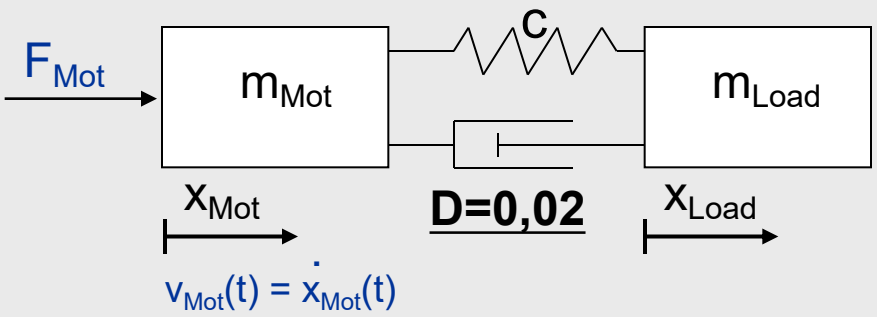
$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

Bode-Diagram 伯德图



2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

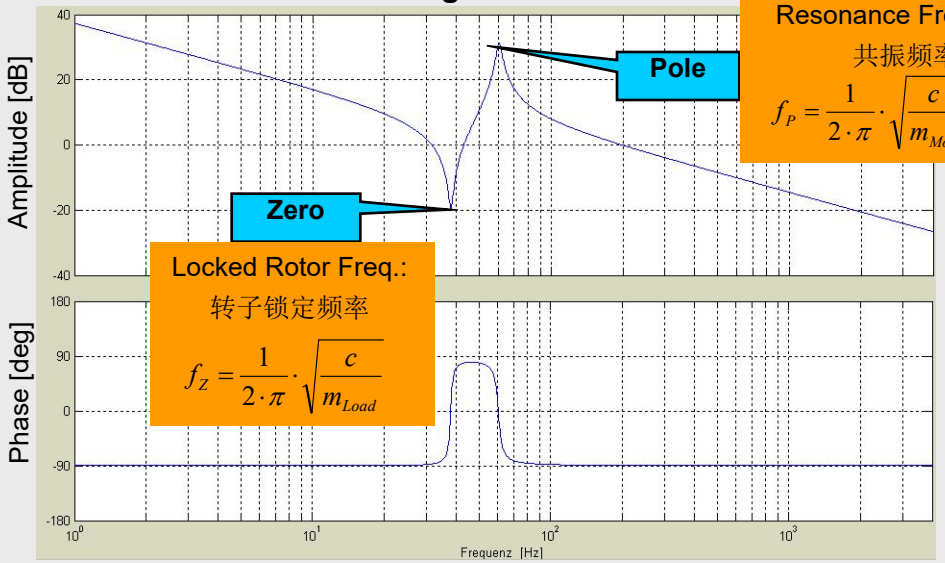
SIEMENS



分别计算机械惯量:电机惯量=3:1和机械惯量:电机惯量=5:1时,可以计算出fp随惯量增加,向右方移动

Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数
$G_{SpeedControllerPlant}(s) = V_{Mot}(s) / F_{Mot}(s)$

Bode-Diagram 伯德图



Resonance Frequency
共振频率:

$$f_P = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{m_{Mot}} + \frac{c}{m_{Load}}}$$

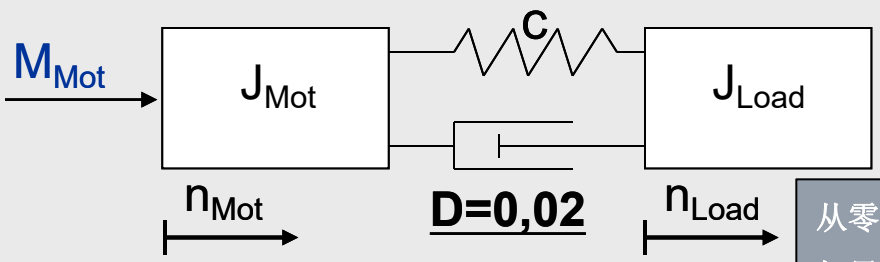
Locked Rotor Freq.:
转子锁定频率

$$f_Z = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{m_{Load}}}$$

c: [N/m]
m: [kg]

2-Mass-Oscillator (Motor and Load Inertia)
双质量振动器 （电机和负载质量）

SIEMENS



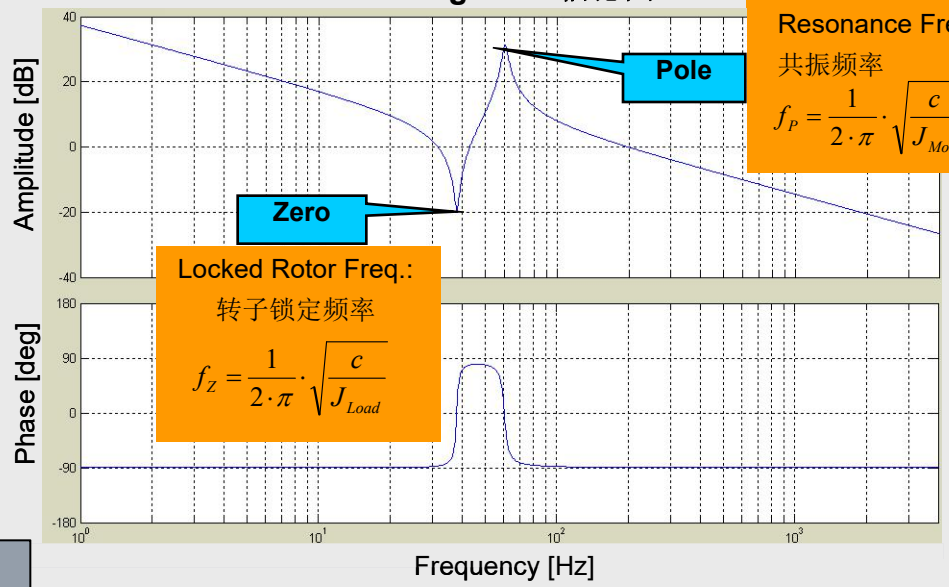
从零点和极点计算公式可以看出：

如果弹性系数大，即刚性好，则转子锁定频率和共振频率高。

如果负载惯量远大于电机惯量，则零点和极点频率差距拉大，不利于驱动的优化

Transfer Function of the Speed Controller plant:
Speed Controller plant的传递函数
$G_{SpeedControllerPlant}(s) = n_{Mot}(s)/ M_{Mot}(s)$

Bode-Diagram 伯德图



Resonance Frequency:
共振频率

$$f_P = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{J_{Mot}} + \frac{c}{J_{Load}}}$$

Locked Rotor Freq.:
转子锁定频率

$$f_Z = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{J_{Load}}}$$

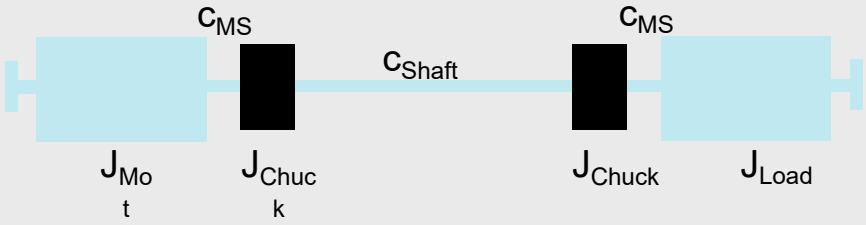
c: [Nm/rad]

J: [kgm²]

参数变化

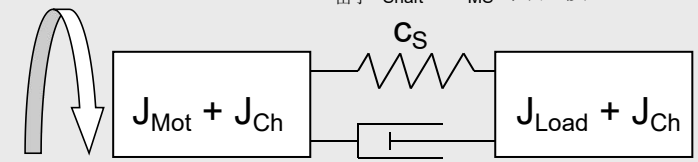
“2”-Mass-Oscillator (Motor and Load Inertia)
双质量振动器 （电机和负载质量）

SIEMENS



because of $c_{Shaft} << c_{MS}$ we use following reduced model:

由于$c_{Shaft} << c_{MS}$ 简化模型



M_{Mot}, φ_{Mot}

电机，卡爪，细杆所有相关参数都已知。根据前面的公式可算出两个频率

$$f_Z = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{J_{Load}}}$$

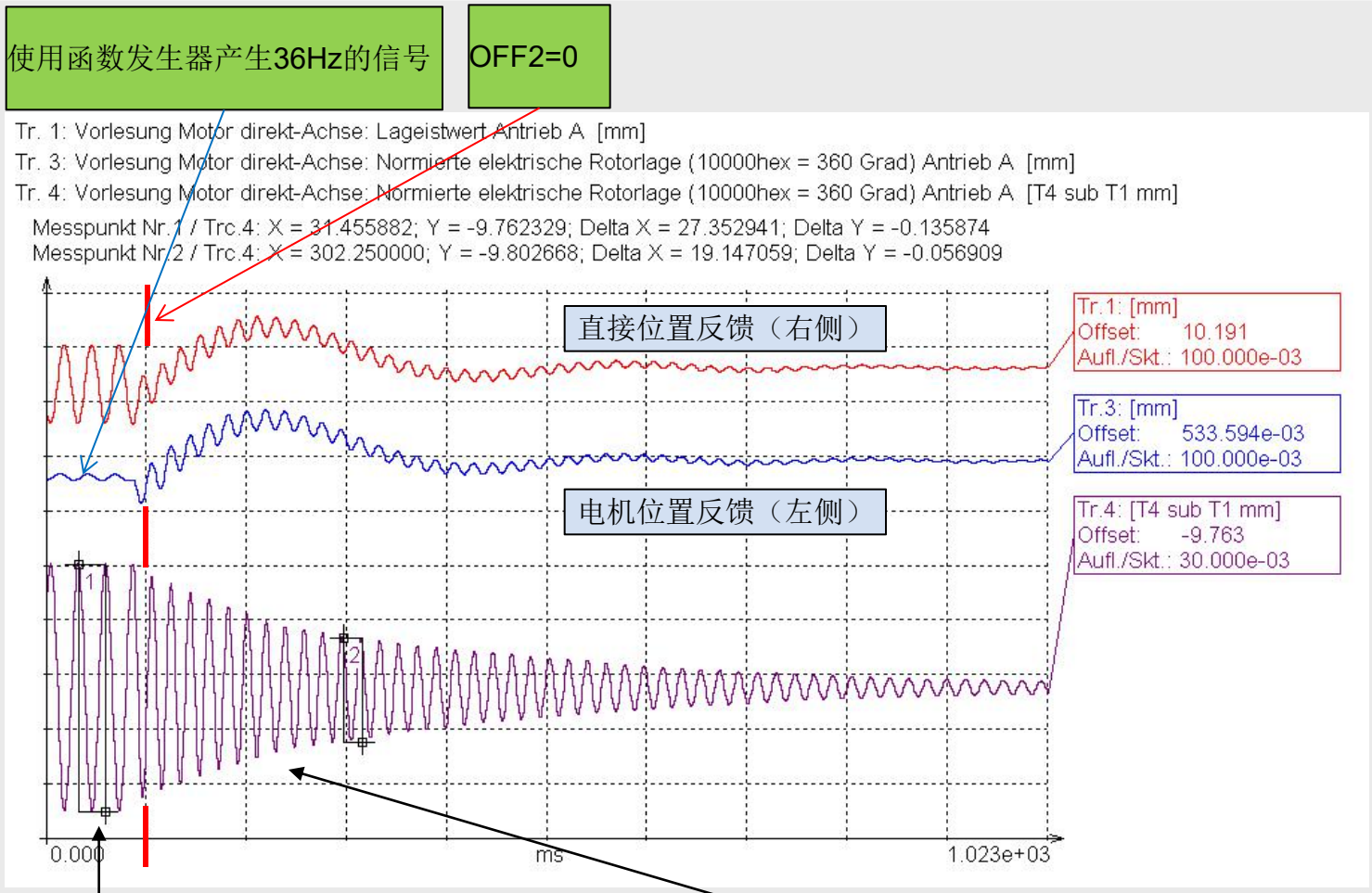
$$f_P = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{c}{J_{Mot}} + \frac{c}{J_{Load}}}$$

36 Hz Locked Rotor Frequency
36 Hz 转子锁定频率

52 Hz Resonance Frequency
52 Hz共振频率

Transition from controlled to uncontrolled system
受控系统到非受控系统的转换

SIEMENS



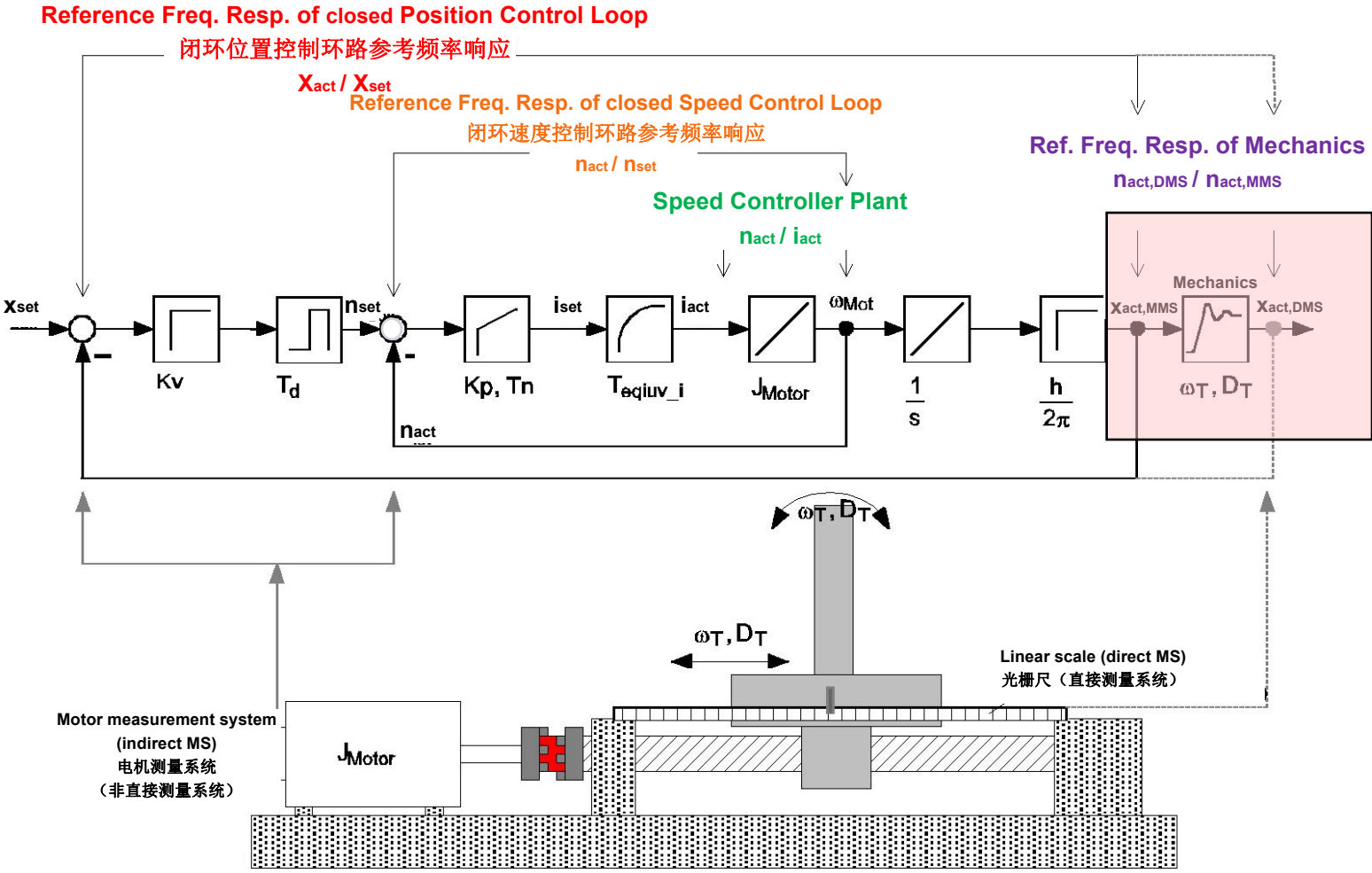
36 Hz Locked Rotor Frequency
36 Hz 转子锁定频率

52 Hz Resonance Frequency
52 Hz共振频率

Freq. Resp. of the Mechanics:
机械频率响应

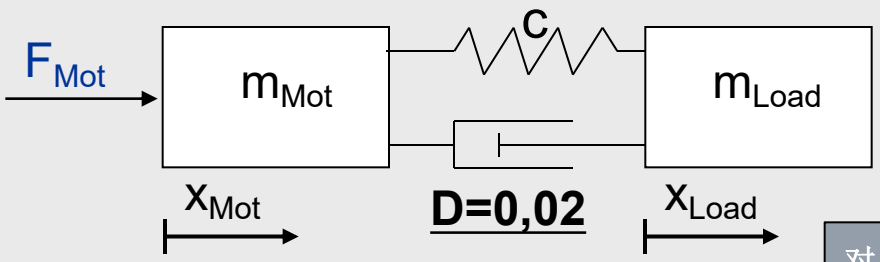
actual speed linearscale
actual speed motor encoder

SIEMENS



2-Mass-Oscillator (Motor and Load Mass)
双质量振动器 （电机和负载质量）

SIEMENS



$v_{Mot}(t) = x_{Mot}(t)$

Transfer Function of the Speed Controller p

$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

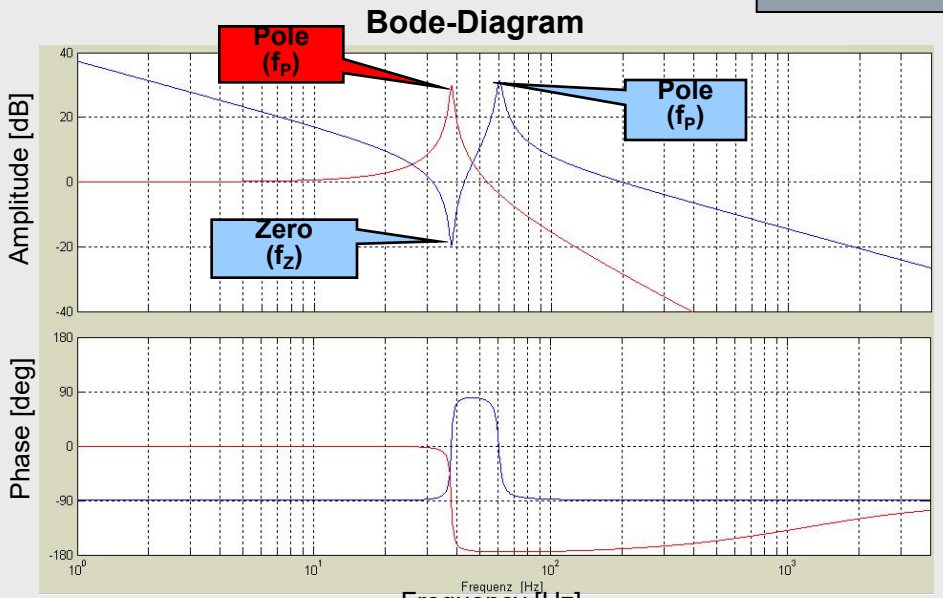
Transfer Function of the Mechanics:

$G_{Mech}(s) = V_{Load}(s)/ V_{Mot}(s)$

对比机械频率响应和速度控制系统响应：

机械频率响应只有转子锁定频率（对应零点）

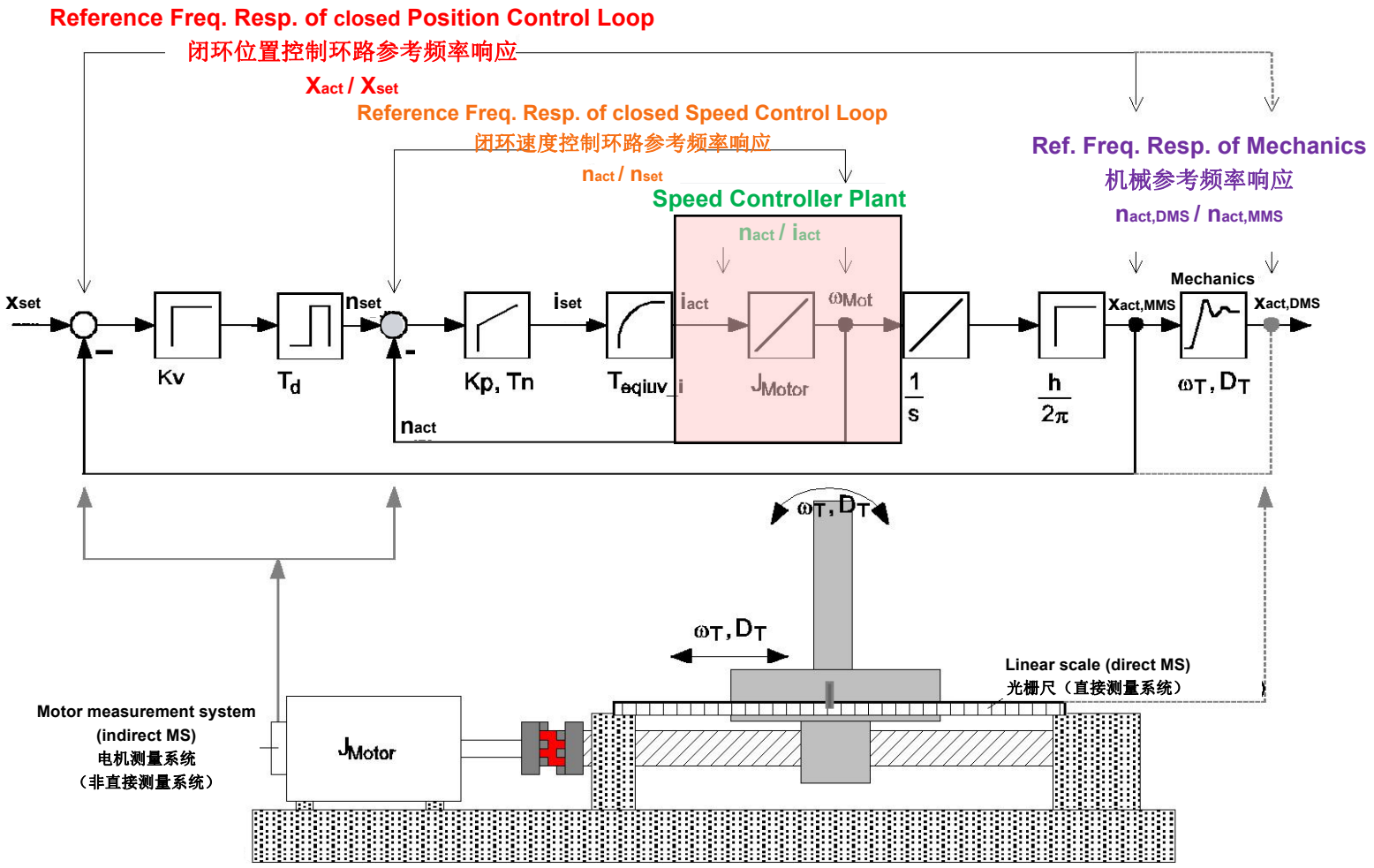
转子锁定频率相位-90度



Freq. Resp. of the Speed Controller Plant:
Speed Controller Plant的频率响应

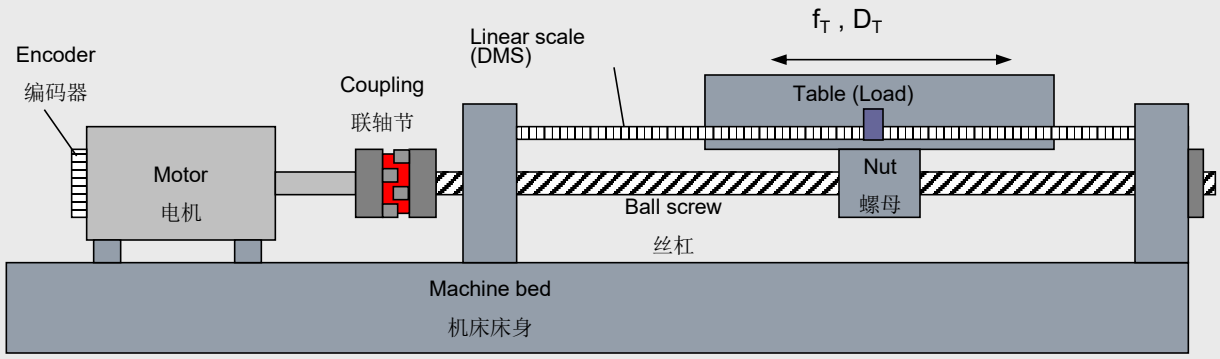
actual speed motor
actual torque motor

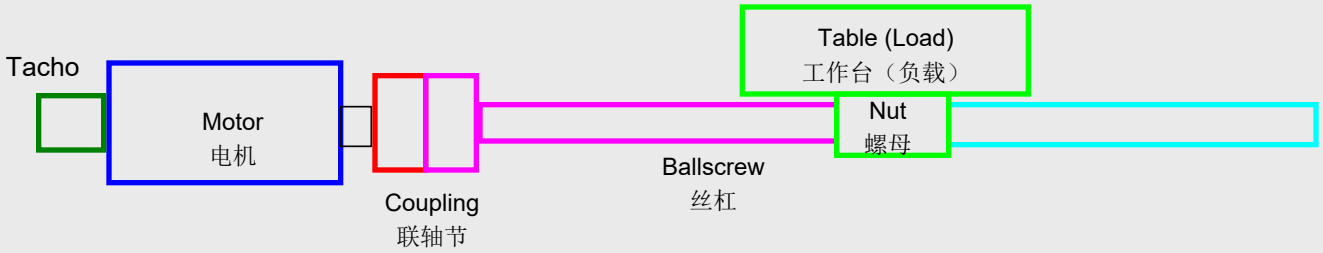
SIEMENS

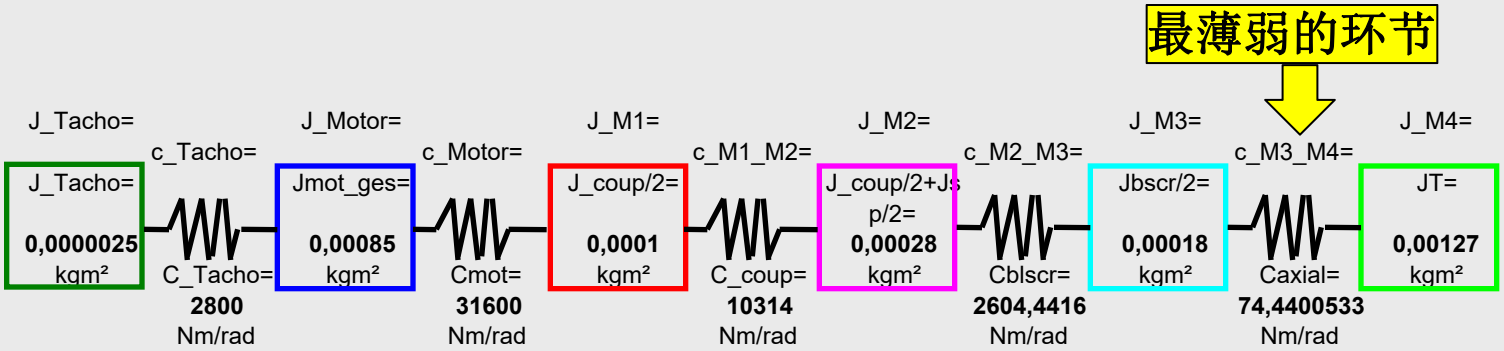


Mass und Stiffness Distribution of a Linear Machine Axis:
机床直线轴的质量和刚性分布

SIEMENS

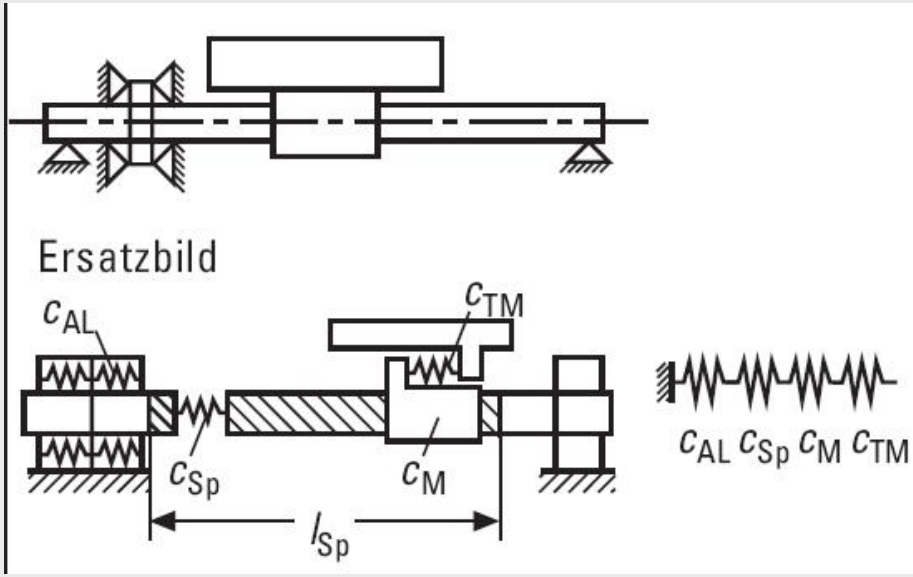






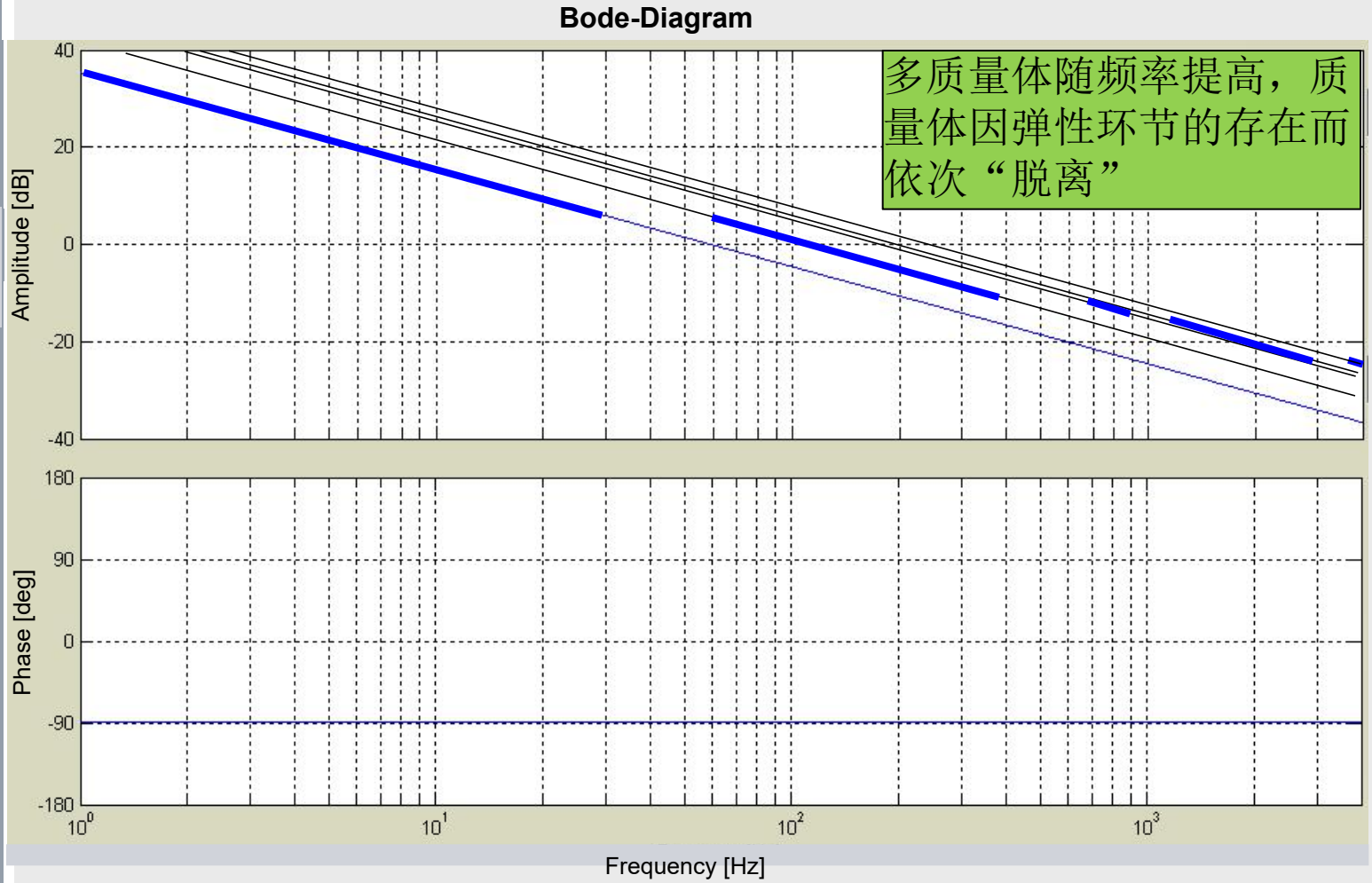
Mass und Stiffness Distribution of a Linear Machine Axis:
机床直线轴的质量和刚性分布

SIEMENS



$$\frac{1}{c_a} = \frac{1}{c_{AL}} + \frac{1}{c_{Sp}} + \frac{1}{c_M} + \frac{1}{c_{TM}}$$

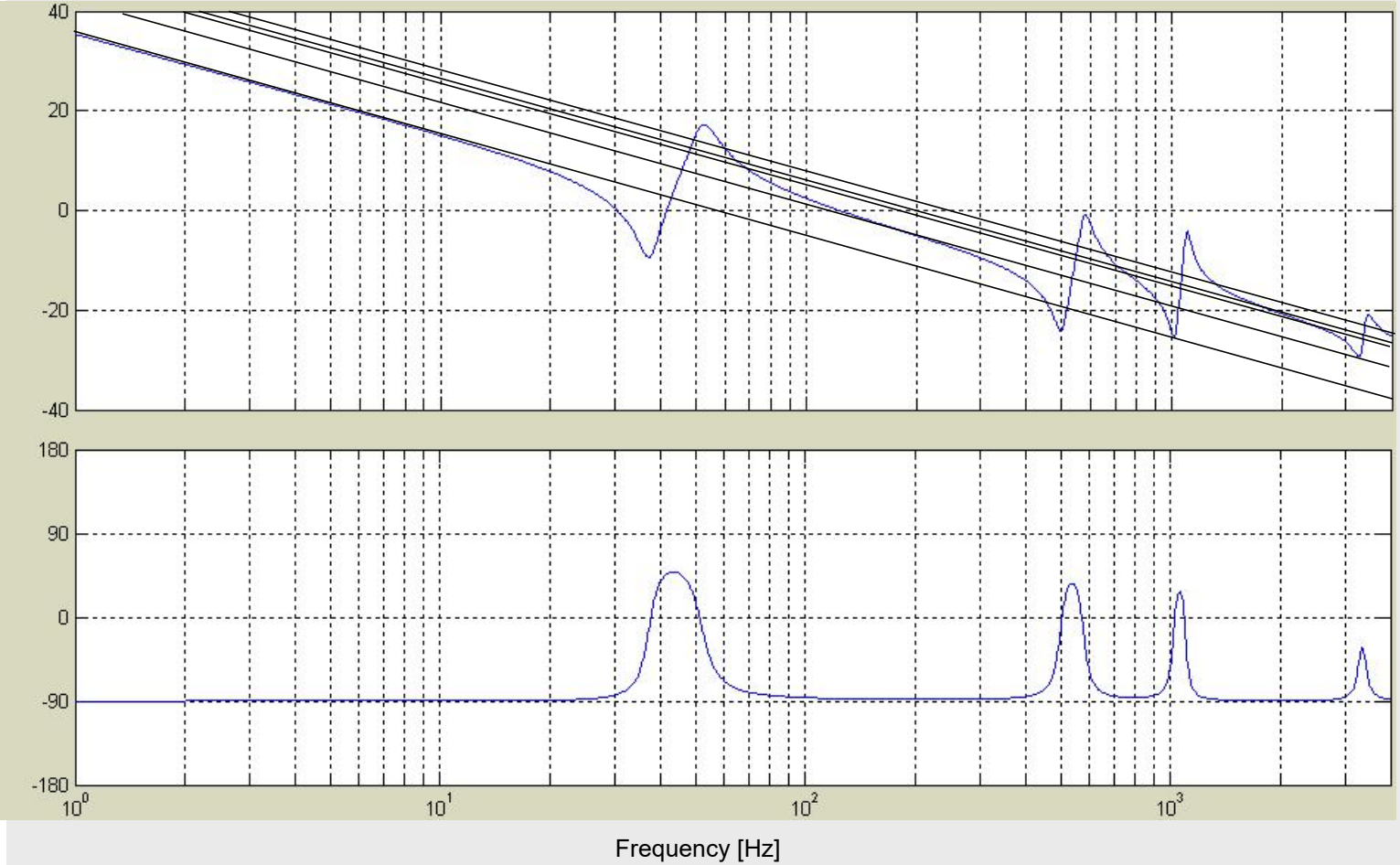
Freq. Resp. of the Speed Controller Plant: Multiple Body System
Speed Controller Plant 的频率响应：多质量系统



Freq. Resp. of the Speed Controller plant: Multiple Body System

$$\frac{\text{actual Speed Motor}}{\text{actual Torque Motor}}$$

SIEMENS



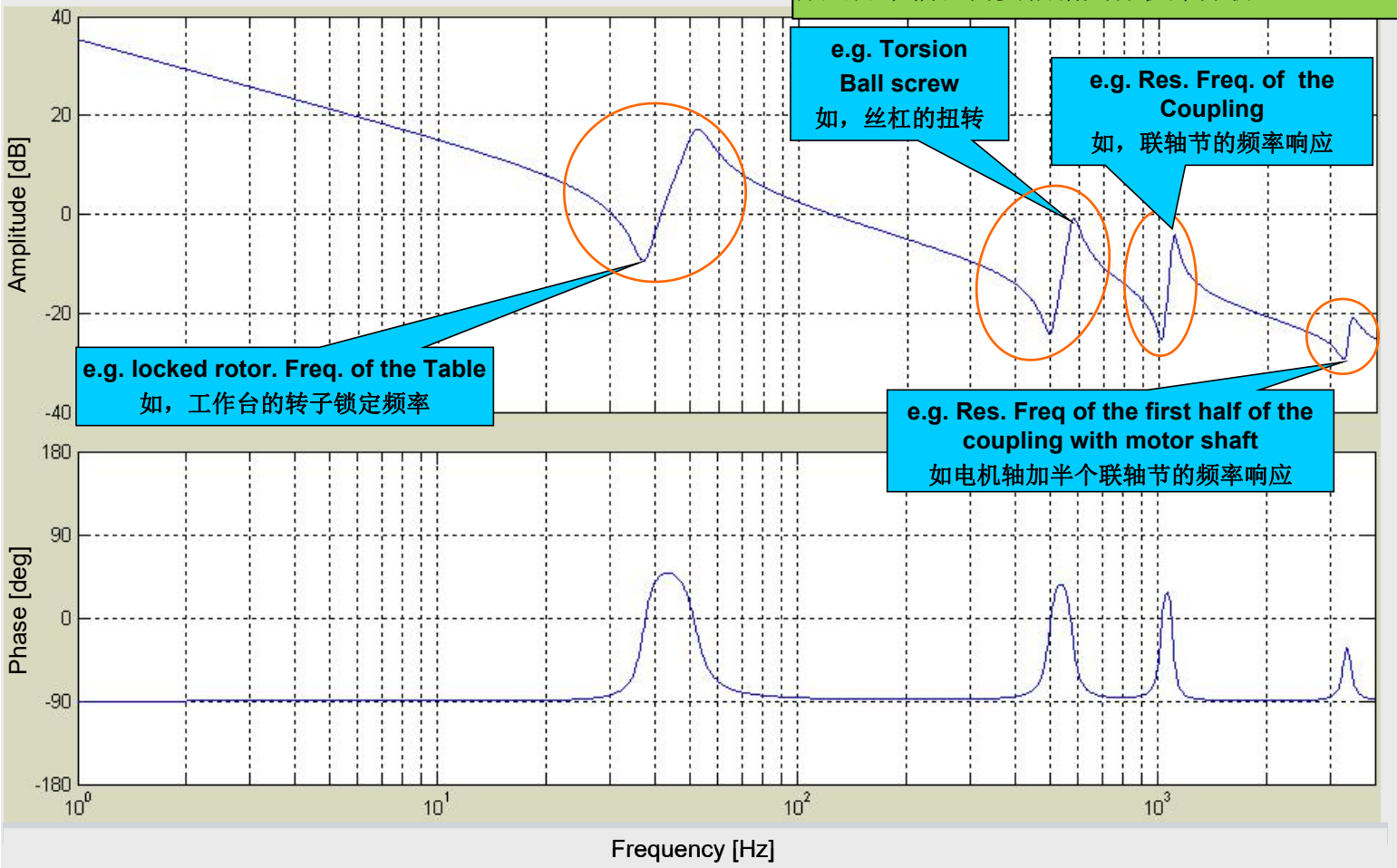
Freq. Resp. of the Speed Controller plant: Multiple Body System

Speed Controller Plant 的频率响应：多质量系统

SIEMENS

$$\frac{\text{actual Speed Motor}}{\text{actual Torque Motor}}$$

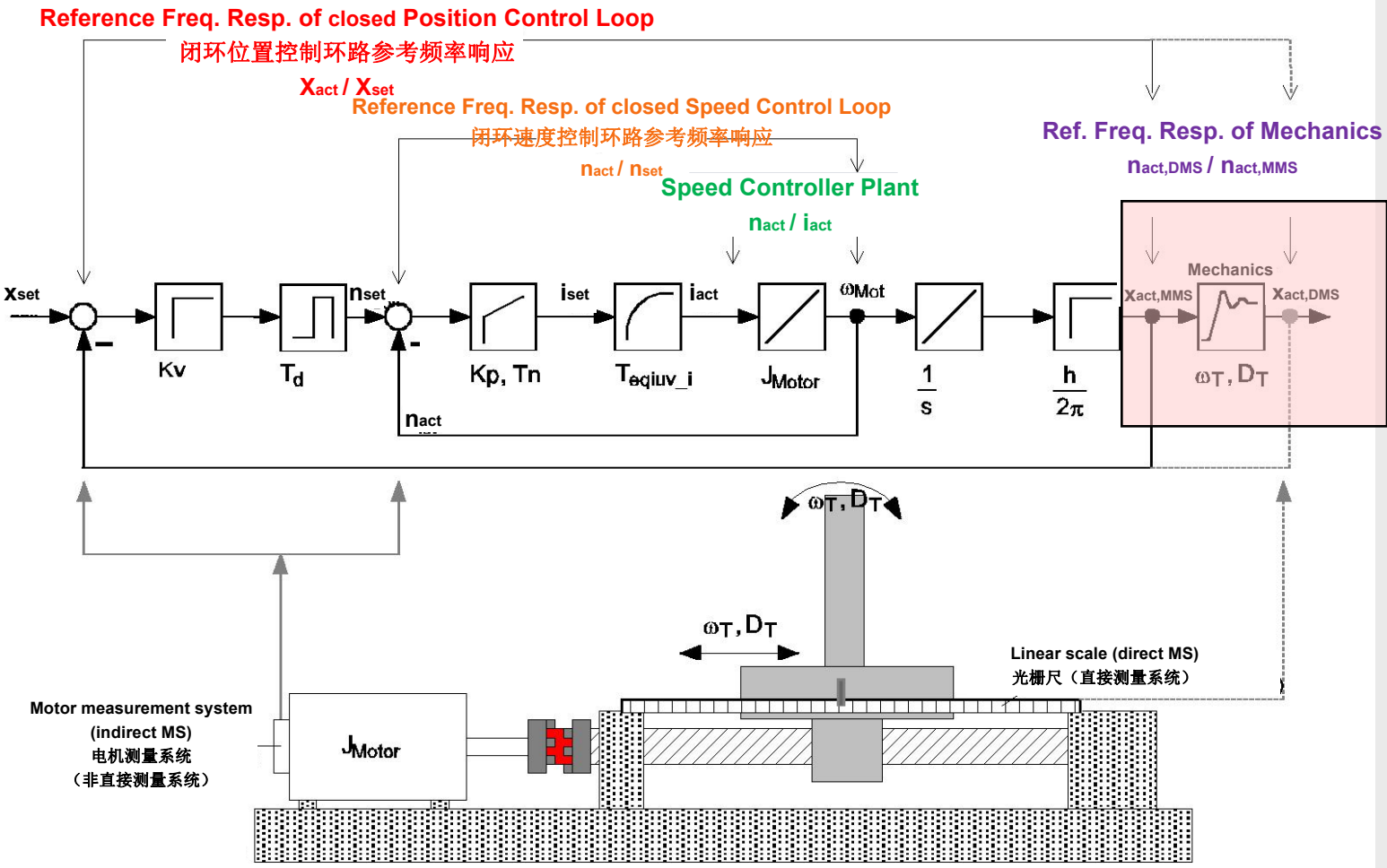
多质量体随频率提高，质量体因弹性环节的存在而依次“脱离”，每组零极点代表一个耦合，具体是哪个耦合需要根据具体机床分析。



Freq. Resp. of the Mechanics:
机械的频率响应

actual speed linear scale
actual speed motor encoder

SIEMENS

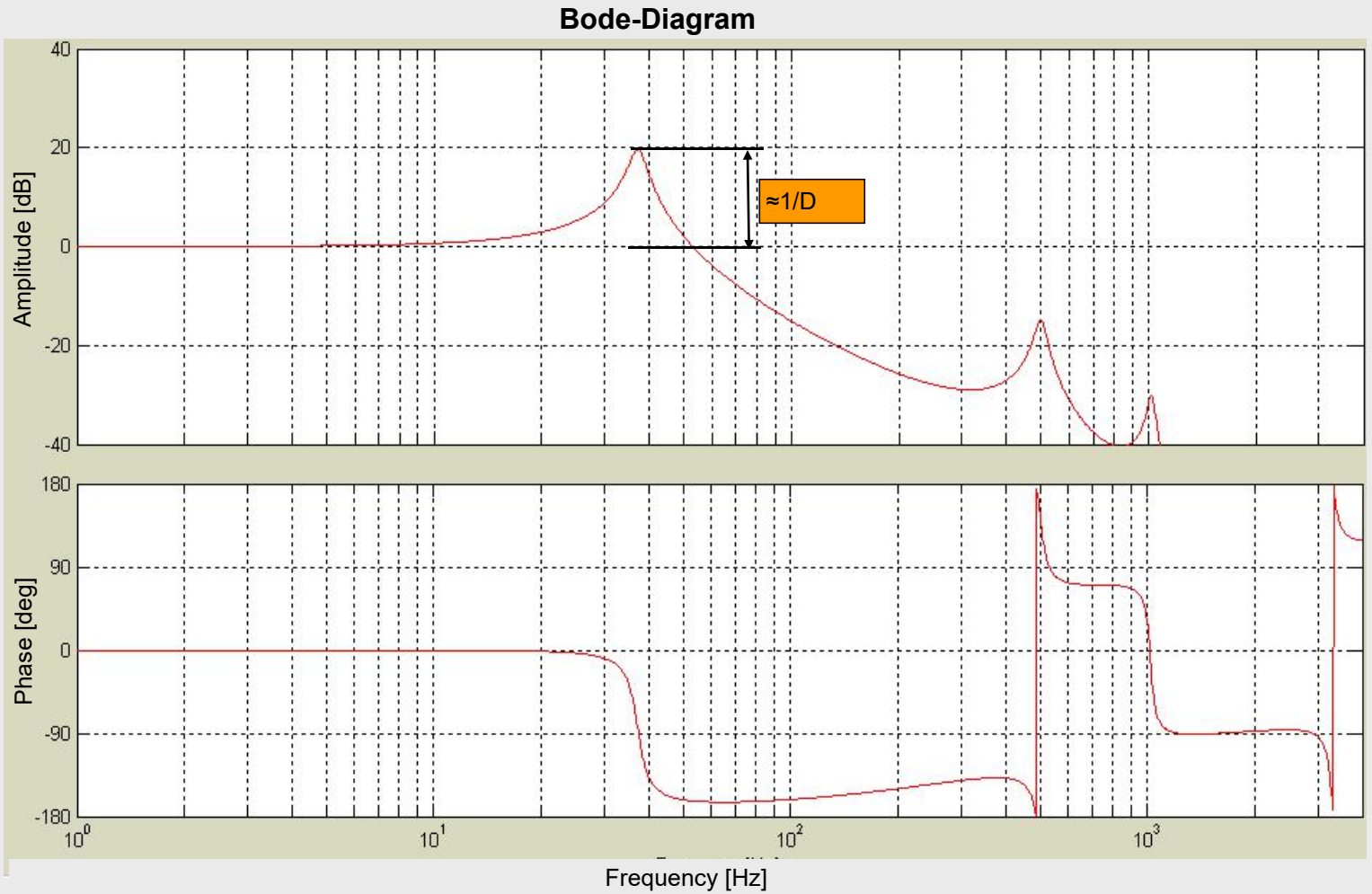


Freq. Resp. of the Mechanics: Multiple Body System

Speed Controller Plant 的频率响应：多质量系统

actual speed linearscale
actual speed motor encoder

SIEMENS

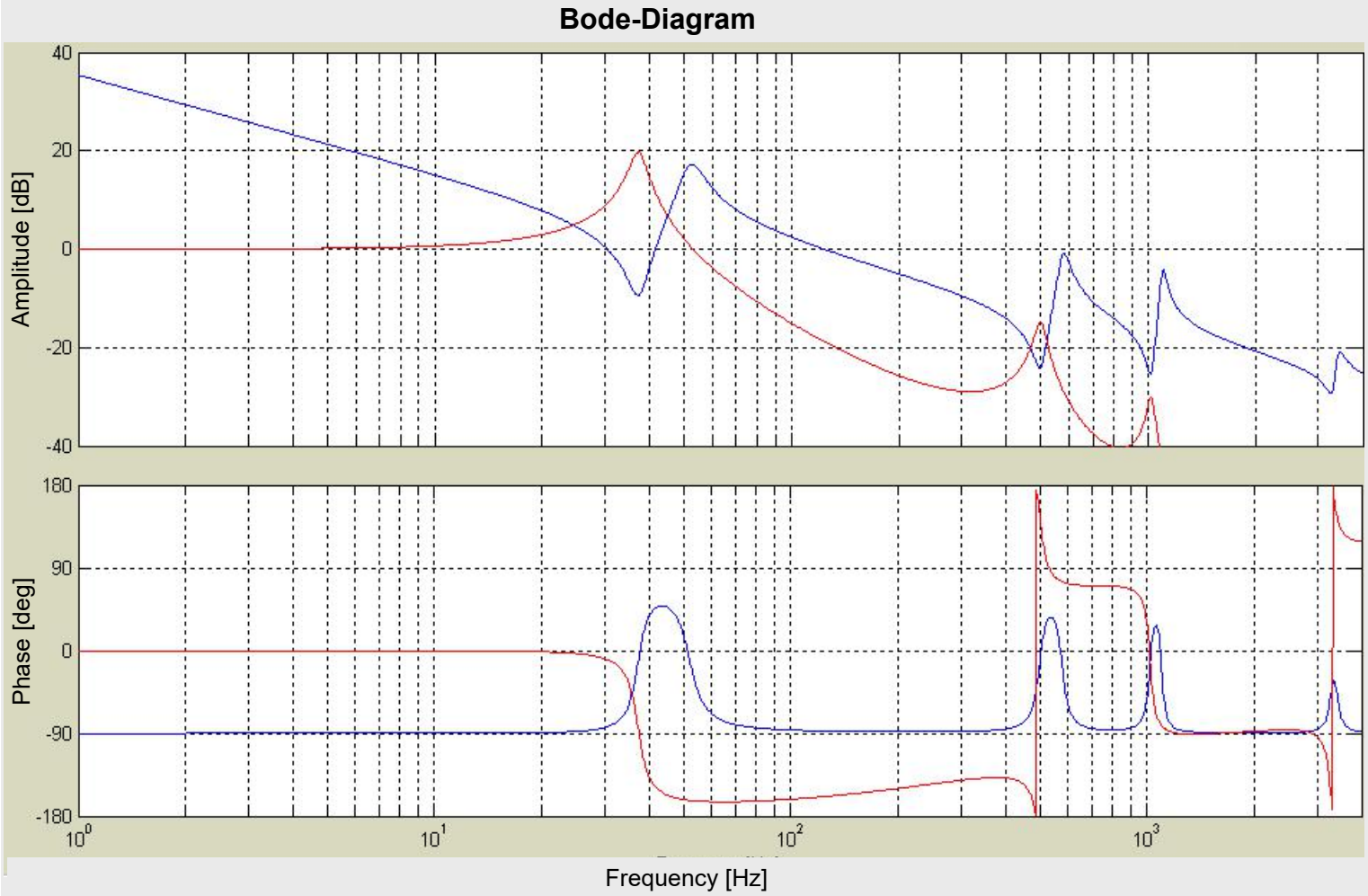


Freq. Resp. of the Mechanics: Multiple Body System

actual speed motor
actual torque motor

actual speed linearscale
actual speed motor encoder

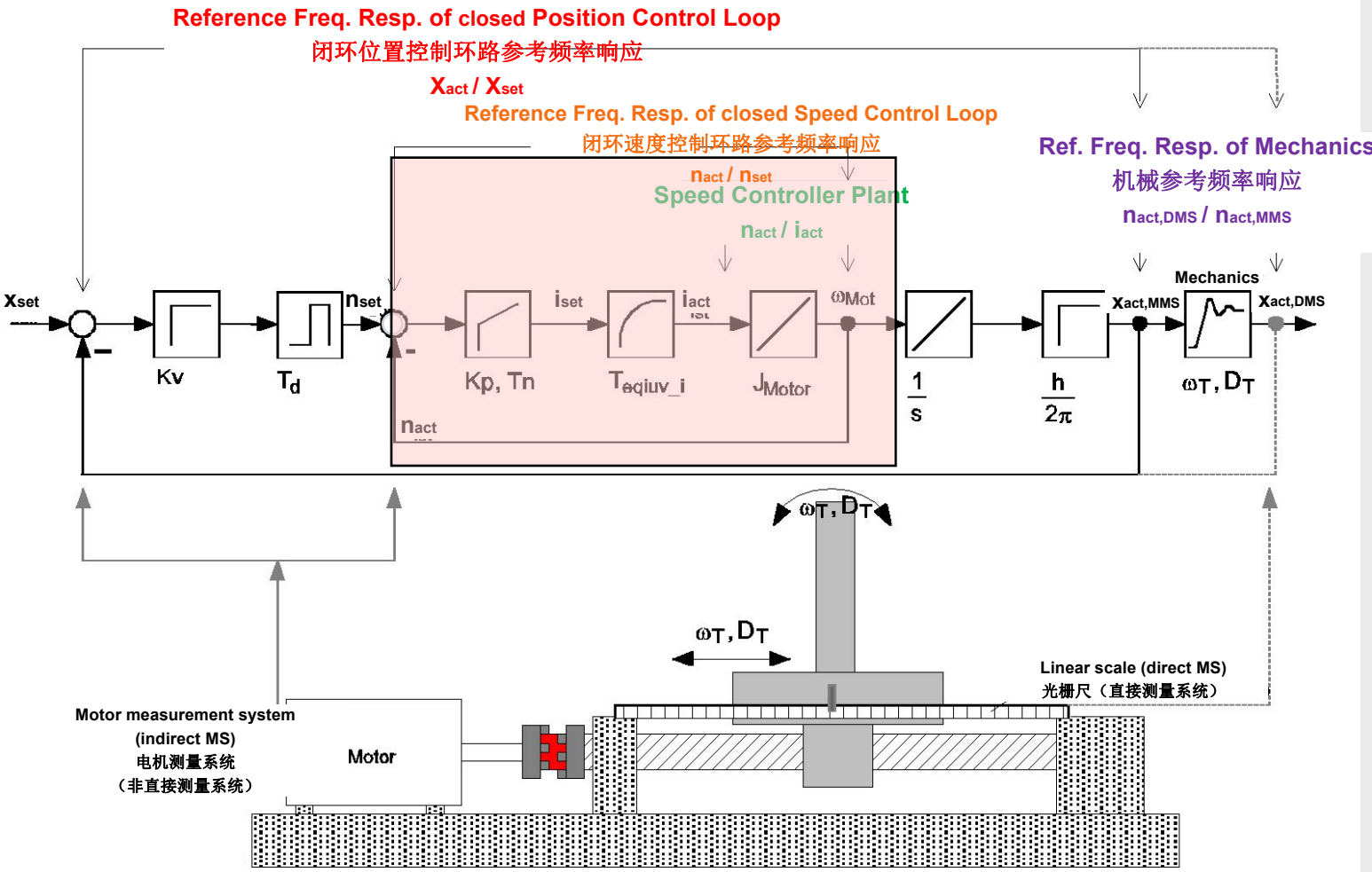
SIEMENS



Freq. Resp. of Closed Speed Control Loop:
闭环速度控制环的频率响应

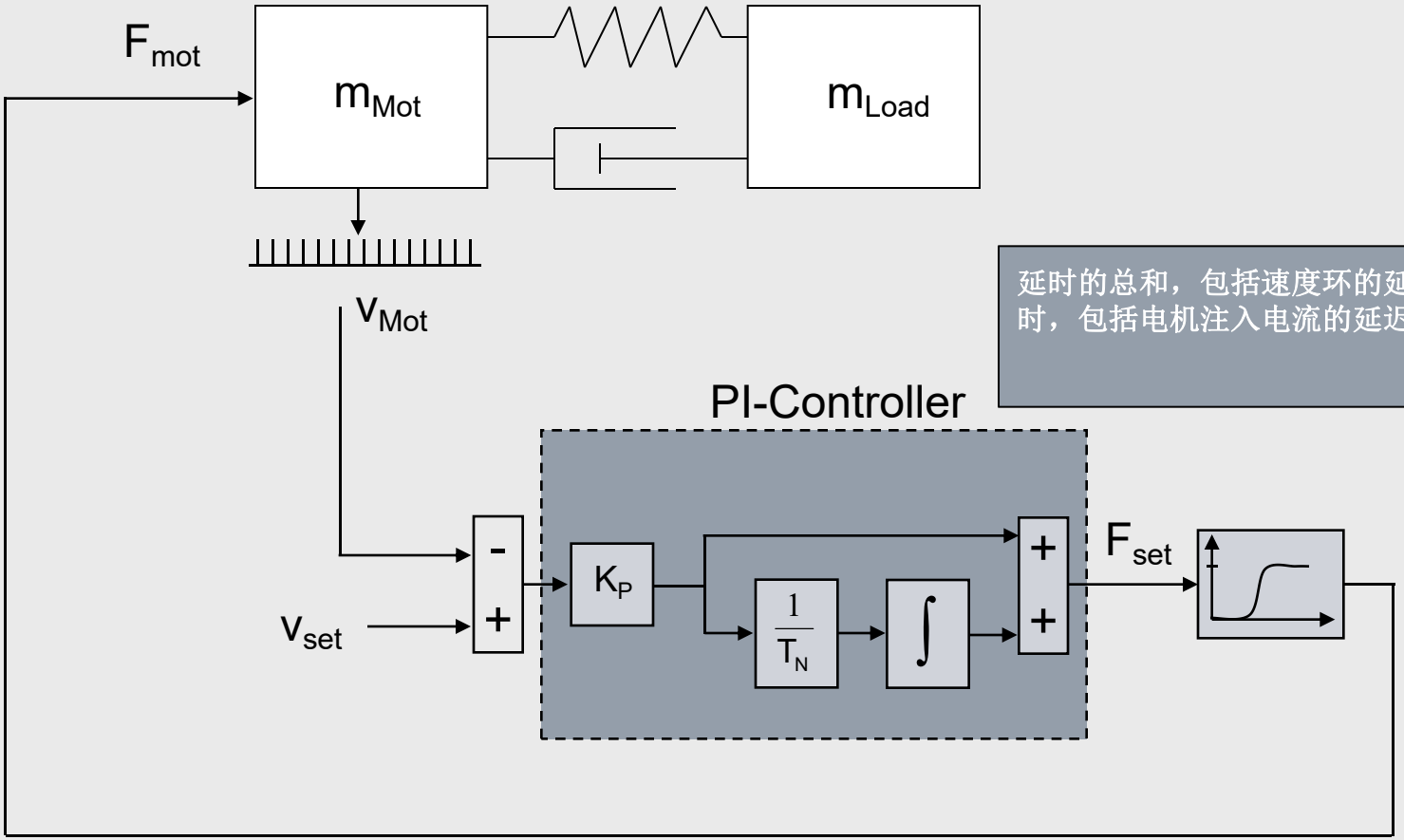
SIEMENS

actual speed motor
commanded speed motor



Speed controller
速度控制器

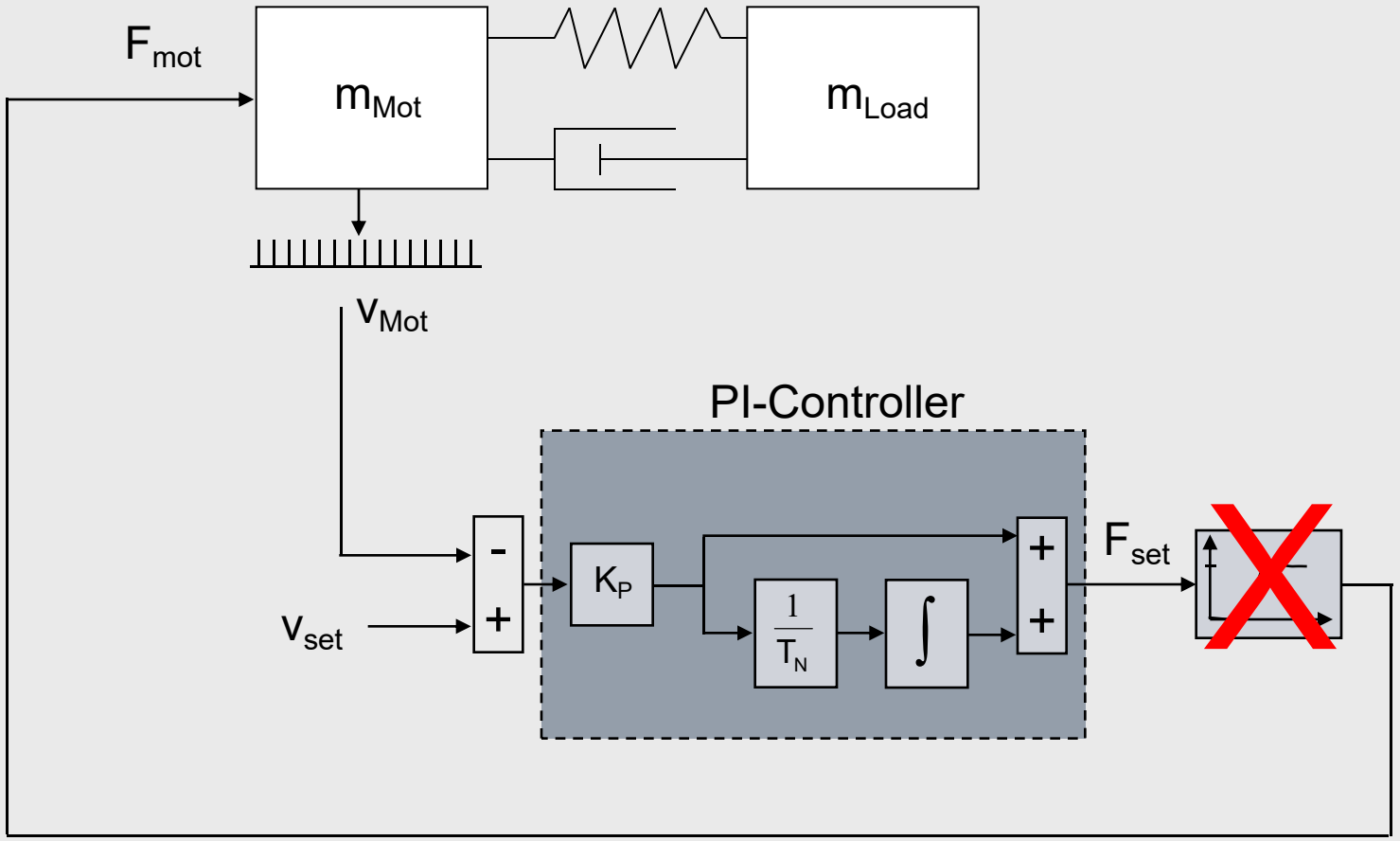
SIEMENS



延时的总和，包括速度环的延时，包括电机注入电流的延迟

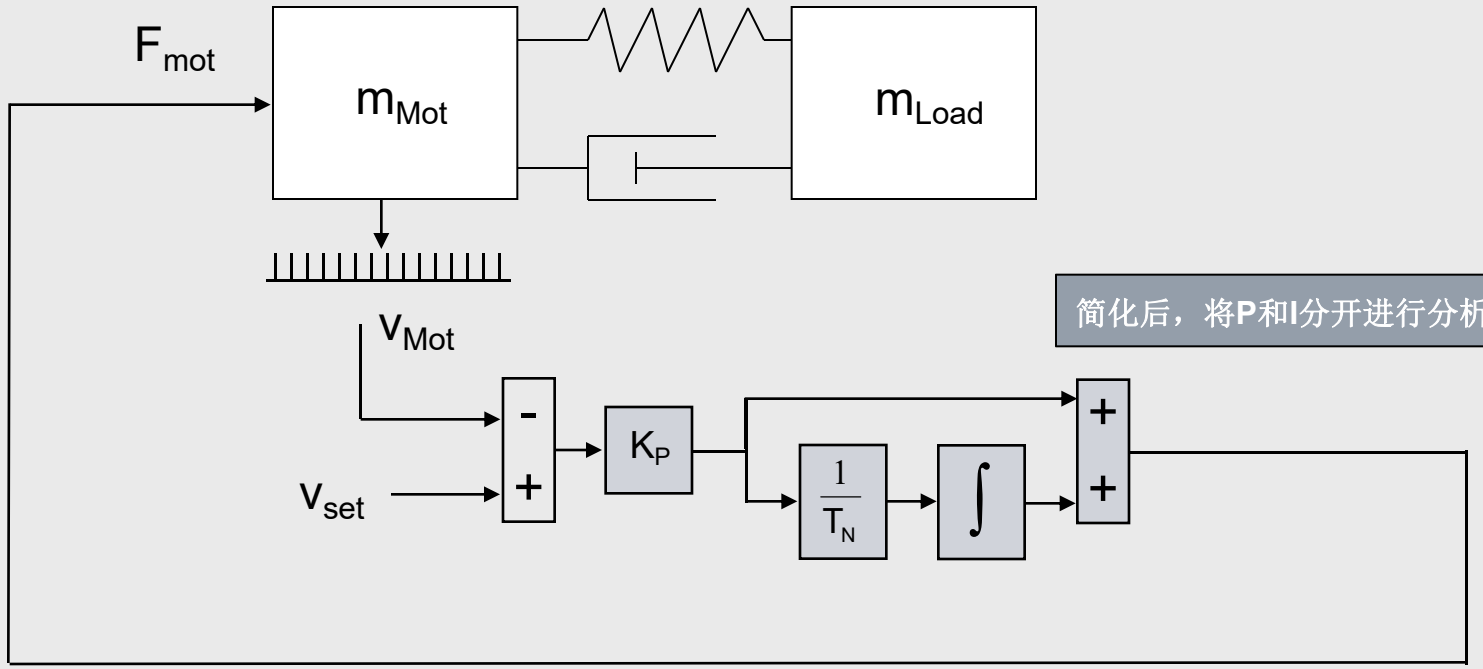
Speed controller
速度控制器

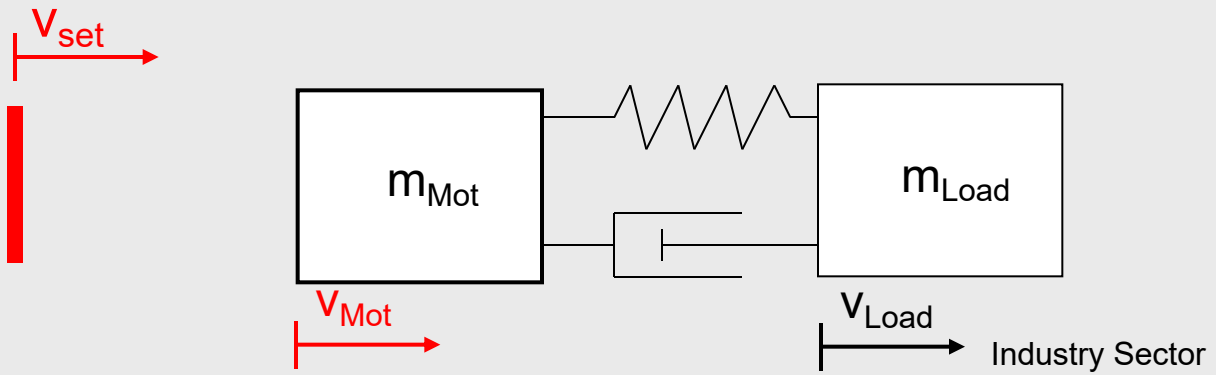
SIEMENS



Mechanical equivalent of speed controller
速度控制器的机械当量

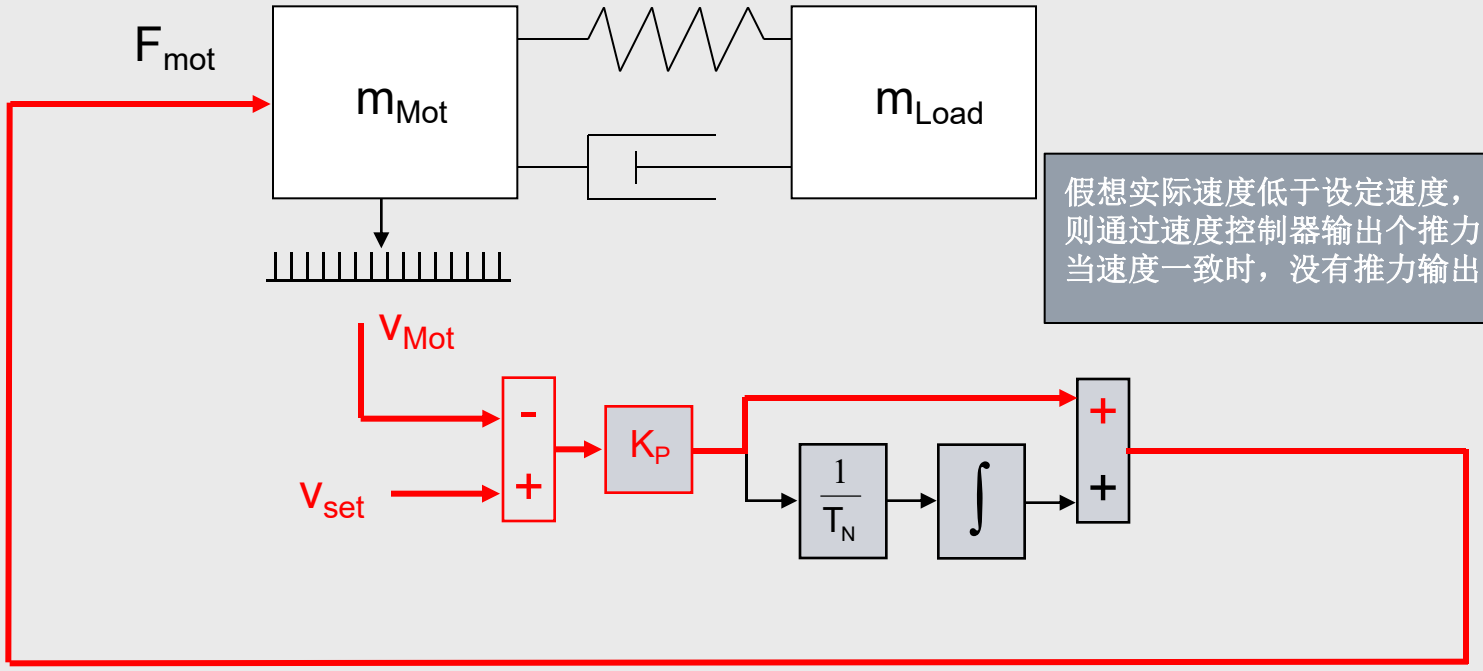
SIEMENS



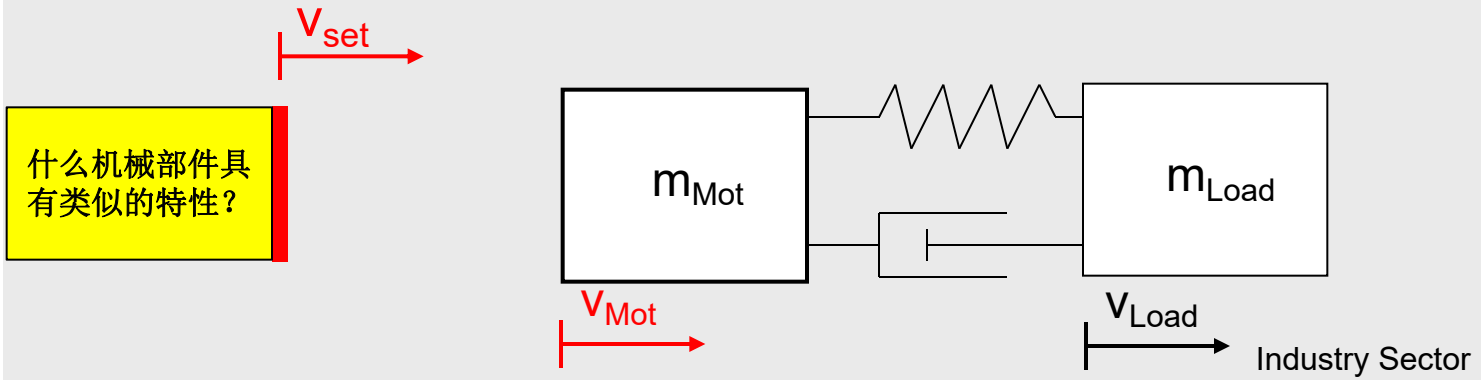


Mechanical equivalent of speed controller
速度控制器的机械当量

SIEMENS



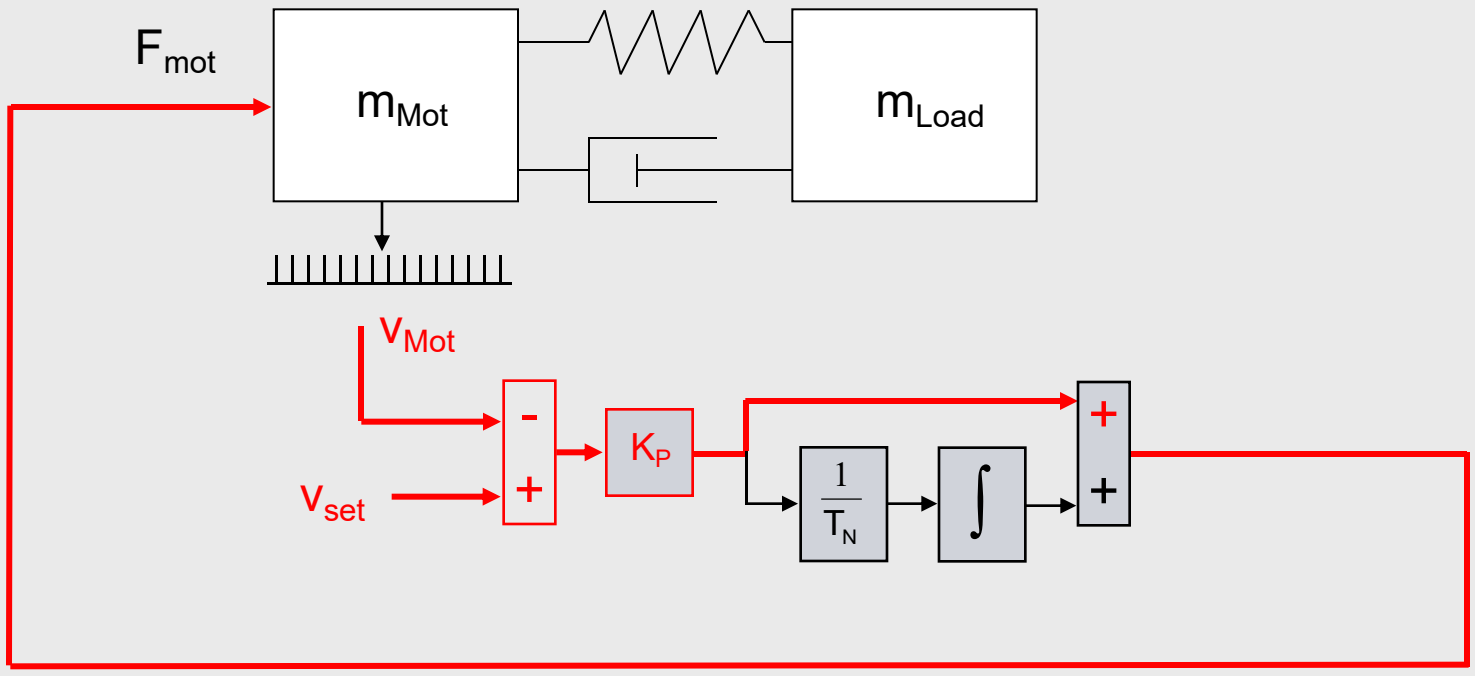
假想实际速度低于设定速度，则通过速度控制器输出个推力；当速度一致时，没有推力输出。

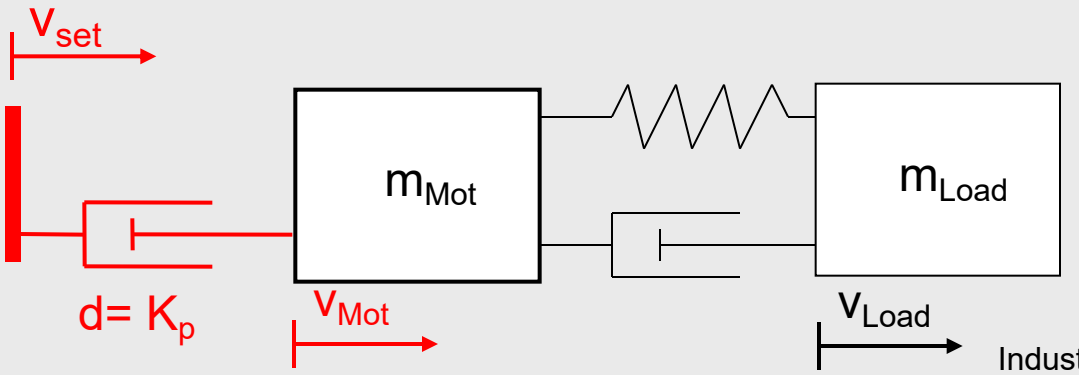


什么机械部件具有类似的特性？

Mechanical equivalent of speed controller
速度控制器的机械当量

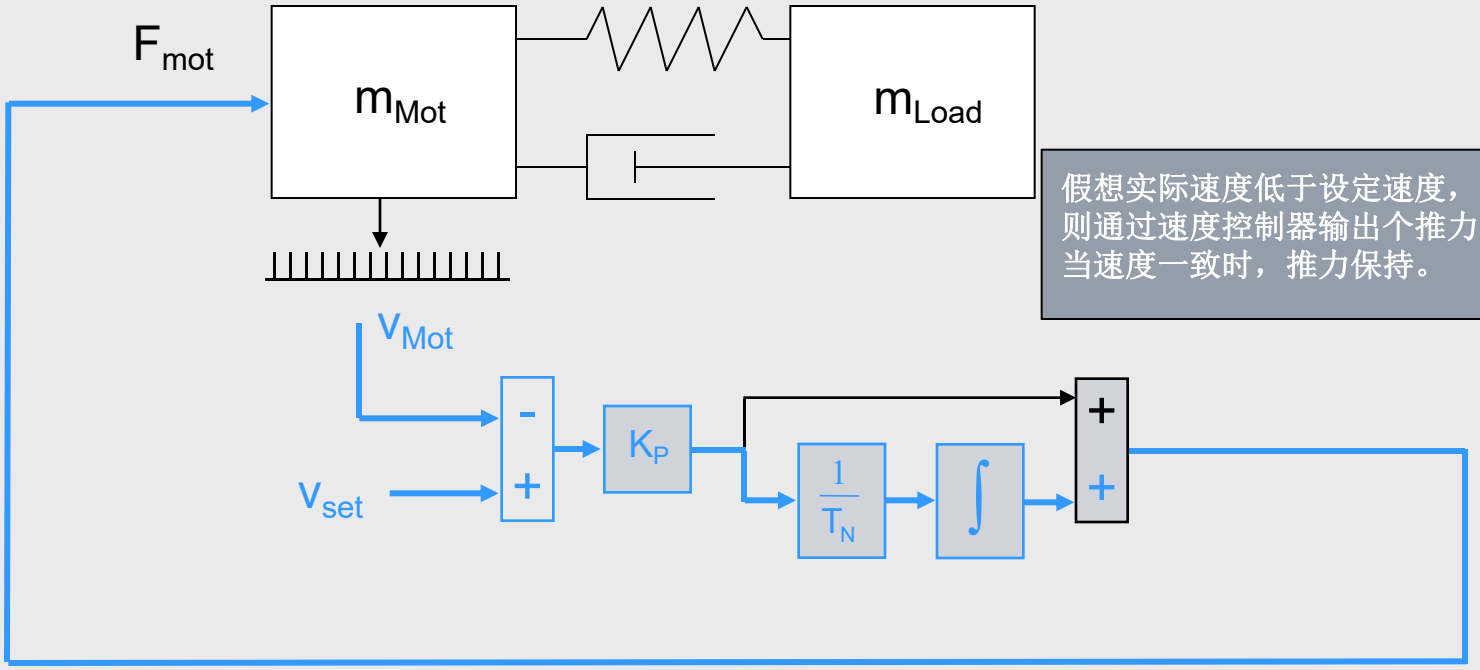
SIEMENS



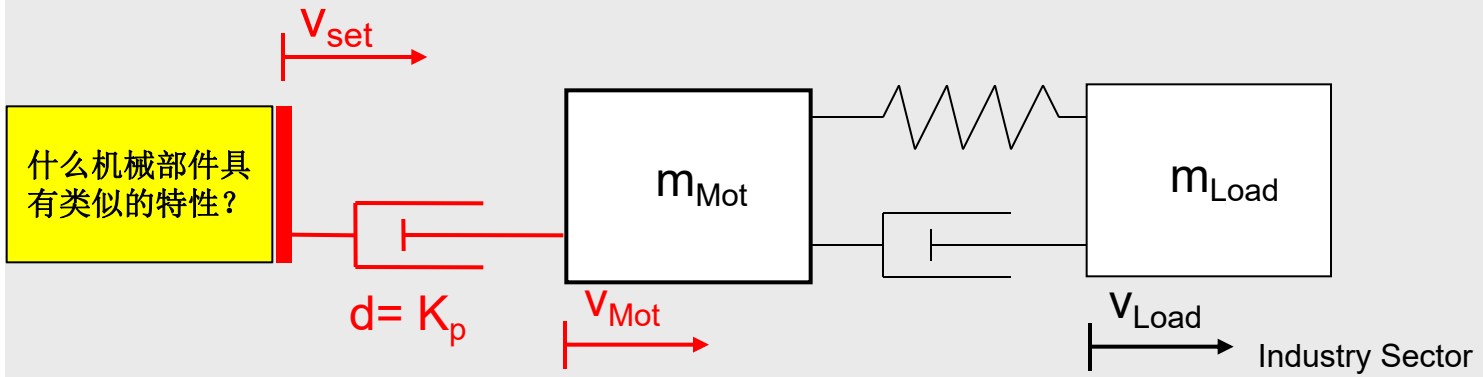


Mechanical equivalent of speed controller
速度控制器的机械当量

SIEMENS

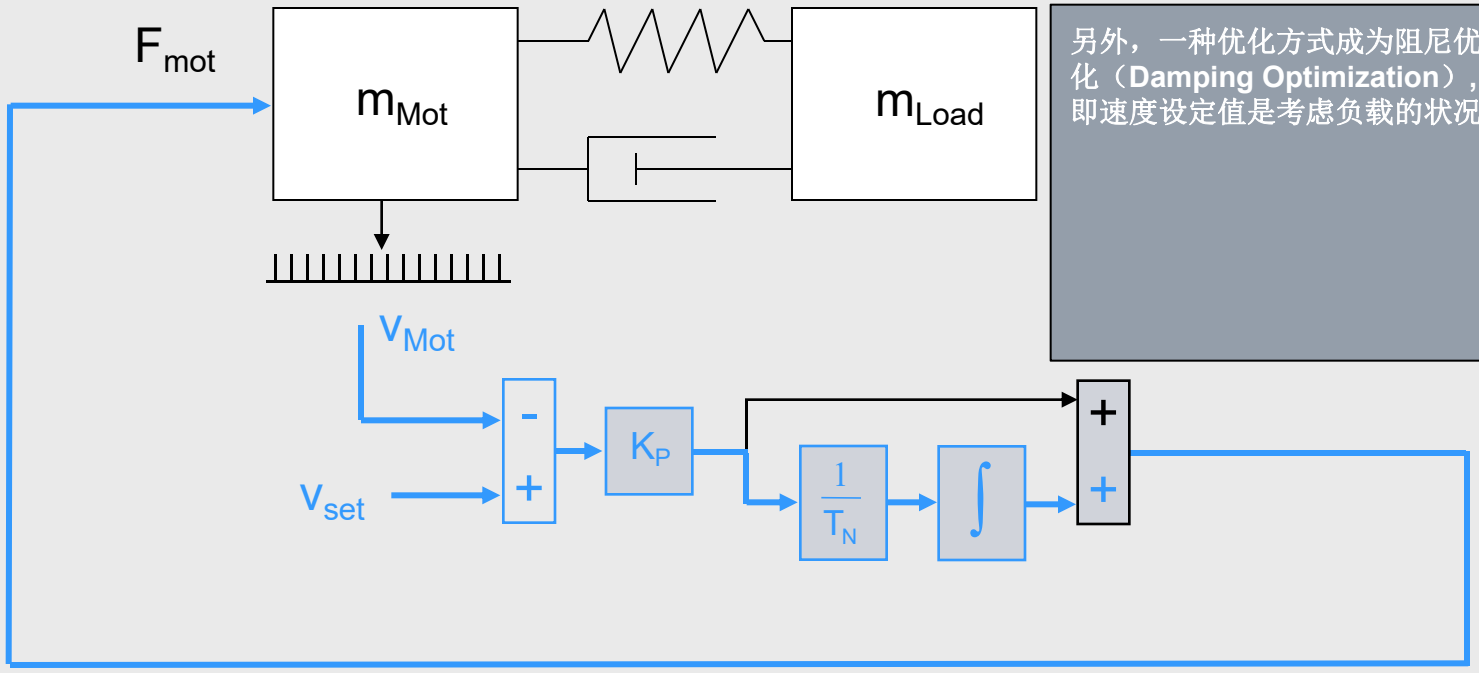


假想实际速度低于设定速度，则通过速度控制器输出个推力；当速度一致时，推力保持。

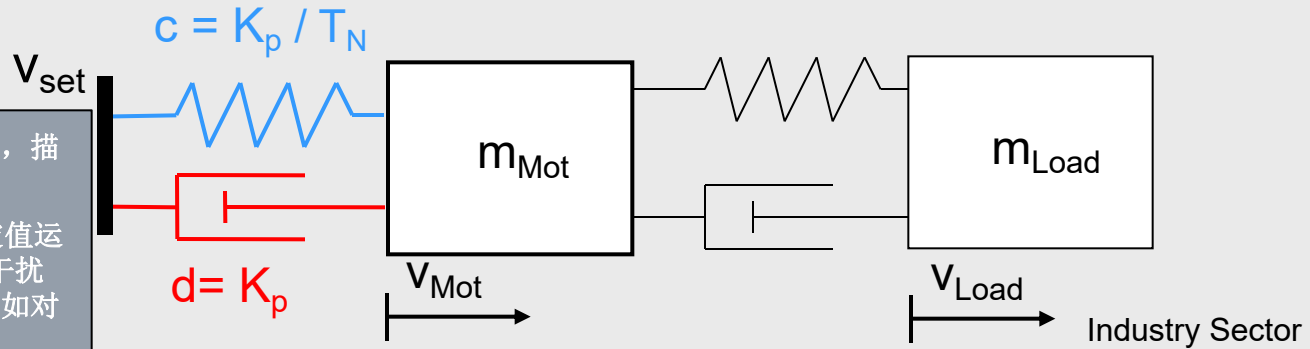


Mechanical equivalent of speed controller
速度控制器的机械当量

SIEMENS



另外，一种优化方式成为阻尼优化（**Damping Optimization**），即速度设定值是考虑负载的状况。

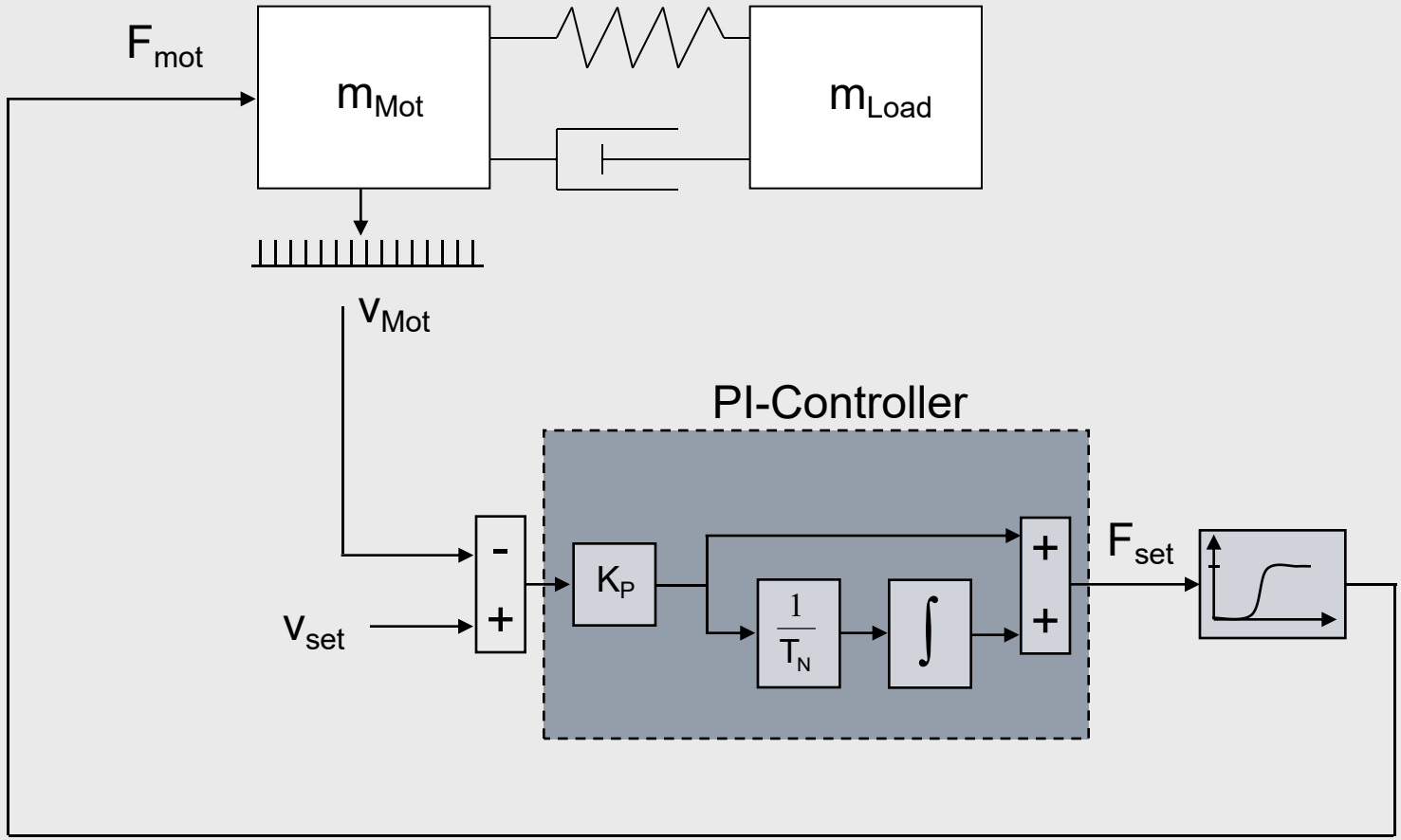


速度环的**PI**调节器相当于弹性+阻尼环节，描述的是速度设定和电机之间的关系。

如果**Kp**大**TN**小，则电机完全按速度设定值运转，但负载会怎么响应。这种优化称为干扰最优优化**(Disturbance optimization)**。如对于皮带轮传动的冲击干扰.

Speed controller
速度控制器

SIEMENS

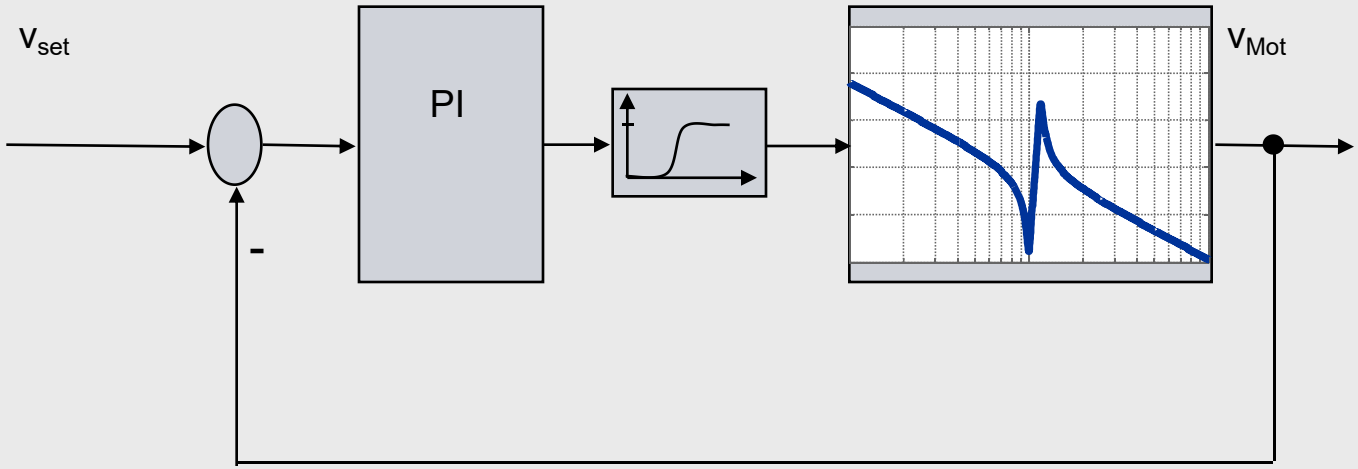


Closed Speed Control Loop
闭环速度控制环路

SIEMENS

Transfer Function of the Speed Controller plant:

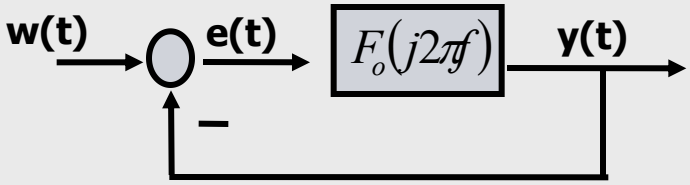
$G_{SpeedControllerPlant}(s) = V_{Mot}(s) / F_{Mot}(s)$



刚刚分析的速度环PI调节器 | 电流环 | 电机端机械频率响应？？？

Nyquist criterion:
奈奎斯特判据

SIEMENS



Transfer function open loop:
开环传递函数

$$F_o(j2\pi f) = \frac{Y(j2\pi f)}{E(j2\pi f)}$$

Transfer function closed loop:
闭环传递函数

$$F_w(j2\pi f) = \frac{Y(j2\pi f)}{W(j2\pi f)}$$

$$F_w(j2\pi f) = \frac{F_o(j2\pi f)}{1 + F_o(j2\pi f)}$$

$$Fw = \frac{F_o \cdot E}{W} = \frac{F_o \cdot E}{(F_o + 1) \cdot E}$$

because $W - Y = E$ at summarypoint

so $W - E = Y = F_o \cdot E$

and $W = (F_o + 1) \cdot E$

$$F_o(j2\pi f) = -1: \qquad F_w(j2\pi f) = \infty$$

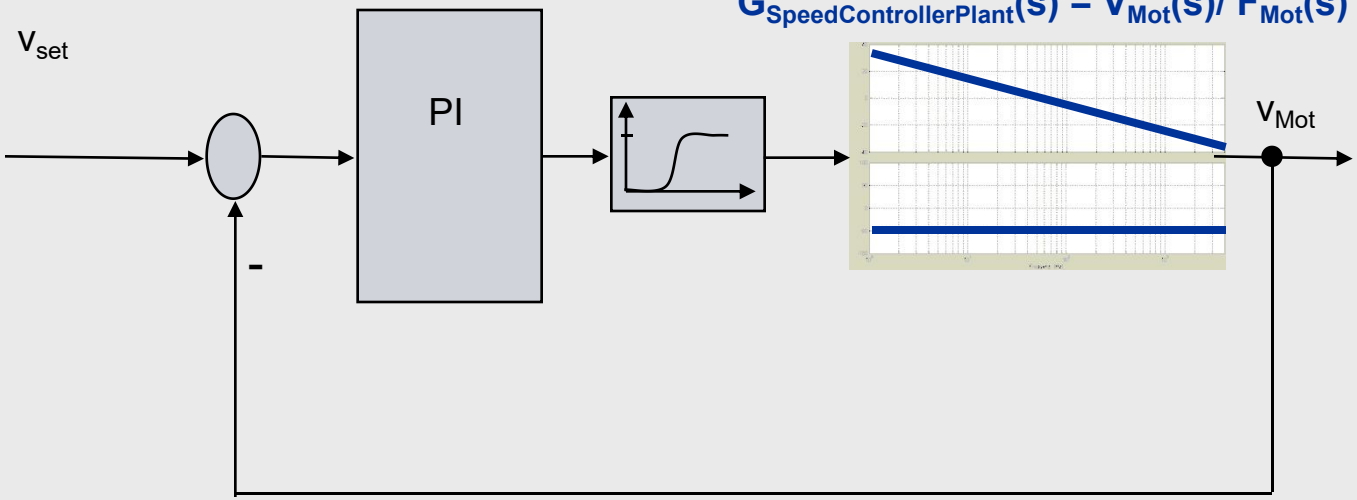
如果开环的频率响应，幅值在0dB，相位为±180度，则闭环的响应就是不稳定的。

Closed Speed Control Loop: 1 Mass System
闭环速度控制环路：单质量体

SIEMENS

Transfer Function of the Speed Controller plant:

$G_{SpeedControllerPlant}(s) = V_{Mot}(s) / F_{Mot}(s)$

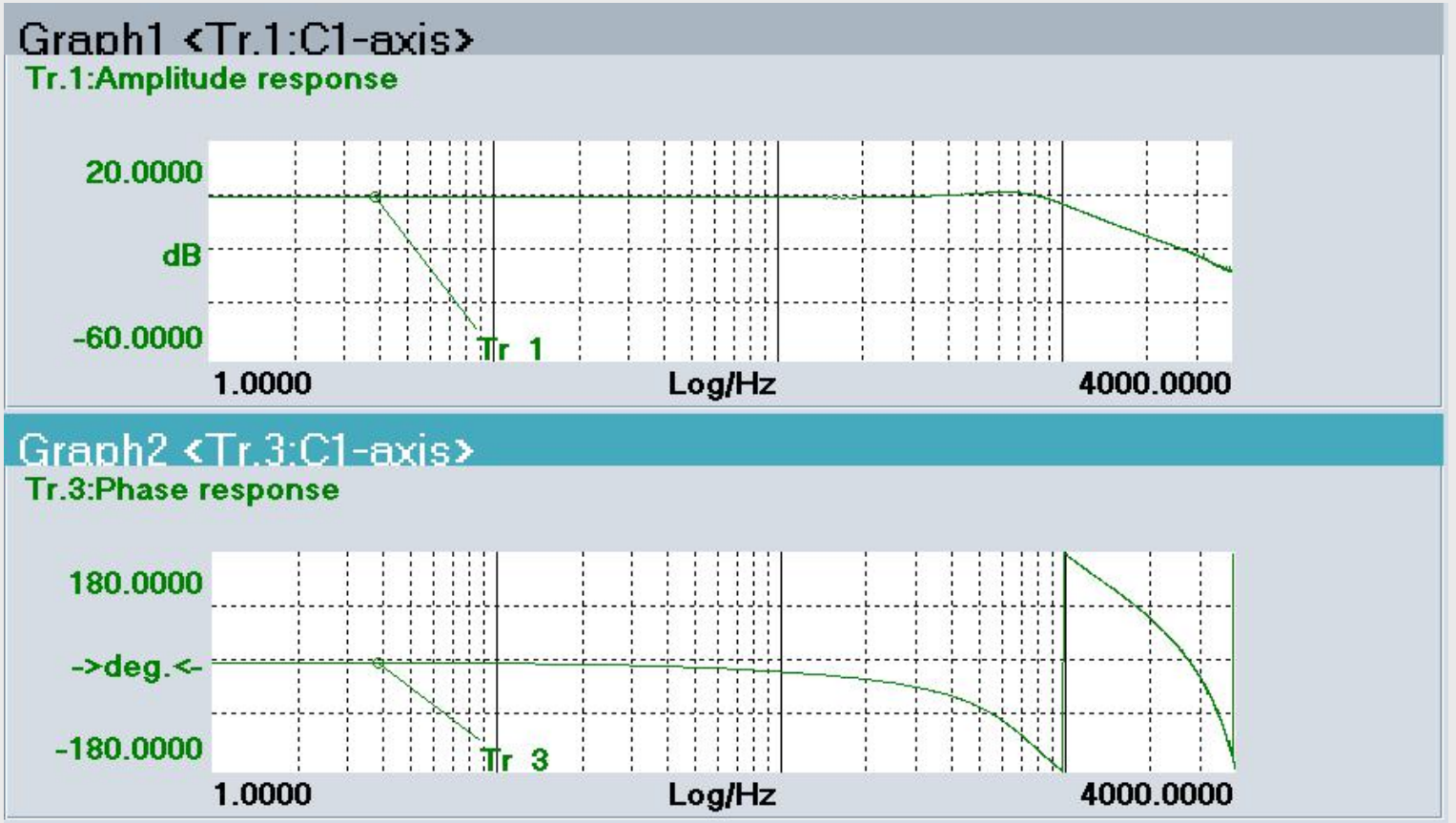


首先，看简单的情况，单质量体，它的响应如简图。

Freq. Resp. of Closed Current Control Loop:
闭环电流控制环的频率响应

SIEMENS

$\frac{\text{actual current motor}}{\text{commanded current motor}}$



电流环框图

P1810.11 Current controller dynamics higher

当电机电流增大后，电机电感因电流饱和会降低，根据前面的结论，电流环的增益也要随之降低。

问题是何时降低，降低多少。电流环的增益与电机电感成正比

电流环适应

为什么不能过**0dB?**

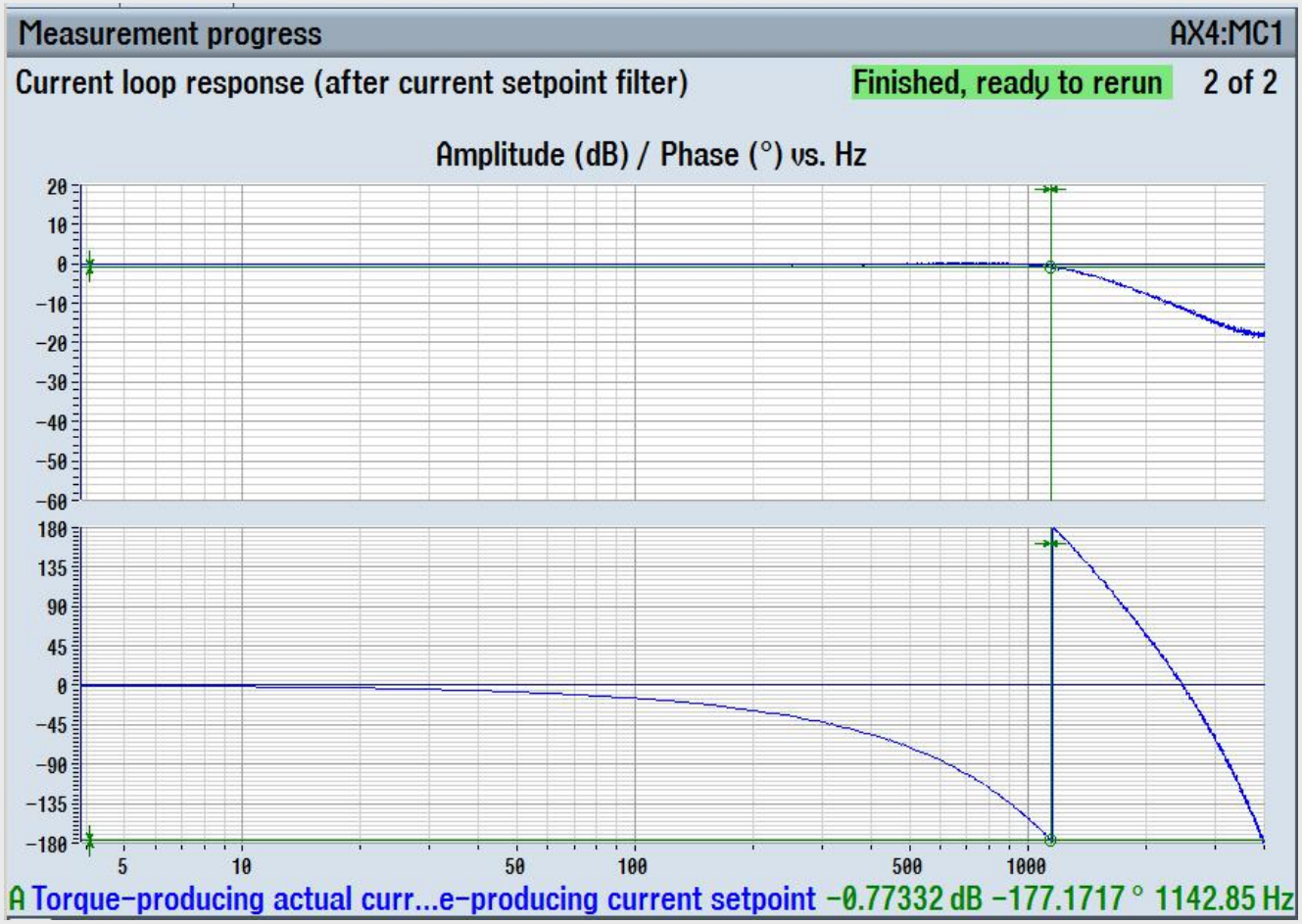
Freq. Resp. of Closed Current Control Loop:

$$\frac{\text{actual current motor}}{\text{commanded current motor}}$$

p1810:Modulator configuration = 800H

☑ Bit 11: Current controller dynamics higher

p118 = 20,5µs

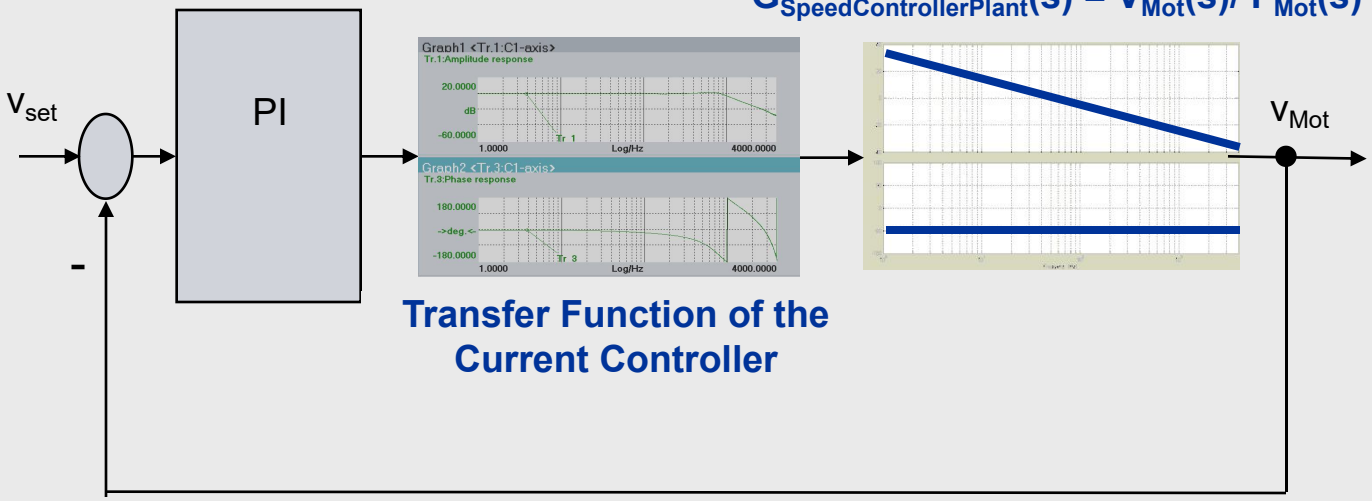


Closed Speed Control Loop: 1 Mass System
闭环速度控制环路：单质量体

SIEMENS

Transfer Function of the Speed Controller plant:

$G_{SpeedControllerPlant}(s) = V_{Mot}(s)/ F_{Mot}(s)$

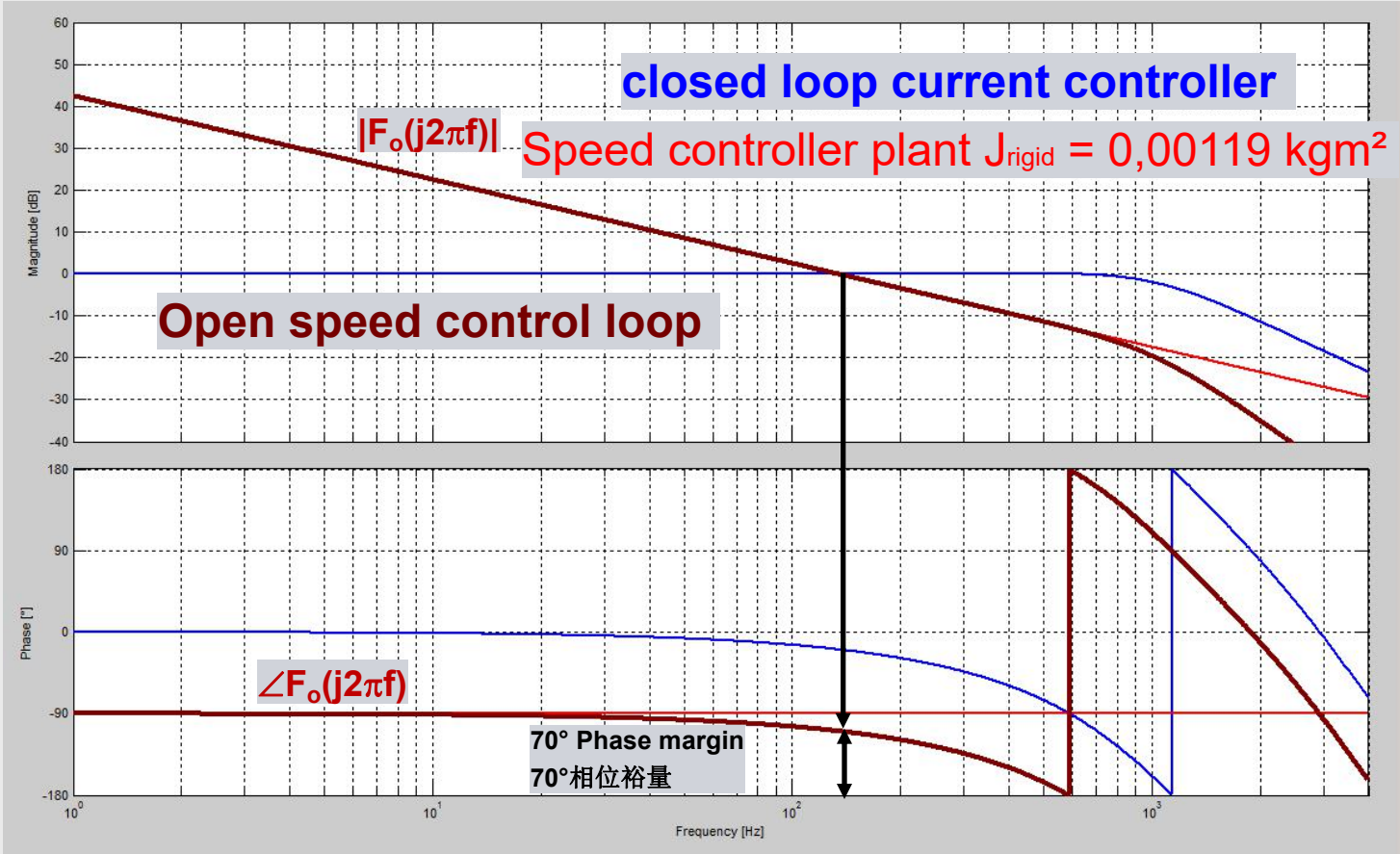


Transfer Function of the Current Controller

如果不考虑速度PI调节器的积分环节，P=1，则速度开环频率响应等于电流环和速度控制系统的频率响应可相乘

Nyquist criterion : Used in bode diagram
奈奎斯特判据：在波德图中使用

SIEMENS



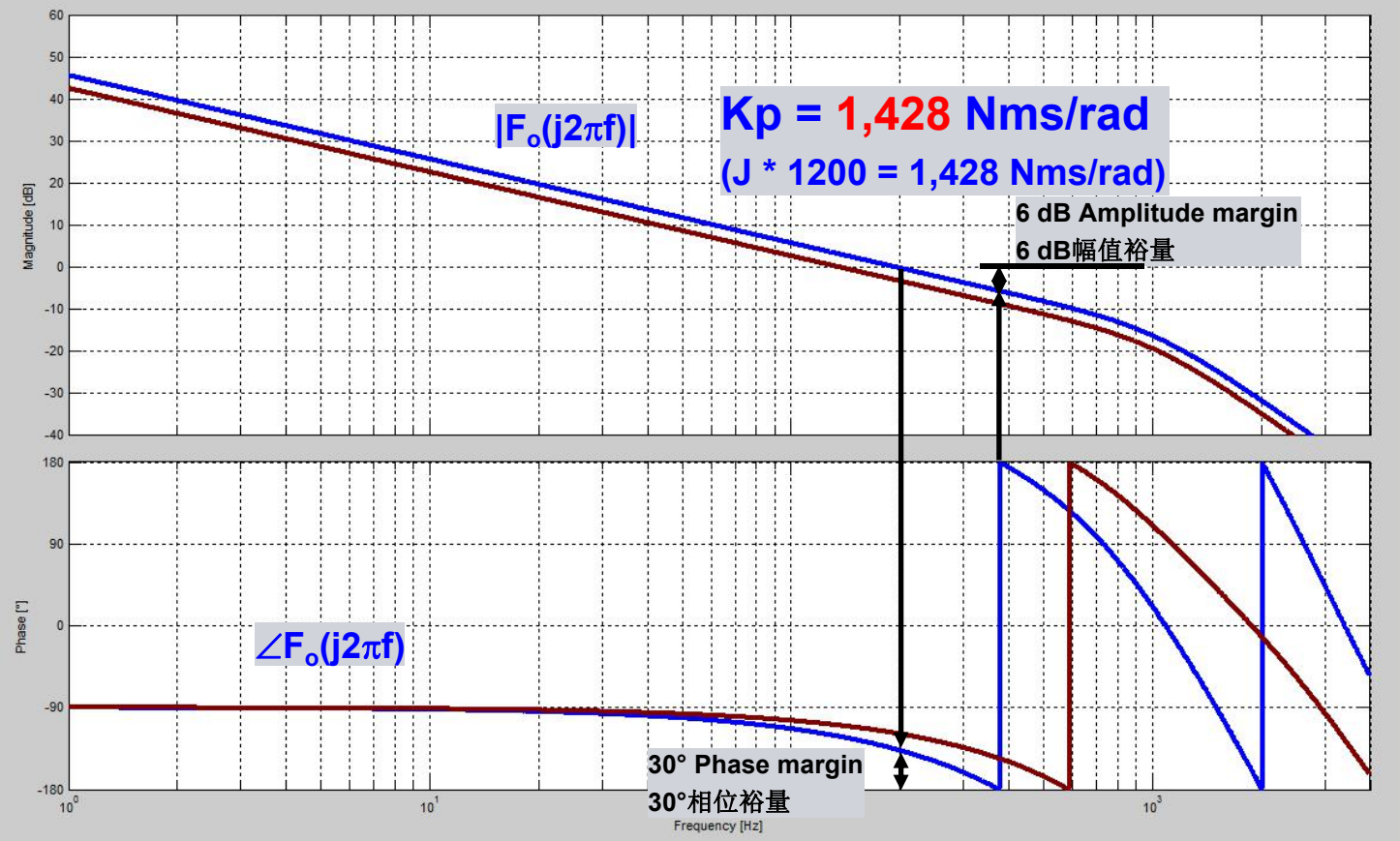
蓝色曲线是电流环频率响应，红色曲线是speed control plant响应,两者相乘在伯德图上是相加（叠加）得到棕色的速度环开环频率响应。根据前面的奈奎斯特判据，要想闭环稳定，开环幅值在0dB时，相位不能等于180度。故有幅值裕量和相位裕量概念。

速度开环频率响应曲线，当幅频曲线穿越0dB的频率，对应相位距离180度多远，即相位裕量

提高增益,幅频曲线向右上方移动,相位裕量减小

Nyquist criterion : Used in bode diagram
奈奎斯特判据：在波德图中使用

SIEMENS

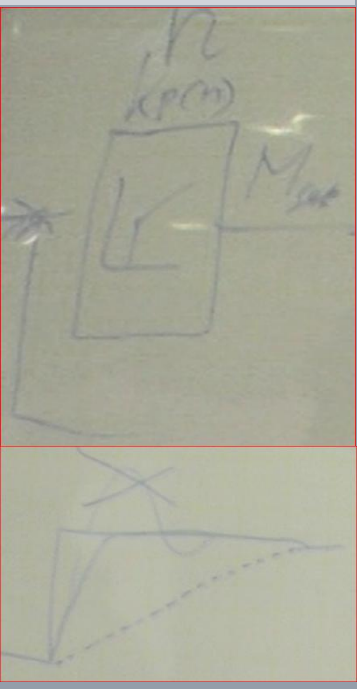


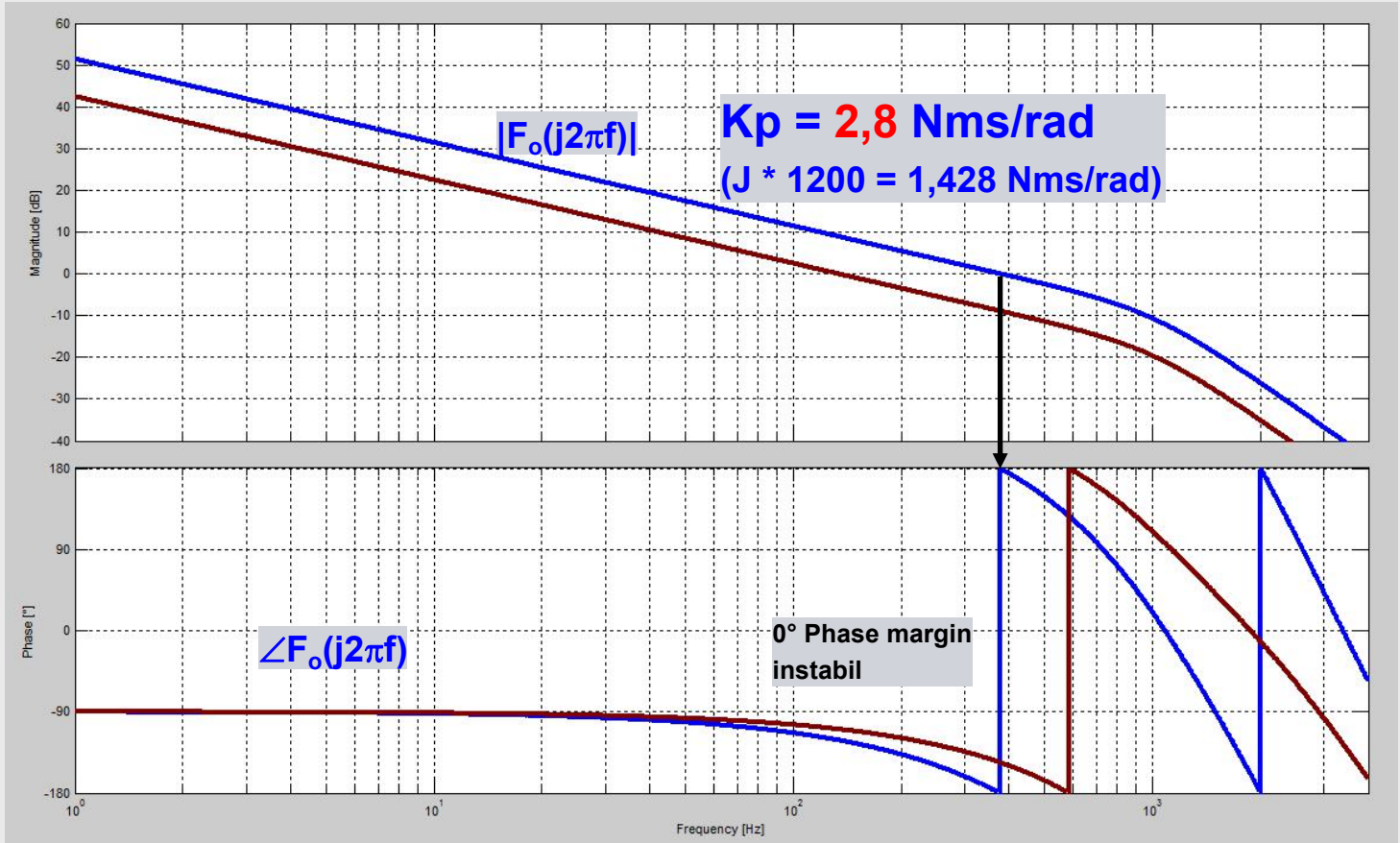
同理，当相位在180度的频率对应幅频曲线距离0dB多远，即幅值裕量

幅值裕量〉6dB, 相位裕量〉30度 闭环可以保证是稳定的。 接近动态性能更好；更大裕量，更稳定。

Nyquist criterion : Used in bode diagram
奈奎斯特判据：在波德图中使用

SIEMENS





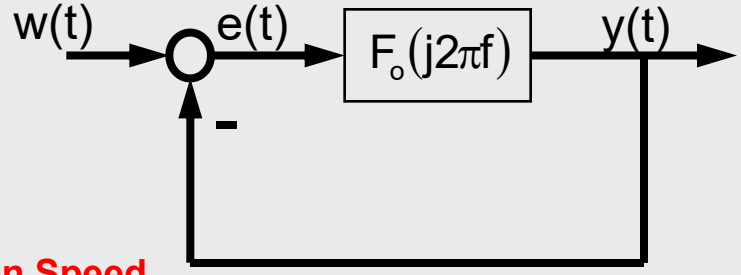
速度环的增益与惯量成正比。所以，为什么有大惯量电机：惯量大→增益大→阻尼好→更好的对干扰的响应。缺点：加速慢。

125μs周期：1200*J　　62.5μs周期：2000*J　pwm开关频率相同，故没有达到两倍

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

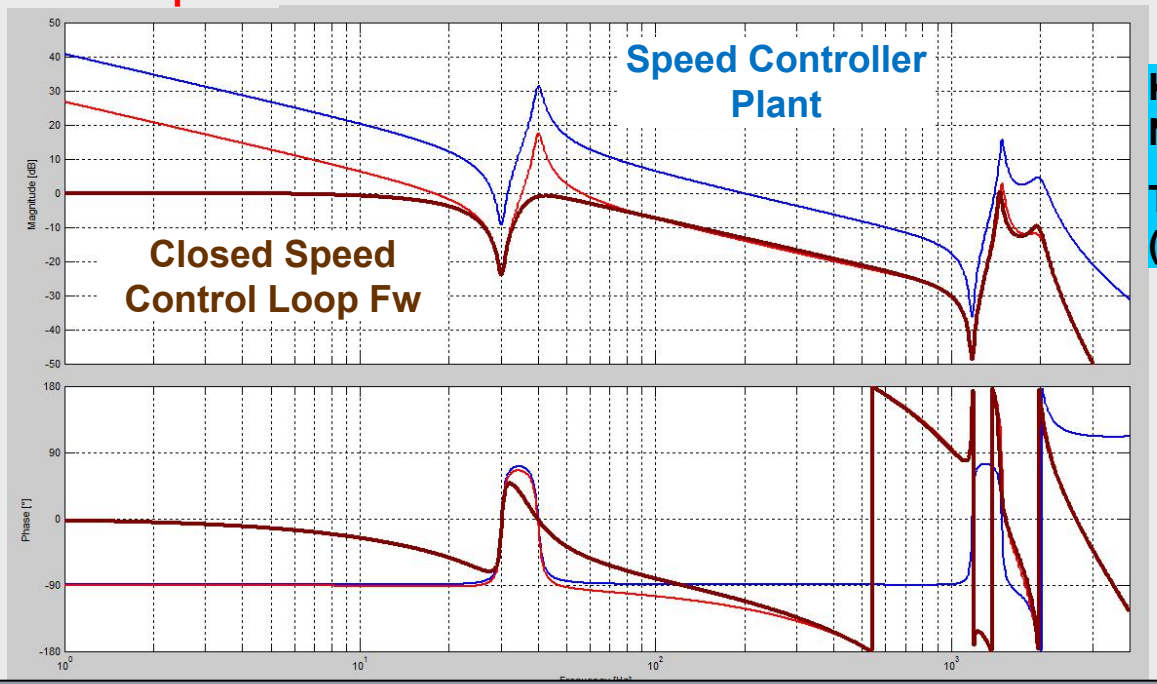
SIEMENS



$$F_o(j2\pi f) = \frac{Y(j2\pi f)}{E(j2\pi f)}$$

$$F_w(j2\pi f) = \frac{Y(j2\pi f)}{W(j2\pi f)} = \frac{F_o(j2\pi f)}{1 + F_o(j2\pi f)}$$

Open Speed Control Loop Fo



Kp = 0,2 Nms/rad

Tn = 0 ms (OFF)

蓝色是**speed controller plant**红色是开环特性，因为**kp**不是**1**，所以红色曲线在蓝色曲线下方。

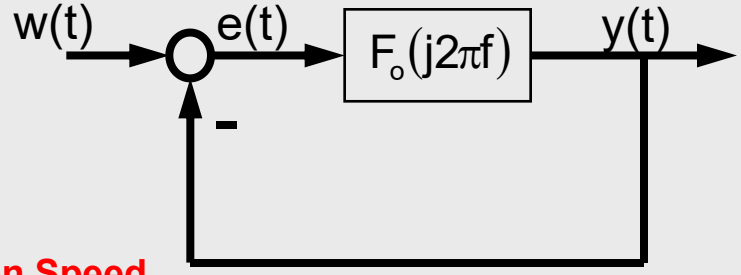
从开环曲线看有足够的相位裕量。注意，多个过**0dB**点相位裕量都够，因此闭环系统是稳定的。

注意最后一个过**0dB**点

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

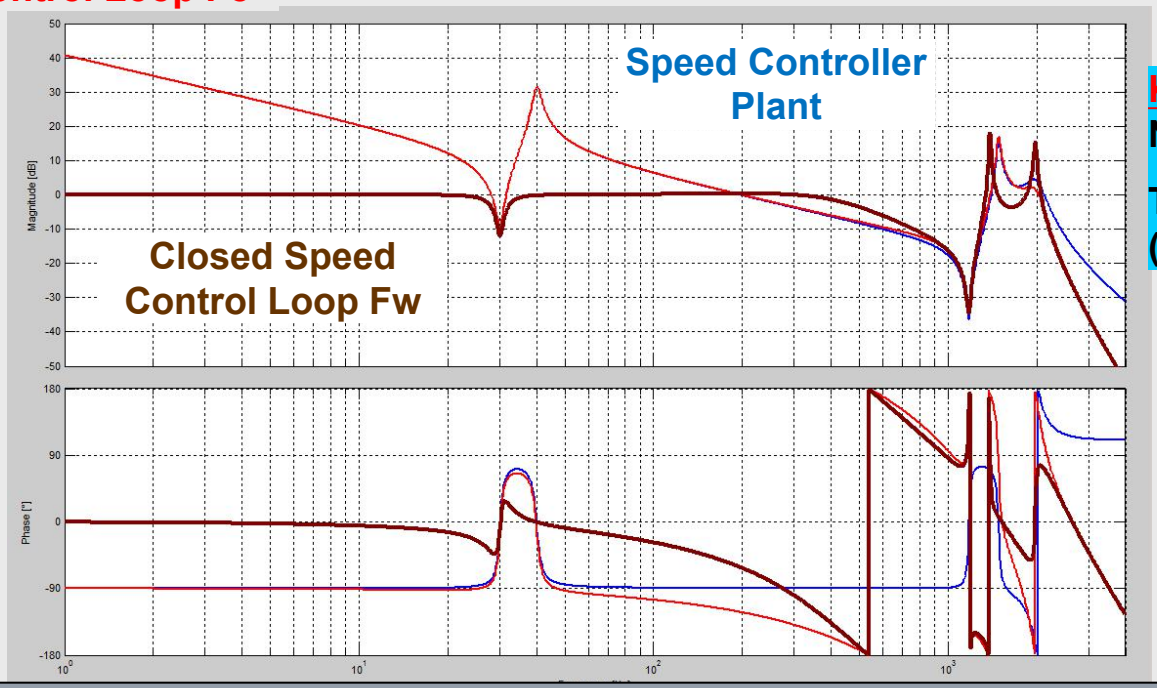
SIEMENS



$$F_o(j2\pi f) = \frac{Y(j2\pi f)}{E(j2\pi f)}$$

$$F_w(j2\pi f) = \frac{Y(j2\pi f)}{W(j2\pi f)} = \frac{F_o(j2\pi f)}{1 + F_o(j2\pi f)}$$

Open Speed Control Loop Fo



Kp = 1 Nms/rad

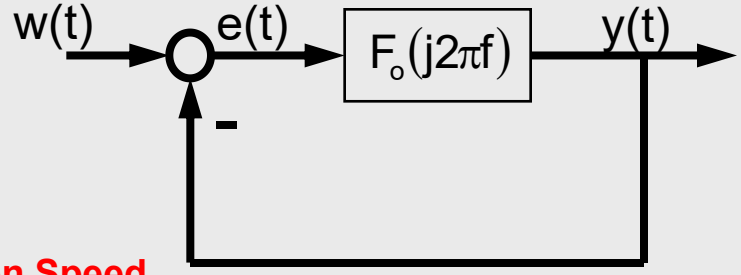
Tn = 0 ms (OFF)

最后一个过0dB点，在提高增益后，马上导致闭环不稳定。注意尖峰

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



$$F_o(j2\pi f) = \frac{Y(j2\pi f)}{E(j2\pi f)}$$

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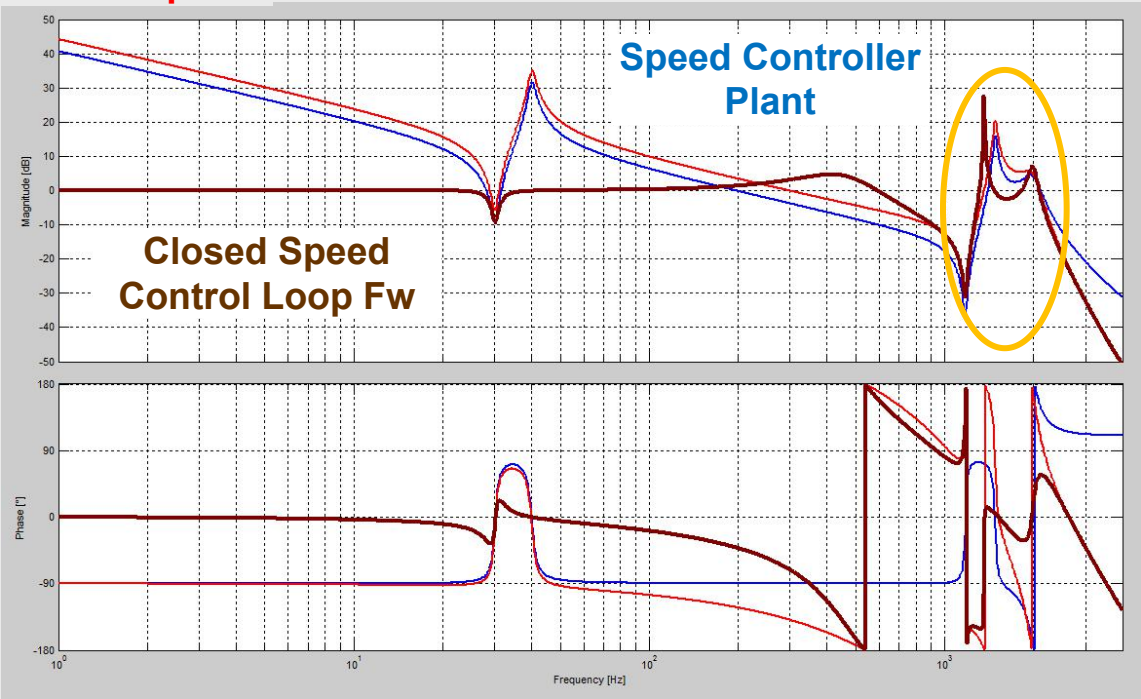
Open Speed Control Loop Fo

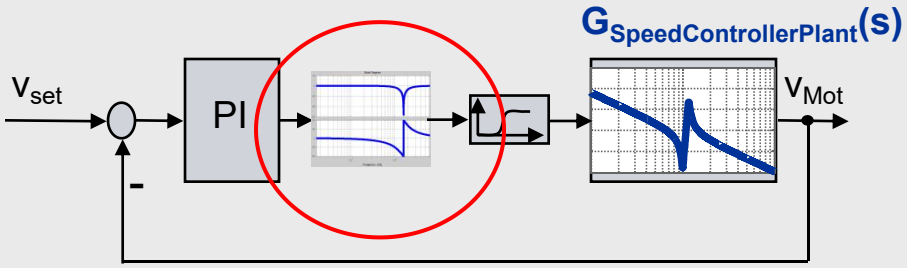


Kp = 1,5 Nms/rad

Tn = 0 ms (OFF)

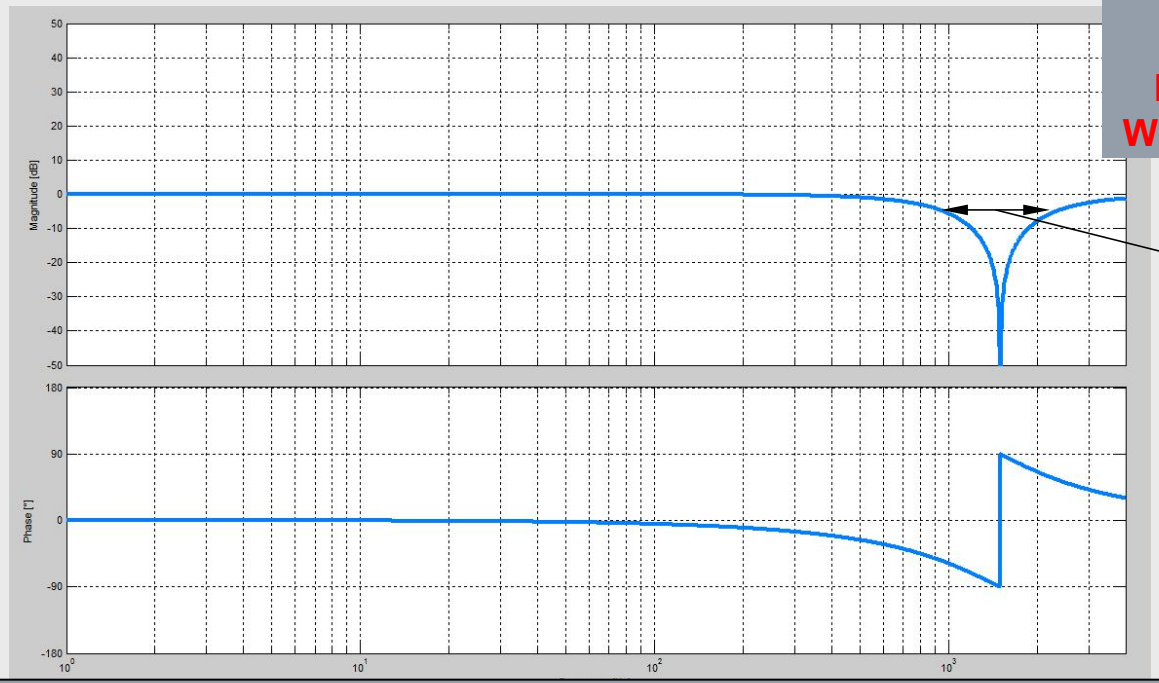
Freq. Resp. of Current Setpoint Band Stop Filter
电流设定点带阻滤波器的频率响应

SIEMENS



Current setpoint filter

BS 1500 Hz
Width. 2000 Hz

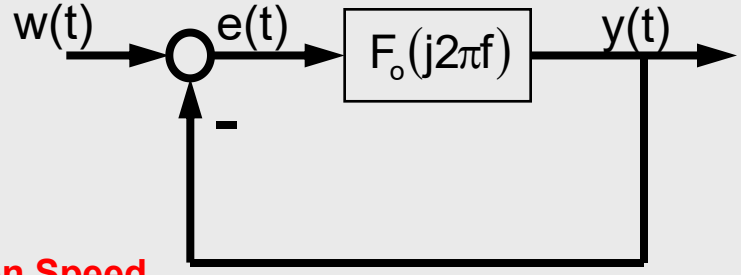


电流设定点滤波器会有相位偏移

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



$$F_o(j2\pi f) = \frac{Y(j2\pi f)}{E(j2\pi f)}$$

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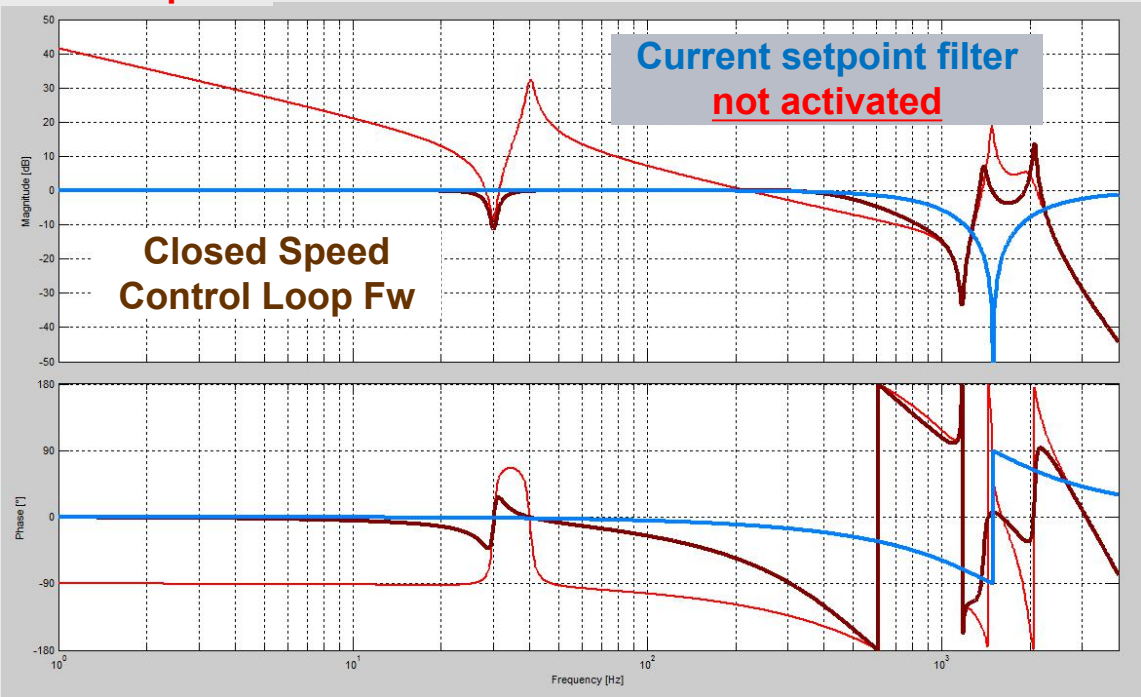
Open Speed Control Loop Fo



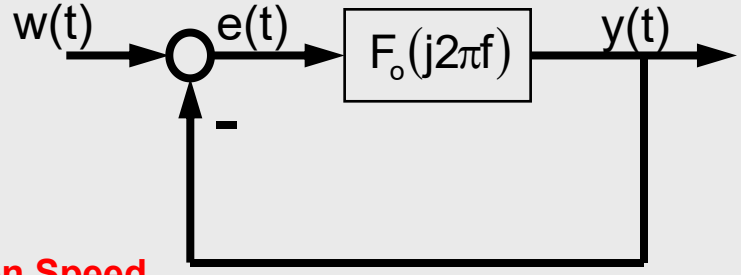
Kp = 1,1 Nms/rad

Tn = 0 ms (OFF)

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



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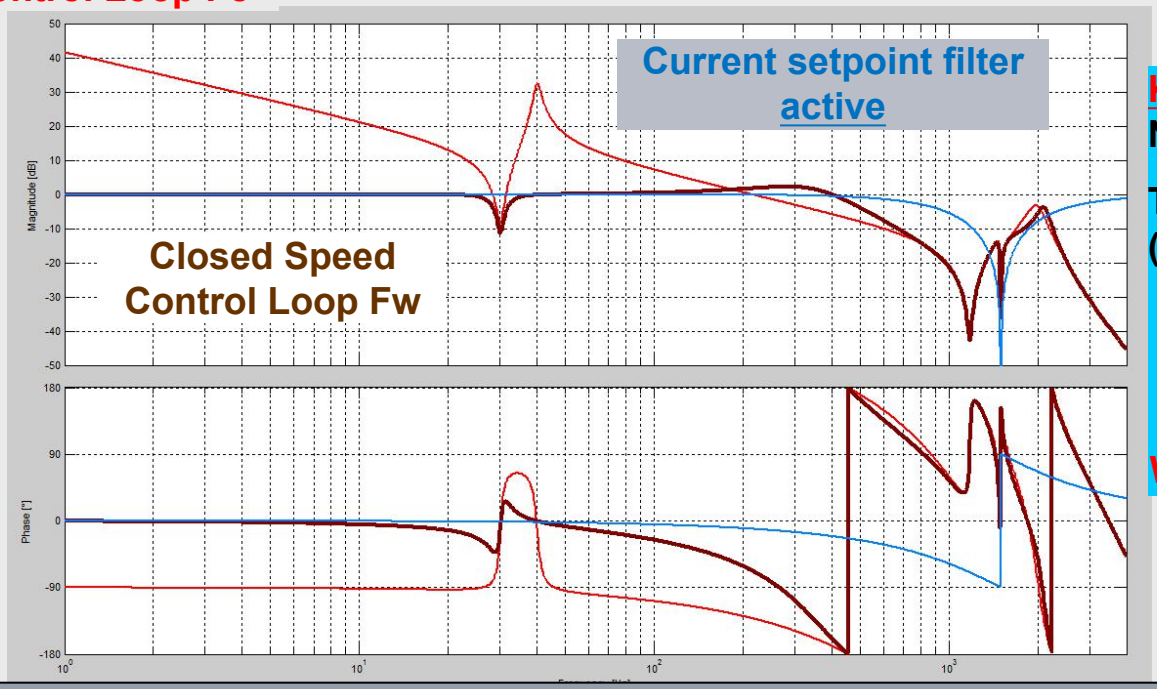
Open Speed Control Loop Fo

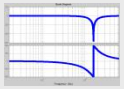


Kp = 1,1 Nms/rad

Tn = 0 ms (OFF)

Current setpoint filter

BS 1500 Hz
Width. 2000 Hz

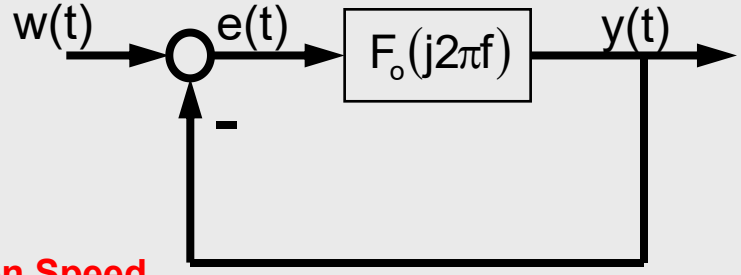


与上页图形比较

Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



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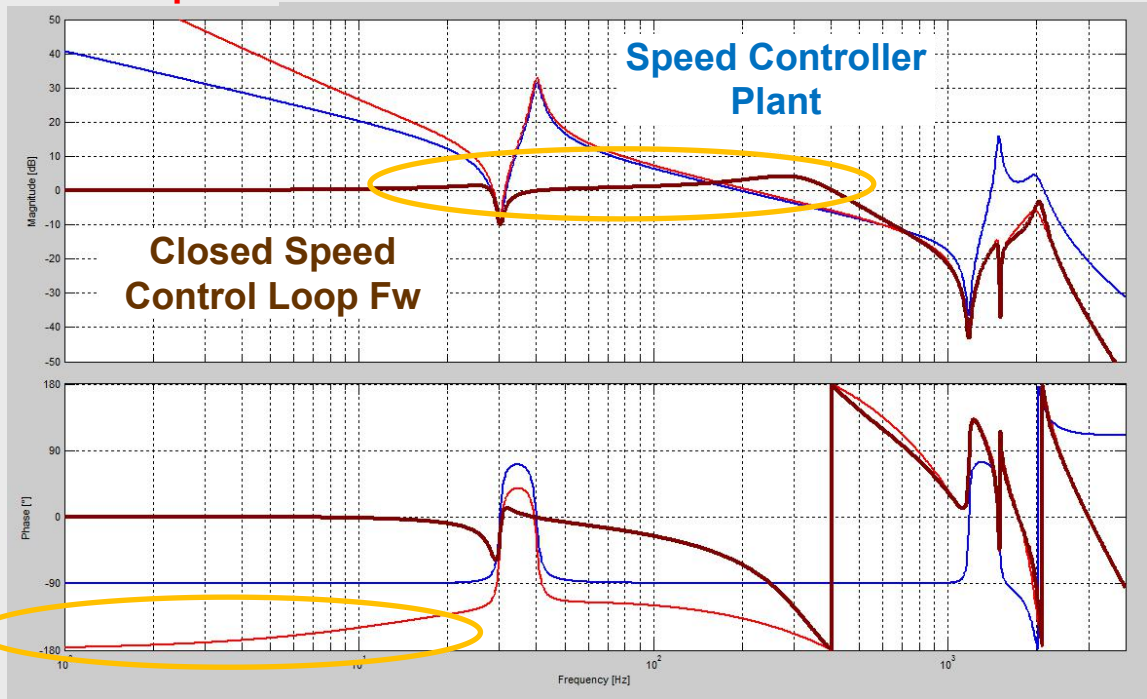
Open Speed Control Loop Fo

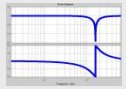


Kp = 1,1 Nms/rad

Tn = 10 ms

Current setpoint filter

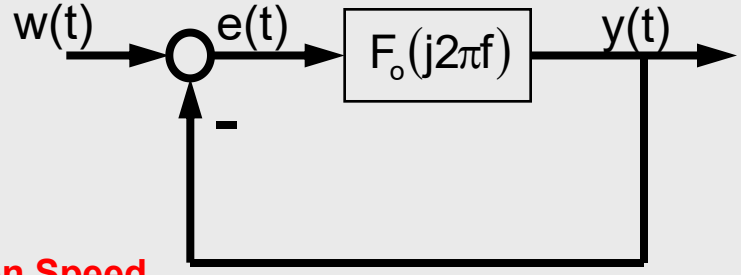
BS 1500 Hz
Width. 2000 Hz



Nyquist criterion : Freq. Resp. of Open and Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



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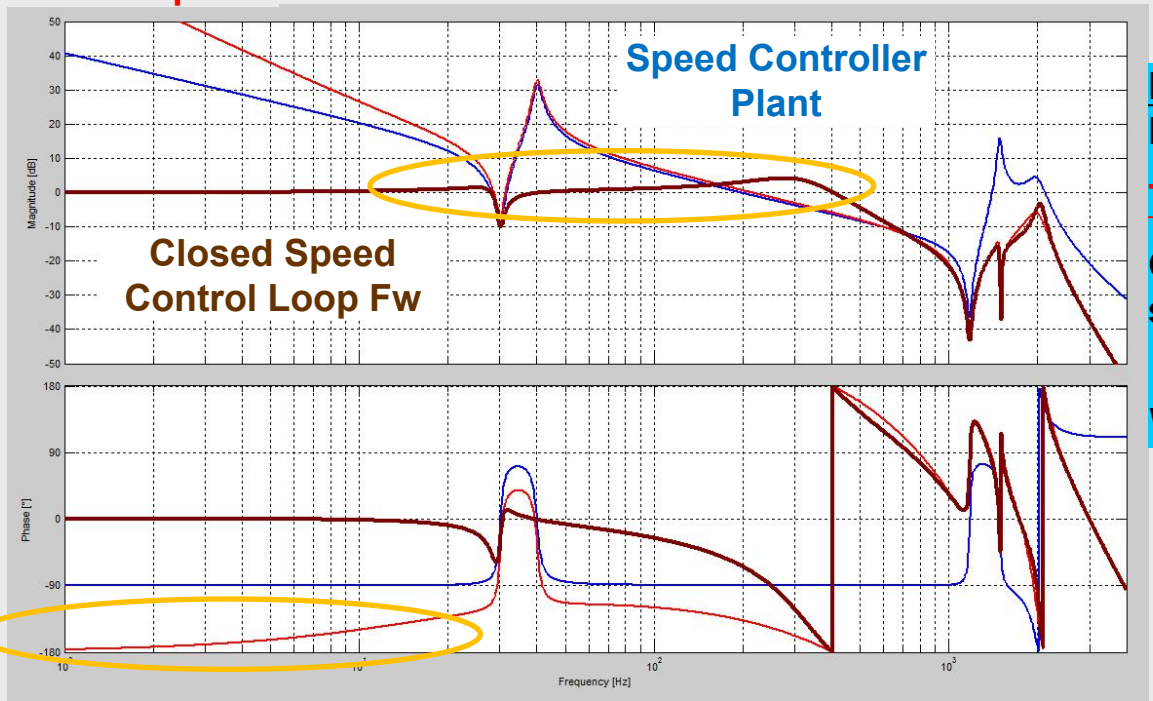
$$F_w(j2\pi f) = \frac{Y(j2\pi f)}{W(j2\pi f)} = \frac{F_o(j2\pi f)}{1 + F_o(j2\pi f)}$$

Open Speed Control Loop Fo

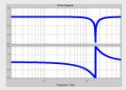


Kp = 1,1 Nms/rad

Tn = 10 ms

Current setpoint filter

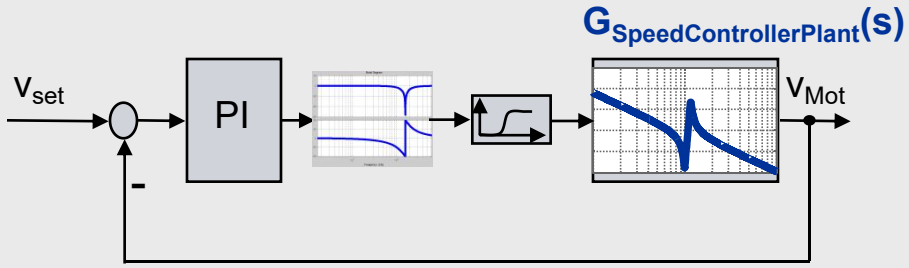
BS 1500 Hz
Width. 2000 Hz

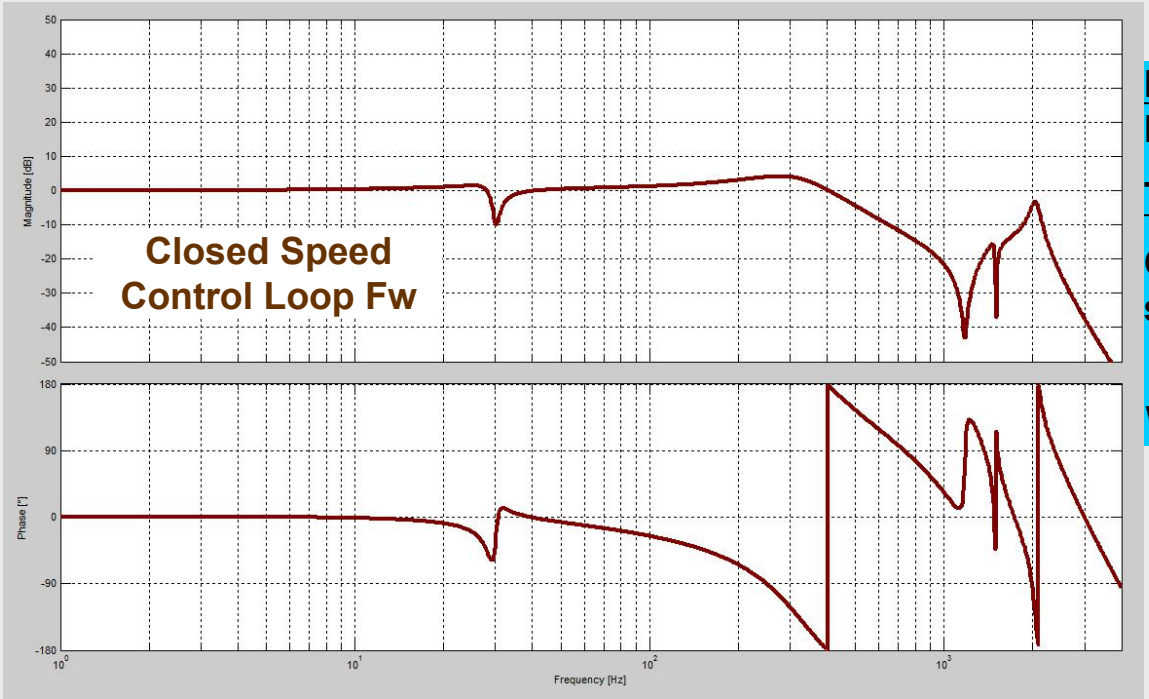


Nyquist criterion : Freq. Resp. of Closed Speed Control Loop

奈奎斯特判据：闭环速度控制环路的开环/闭环频率响应

SIEMENS



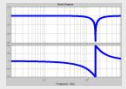


Kp = 1,1 Nms/rad

Tn = 10 ms

Current setpoint filter

BS 1500 Hz
Width. 2000 Hz

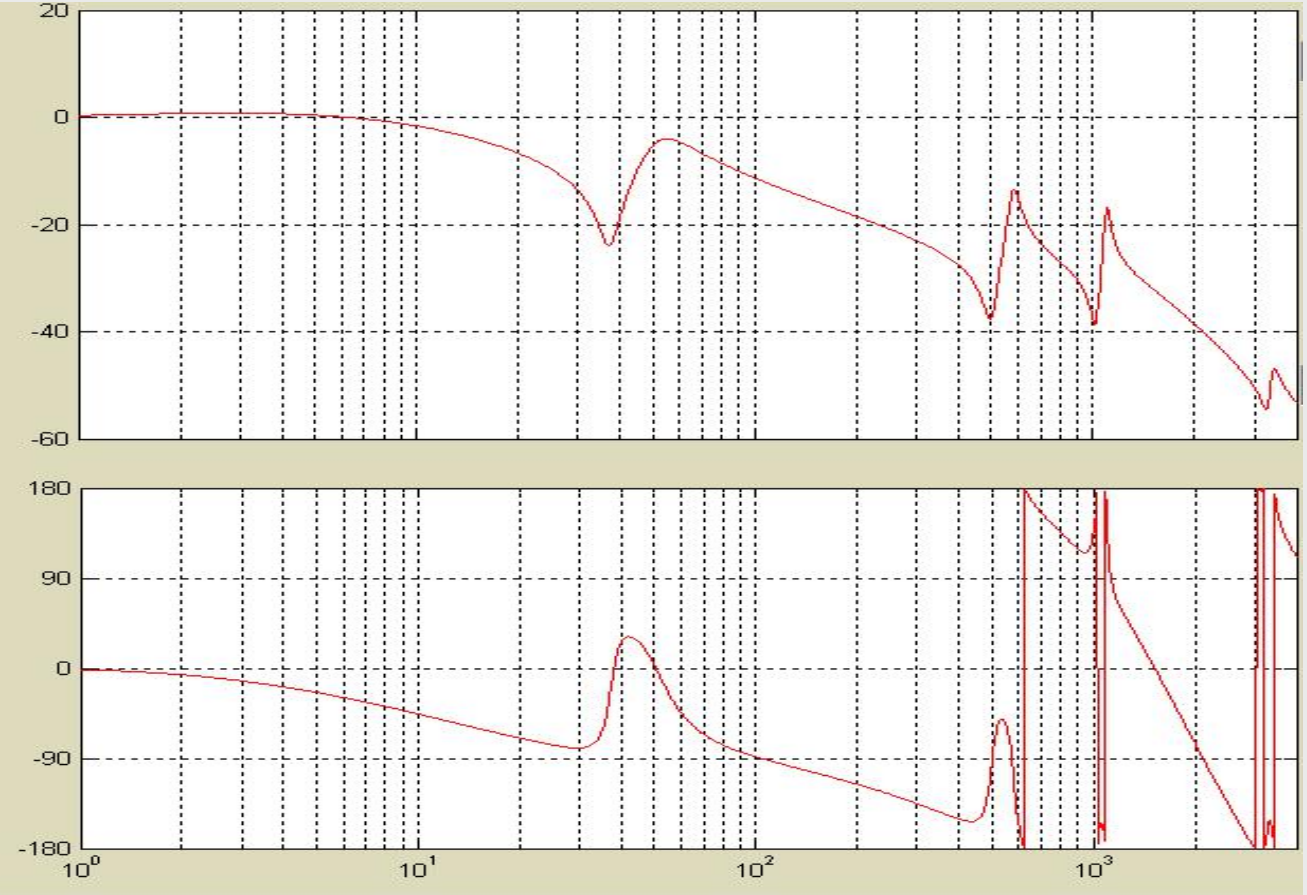


Freq. Resp. of Closed Speed Control Loop:、
闭环速度控制回路的频率响应

$$\frac{\textit{actual Speed Motor}}{\textit{commanded Speed Motor}}$$

SIEMENS

Bode-Diagram



Kp = 0,2 Nms/rad

Tn = 100 ms

Freq. Resp. of Closed Speed Control Loop: Kp increased!
闭环速度控制回路的频率响应：提高Kp

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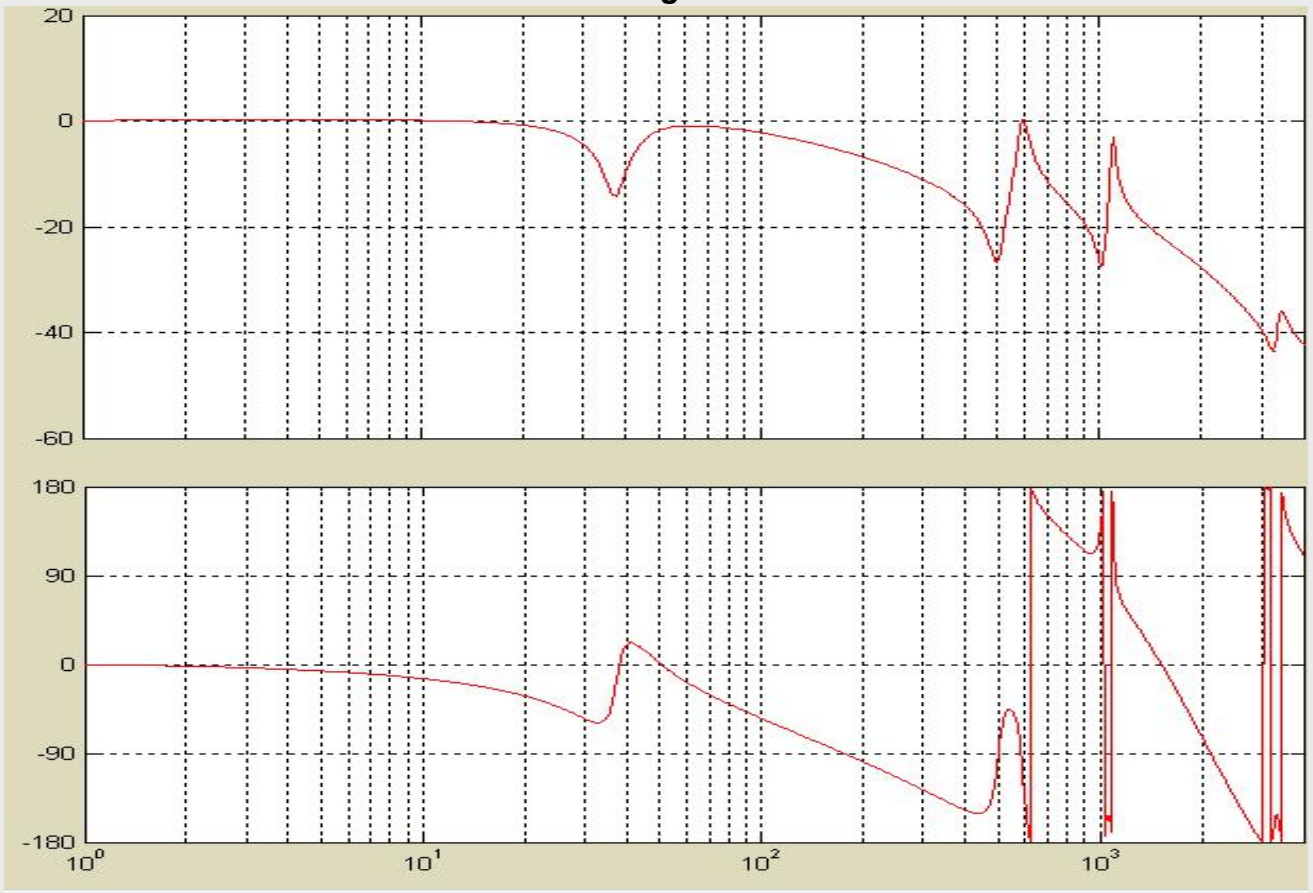
$$\frac{\text{actual Speed Motor}}{\text{commanded Speed Motor}}$$

Bode-Diagram



Kp = 0,7 Nms/rad

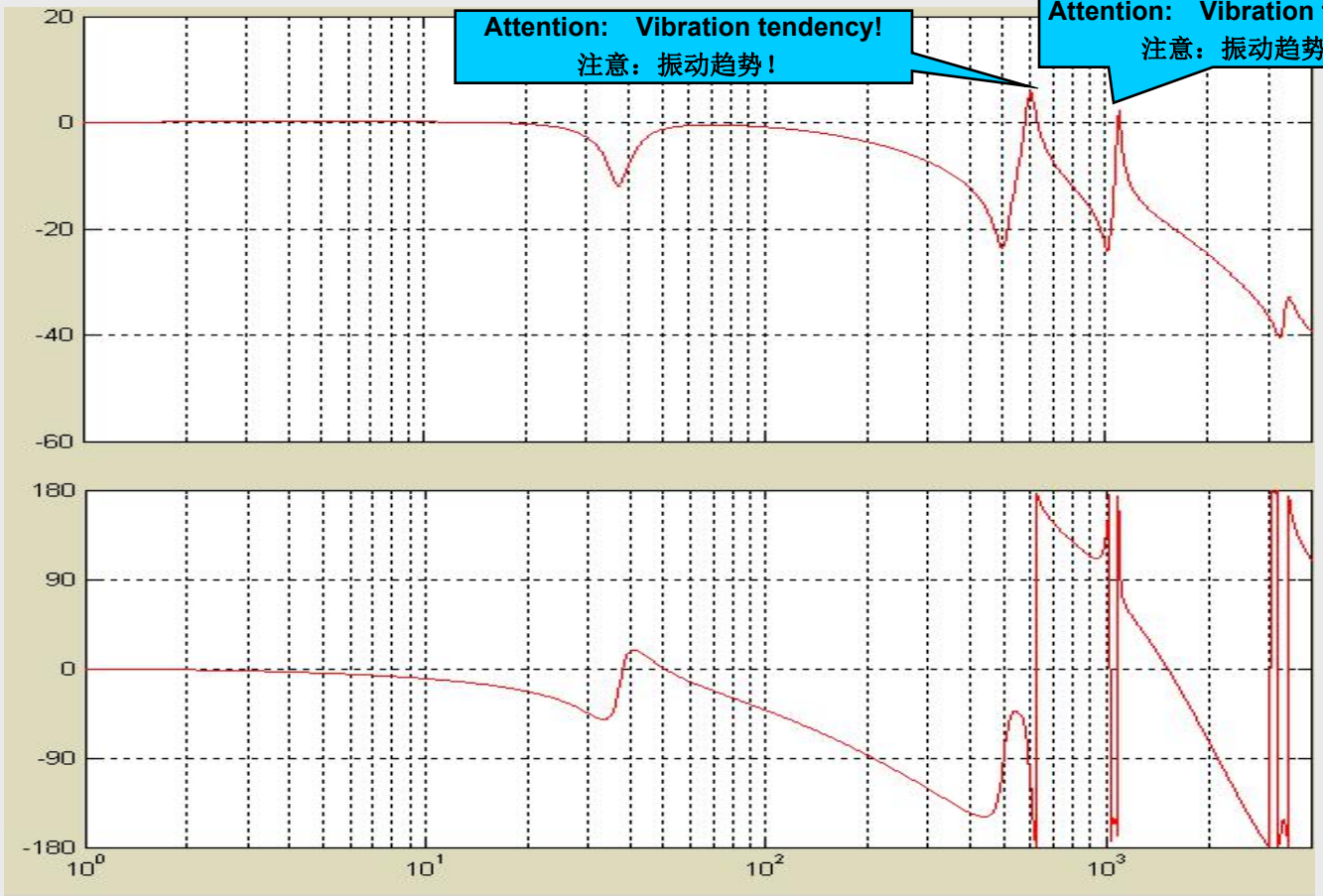
Tn = 100 ms

Freq. Resp. of Closed Speed Control Loop: Kp even more increased!
闭环速度控制回路的频率响应：提高Kp

SIEMENS

$$\frac{\textit{actual Speed Motor}}{\textit{commanded Speed Motor}}$$

Bode-Diagram

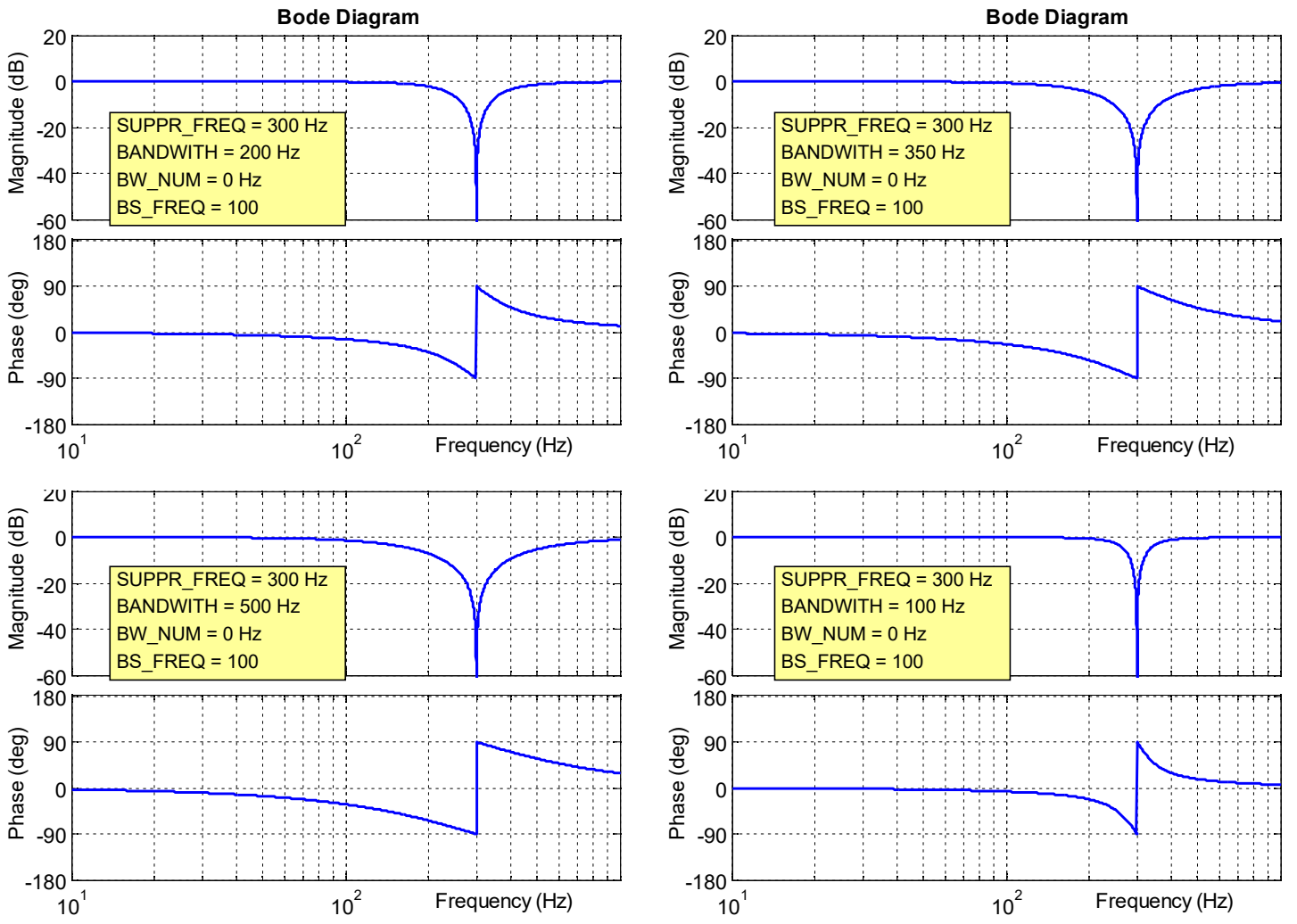


Kp = 1 Nms/rad

Tn = 100 ms

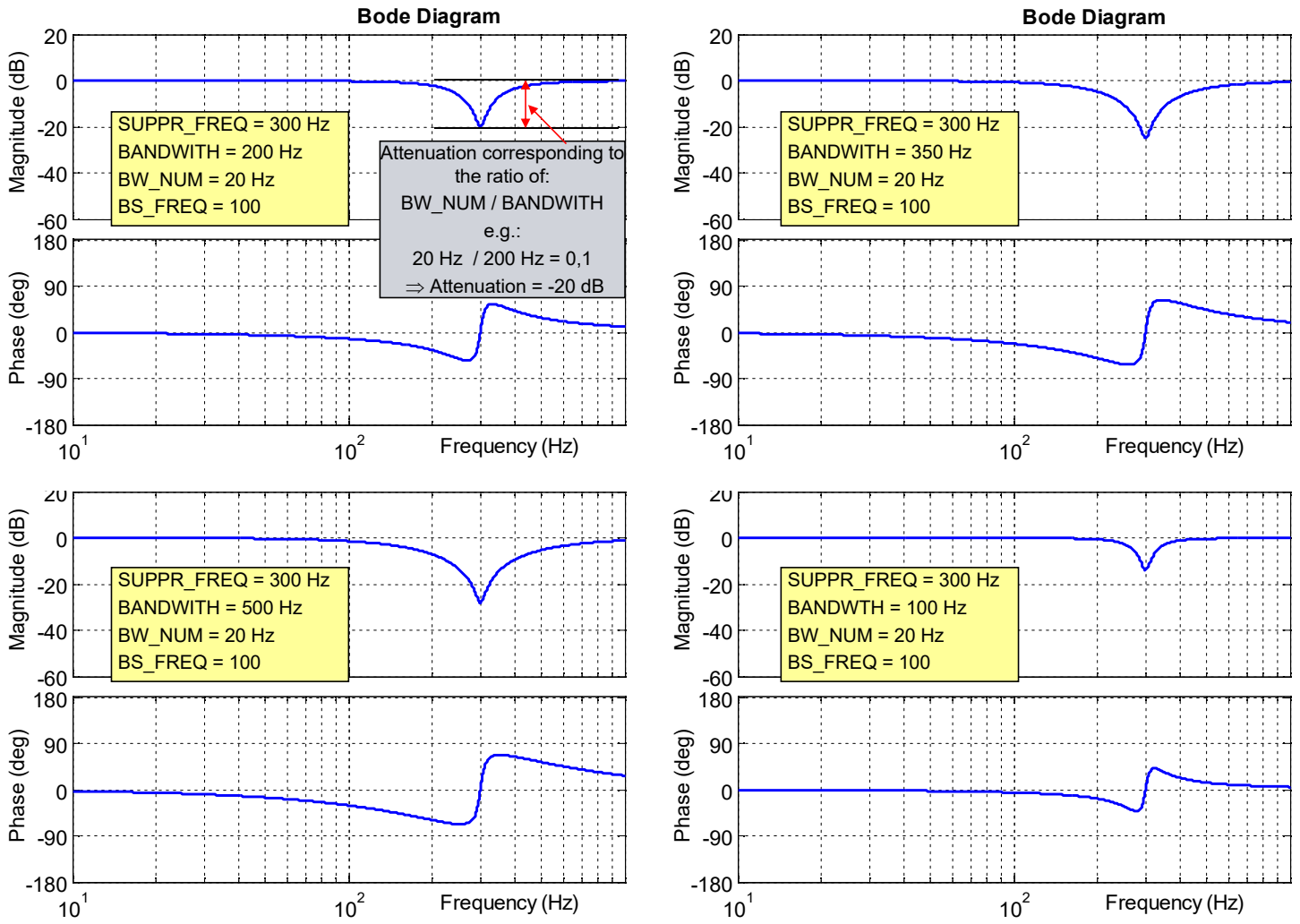
Examples for Current Setpoint Band Stop Filters:
电流设定点带阻滤波器例

SIEMENS



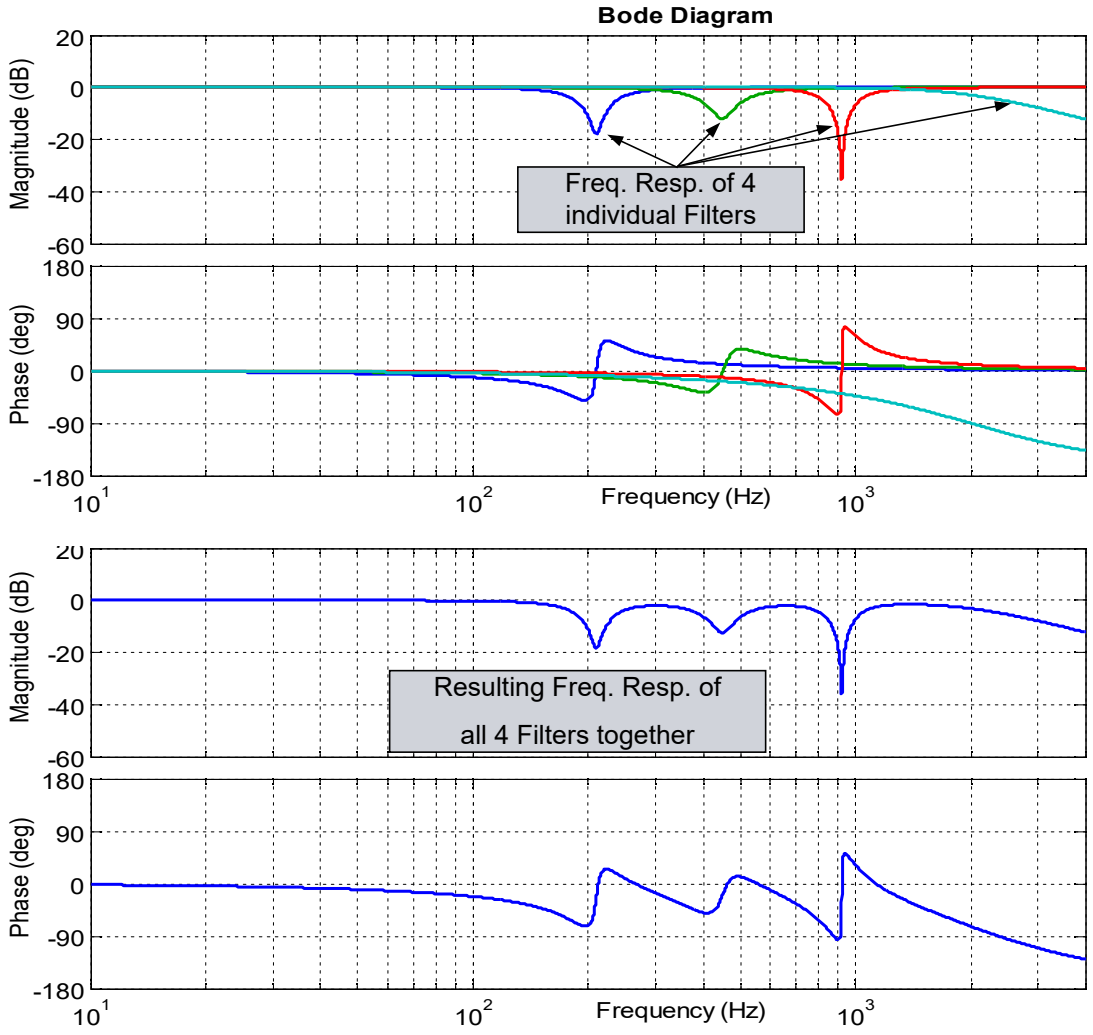
Examples for Current Setpoint Band Stop Filters:
电流设定点带阻滤波器例

SIEMENS



Exemplary Freq. Resp. of 4 active Current Setpoint Filters:
4个电流设定滤波器生效后典型频率响应

SIEMENS



Low pass PT2:
FILT_1_FREQUENCY = 2000 Hz
FILT_1_DAMPING = 350 Hz

Band stop:
FILT_2_SUPPR_FREQ = 210 Hz
FILT_2_ BANDWITH = 80 Hz
FILT_2_ BW_NUM = 10 Hz
FILT_2_ BS_FREQ = 100

Band stop :
FILT_3_SUPPR_FREQ = 450 Hz
FILT_3_ BANDWITH = 200 Hz
FILT_3_ BW_NUM = 50 Hz
FILT_3_ BS_FREQ = 100

Band stop :
FILT_3_SUPPR_FREQ = 920 Hz
FILT_3_ BANDWITH = 300 Hz
FILT_3_ BW_NUM = 5 Hz
FILT_3_ BS_FREQ = 100

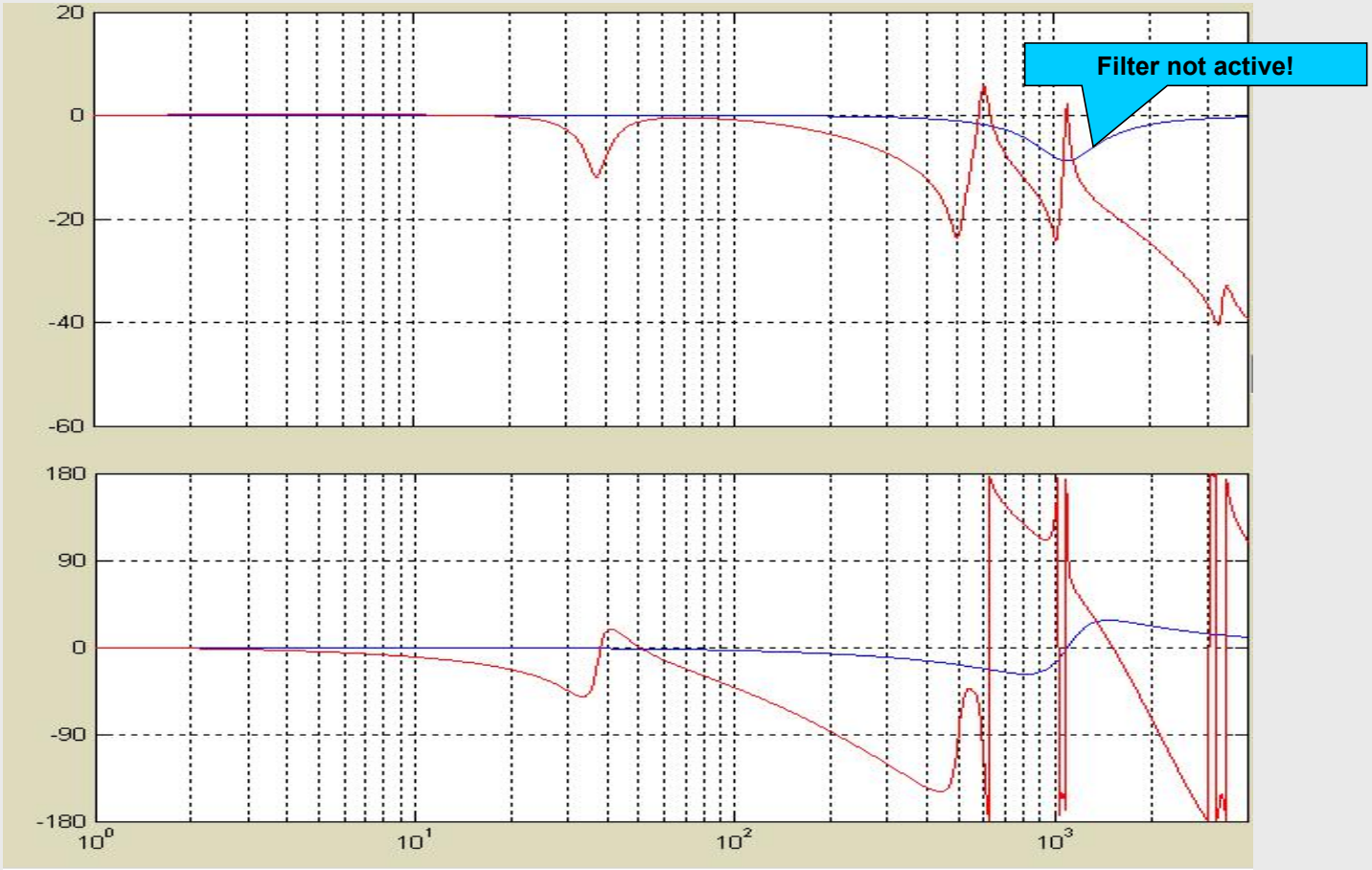
Lower picture:
Resulting Freq. Resp. of all current setpoint filters
(only filters without the influence of the mechanics etc.)

Freq. Resp. of a Band Stop at 1100 Hz:
1100Hz带阻滤波器频率响应

SIEMENS

$$\frac{Output\ \ Filter}{Input\ \ Filter}$$

Bode-Diagram



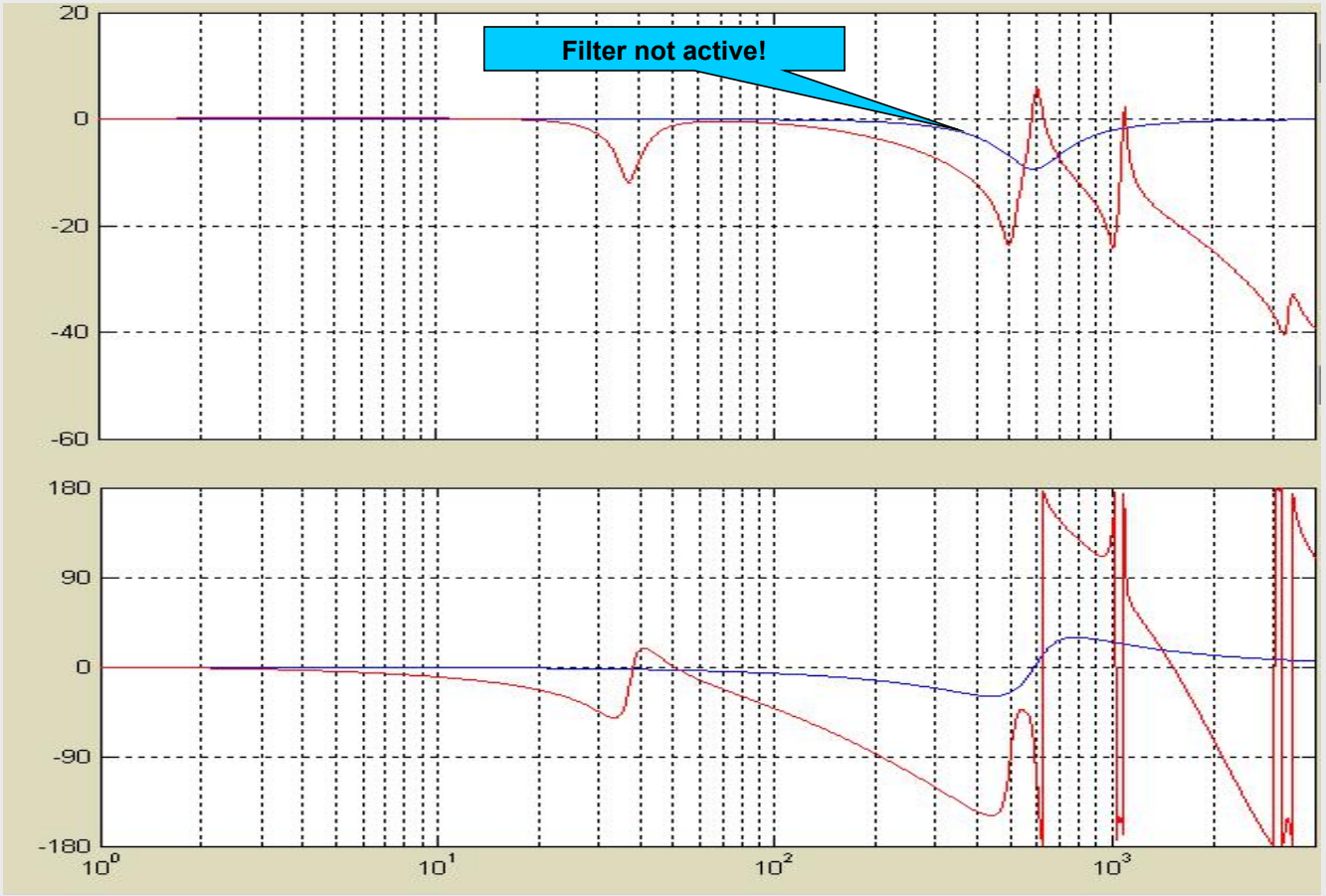
Band stop: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz

Freq. Resp. of a Band Stop at 590 Hz:
590Hz带阻滤波器频率响应

$$\frac{Output\ \ Filter}{Input\ \ Filter}$$

SIEMENS

Bode-Diagram



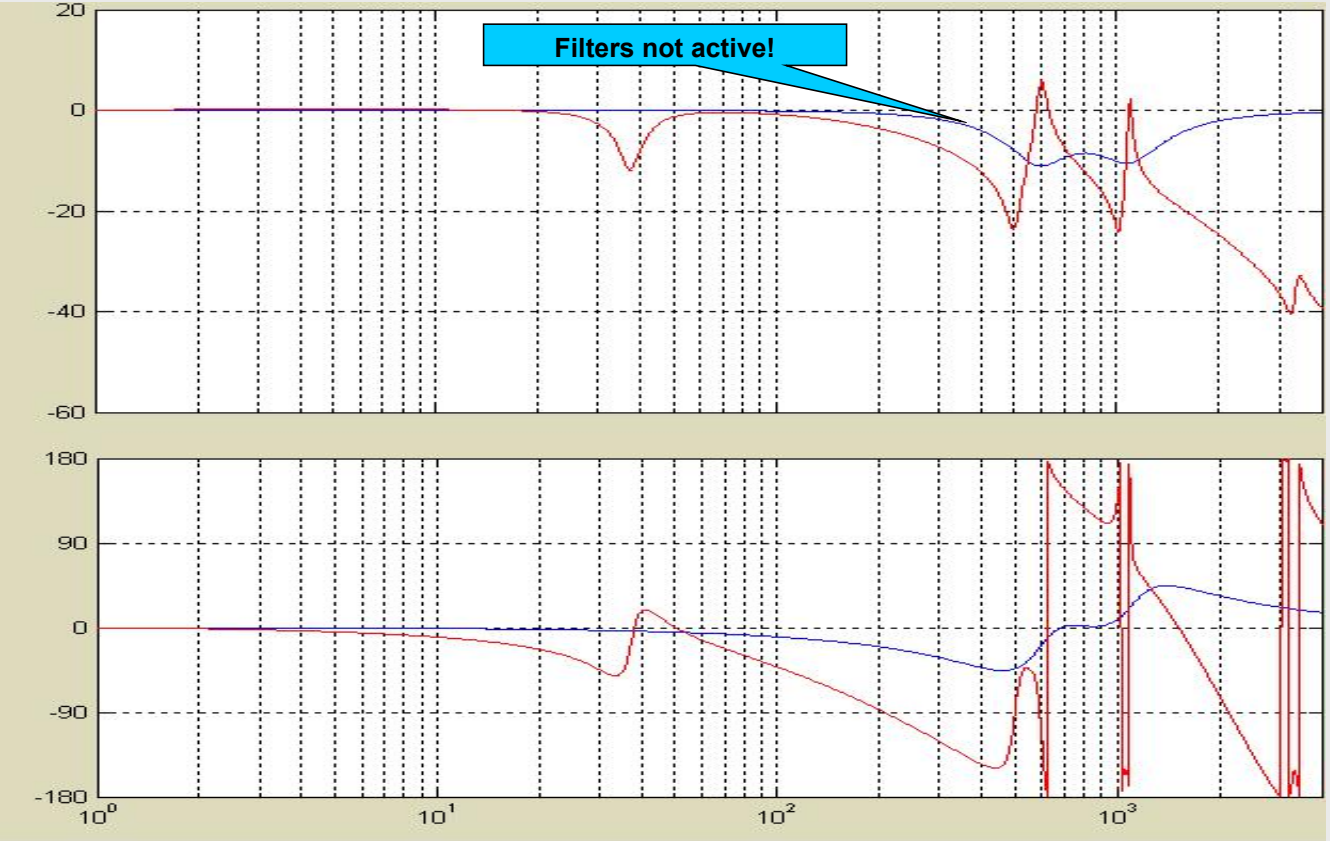
Band stop: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz

Freq. Resp. of Both Band Stop Filters at 590 Hz and 1100 Hz:
590Hz和1100Hz带阻滤波器频率响应

$$\frac{Output\ \ Filter}{Input\ \ Filter}$$

SIEMENS

Bode-Diagram



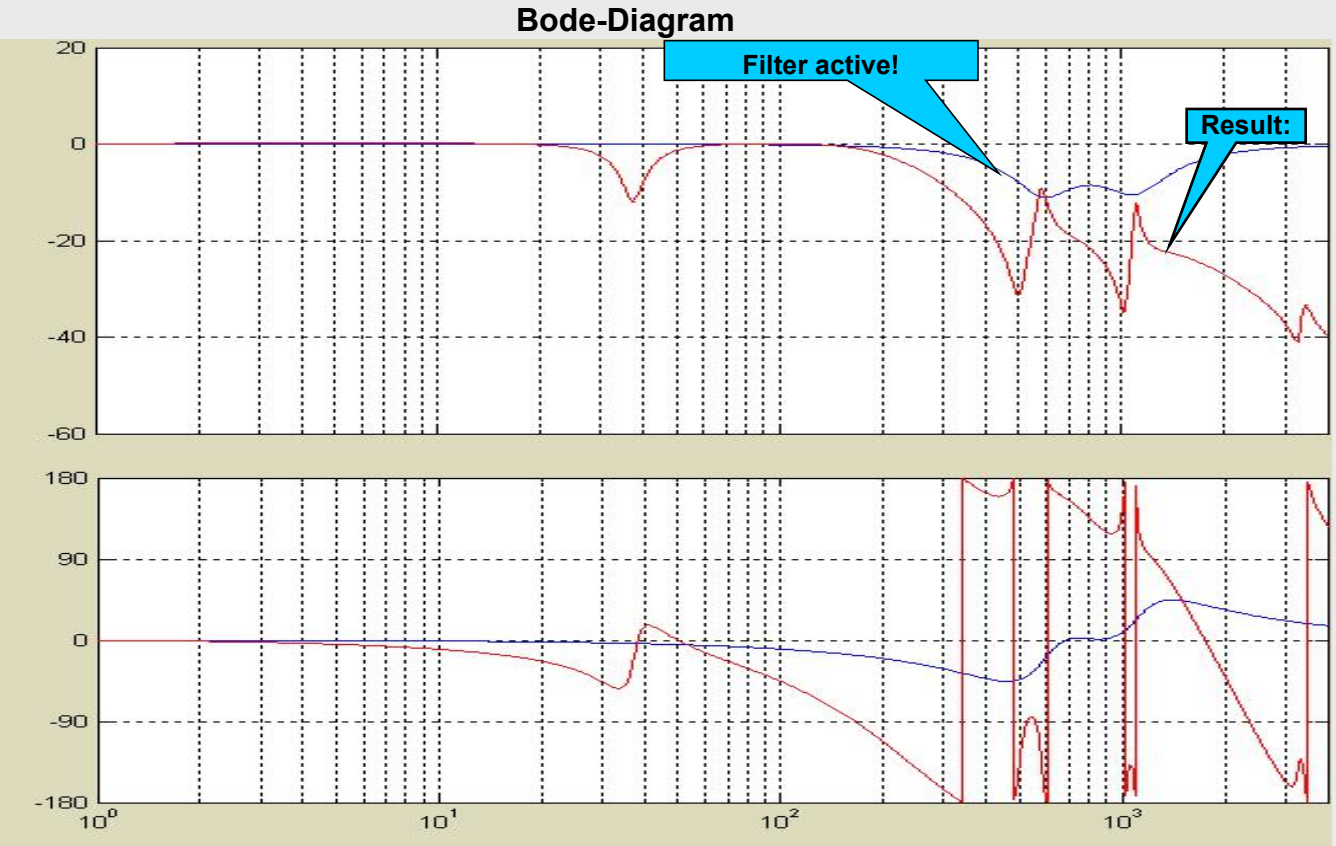
Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz

Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz

Freq. Resp. of the Closed Speed Control Loop Including the Current Setpoint Filters: With Kp = 1 Stabile und Reserve

带电流设定点滤波器的闭环速度控制频率响应， Kp=1

SIEMENS

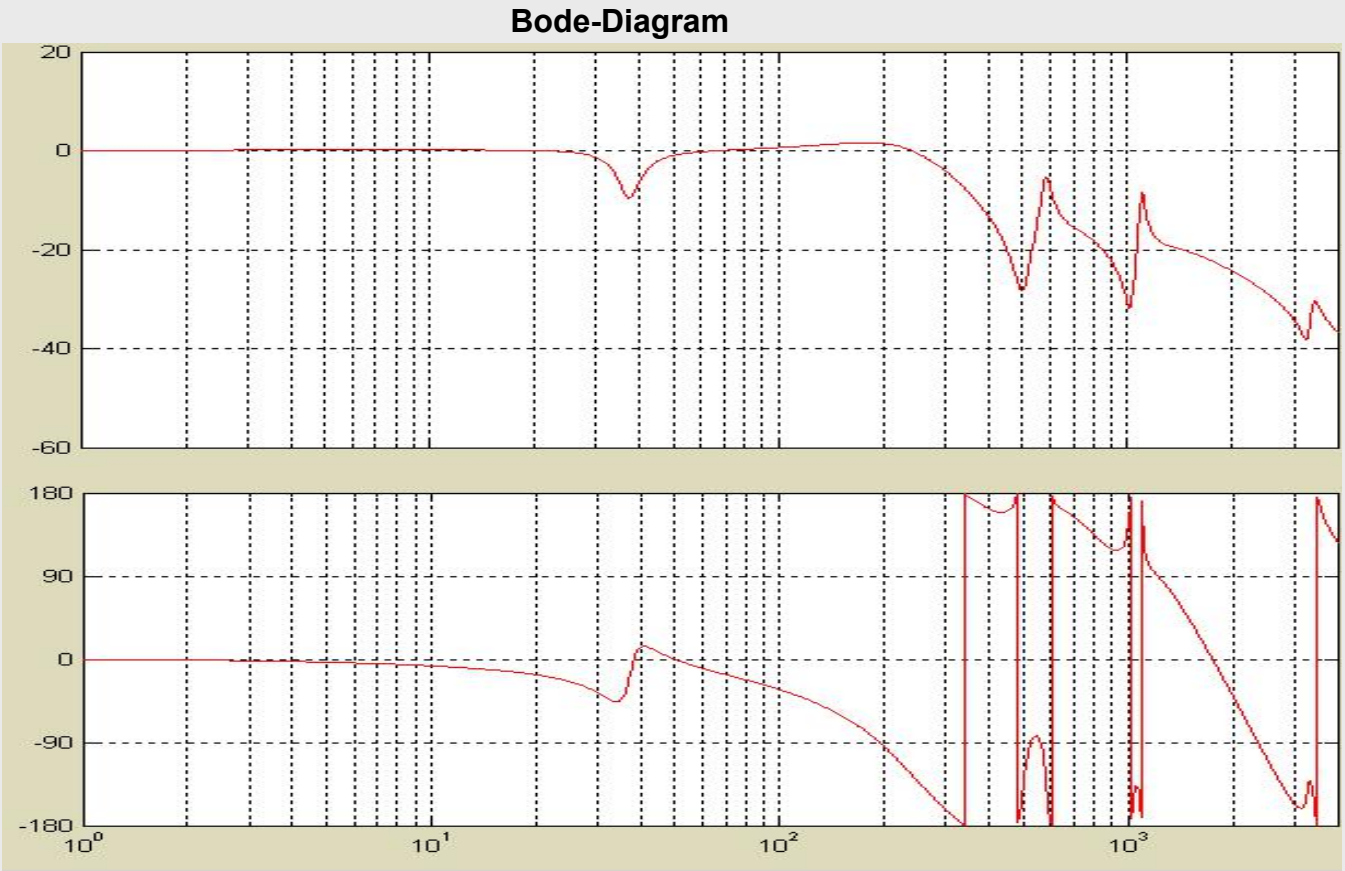


Kp = 1Nms/rad	**Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz**
Tn = 100 ms	**Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz**

Freq. Resp. of the Closed Speed Control Loop Including the Current Setpoint Filters: Kp increased

带电流设定点滤波器的闭环速度控制频率响应， 提高Kp

SIEMENS



Kp = 1,4 Nms/rad	**Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz**
Tn = 100 ms	**Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz**

Freq. Resp. of the Closed Speed Control Loop Including the Current Setpoint Filters: Tn reduced

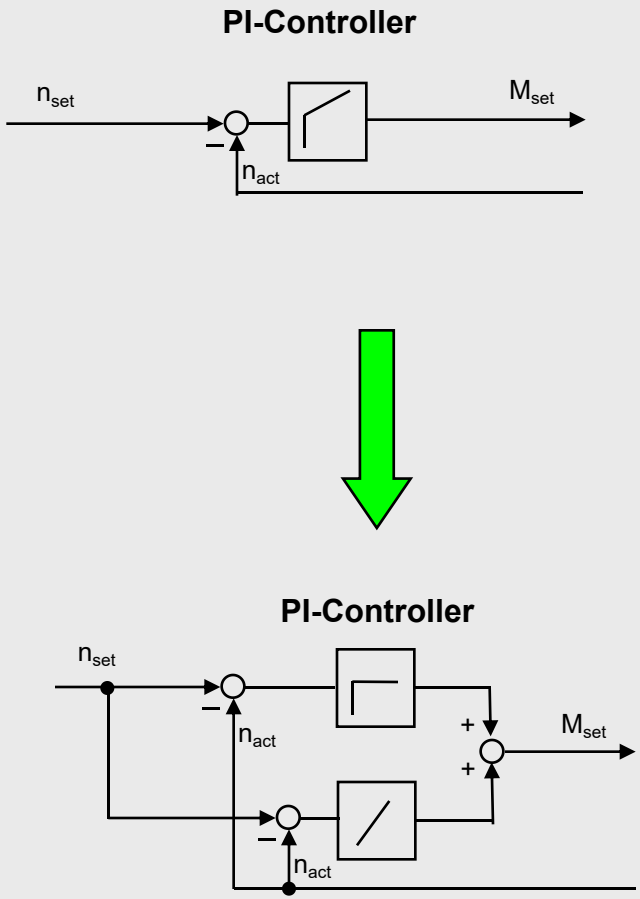
带电流设定点滤波器的闭环速度控制频率响应， 减小Tn

SIEMENS

Kp = 1,4 Nms/rad	**Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz**
Tn = 8 ms	**Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz**

Functional Principle “Reference-Model”: PI-Controller
“Reference Model(参考模型)”功能原理， PI-控制器

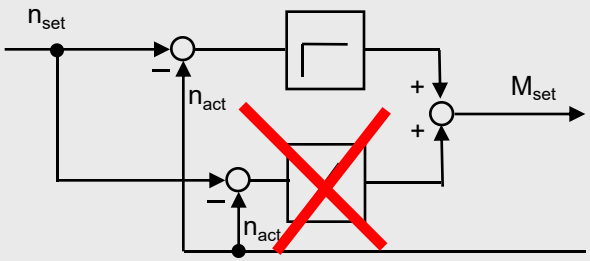
SIEMENS



Functional Principle “Reference-Model”: Just P-Controller
“Reference Model(参考模型)”功能原理， 只有P控制器

SIEMENS

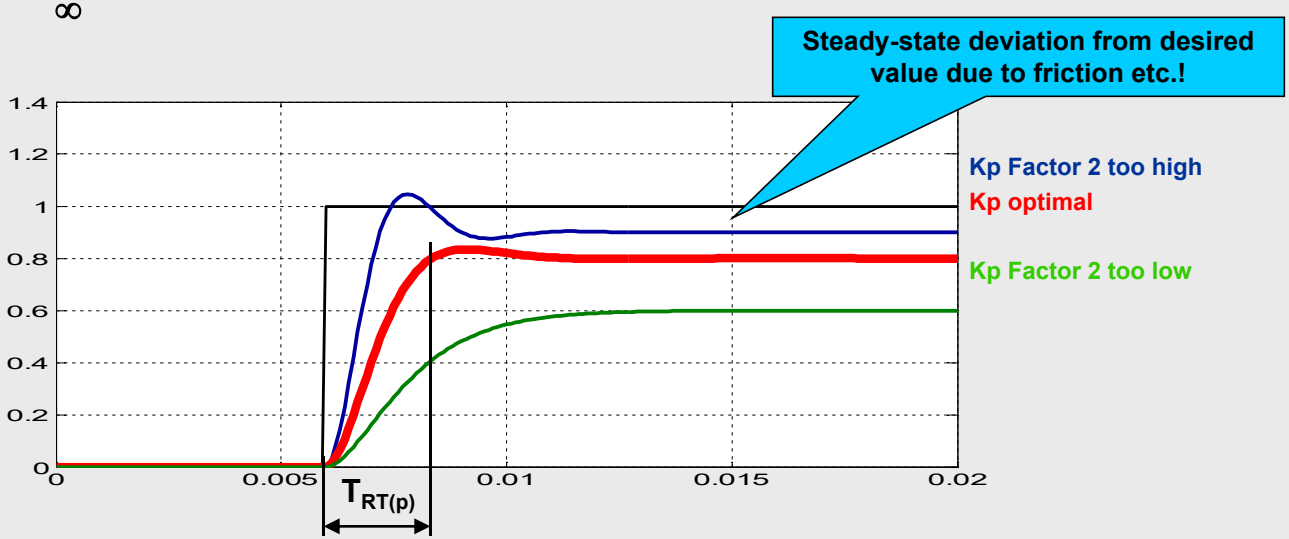
P-Controller



优化速度环，先优化P环节,关掉积分环节（先按**disturbance optimization**）

测量上升时间，从开始到第一次到达最终幅值的时间。

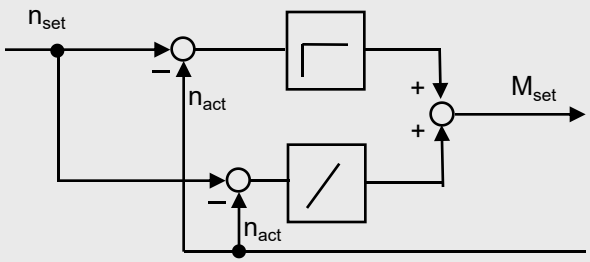
Step response:
P-controlled closed Speed Controller $T_N = \infty$



Functional Principle “Reference-Model”: PI-Controller $T_N = T_{RT(p)}$
“Reference Model(参考模型)”功能原理， PI-控制器 $T_N = T_{RT(p)}$

SIEMENS

PI-Controller



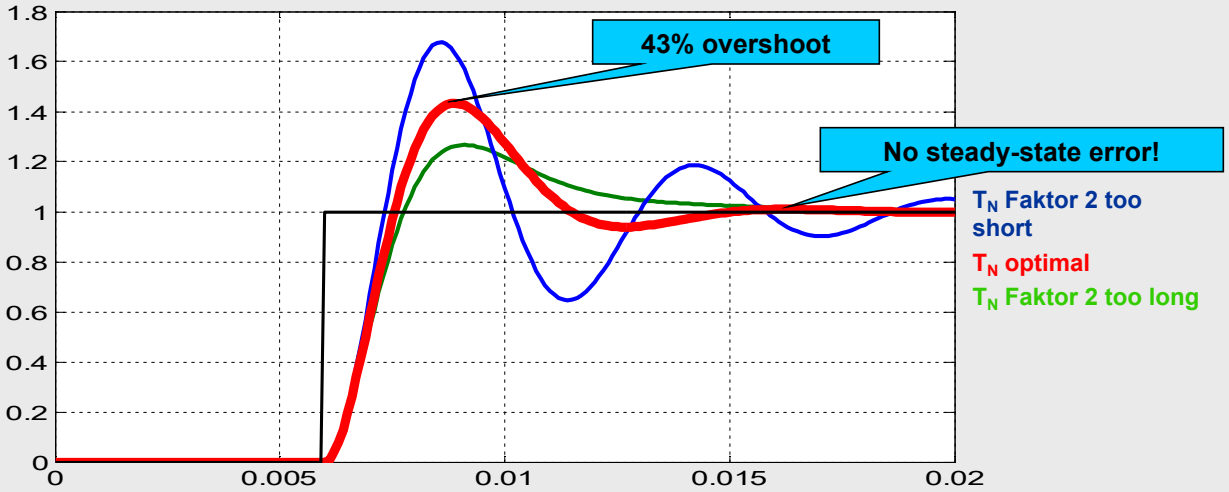
把测量的时间作为积分环节的时间

这种优化成为**synmatrical optimization**

设定值大于实际值＝后面实际值大于设定值

Step response:

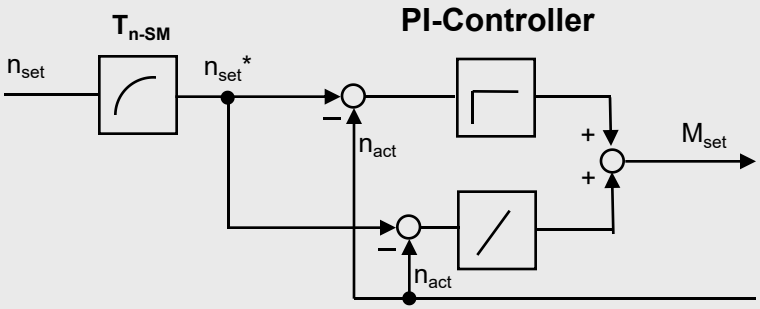
PI-controlled closed Speed Controller $T_N = T_{RT(p)}$



Functional Principle “Reference-Model”: PI-Controller $T_N = T_{RT(p)}$ With Speed Setpoint Smoothing $T_{n\text{-}SM} = T_{RT(p)}$

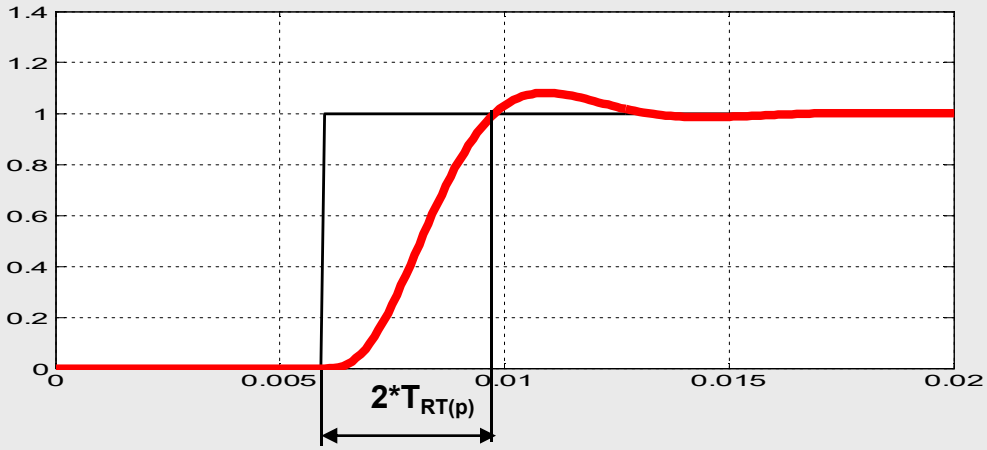
“Reference Model(参考模型)”功能原理， PI-控制器 $T_N = T_{RT(p)}$ 带速度设定点平滑 $T_{n\text{-}SM} = T_{RT(p)}$

SIEMENS



Step response:
PI-controlled closed Speed Controller with speed setpoint smoothing

$T_{n\text{-}SM} = T_{RT(p)}$

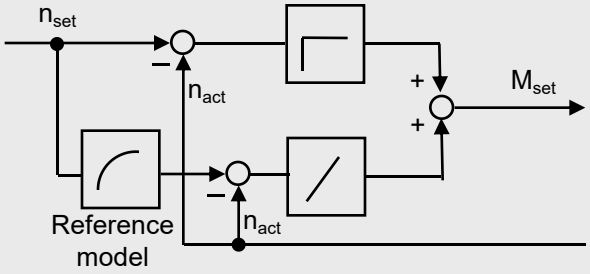


Functional Principle “Reference-Model”: PI-Controller With Reference Model

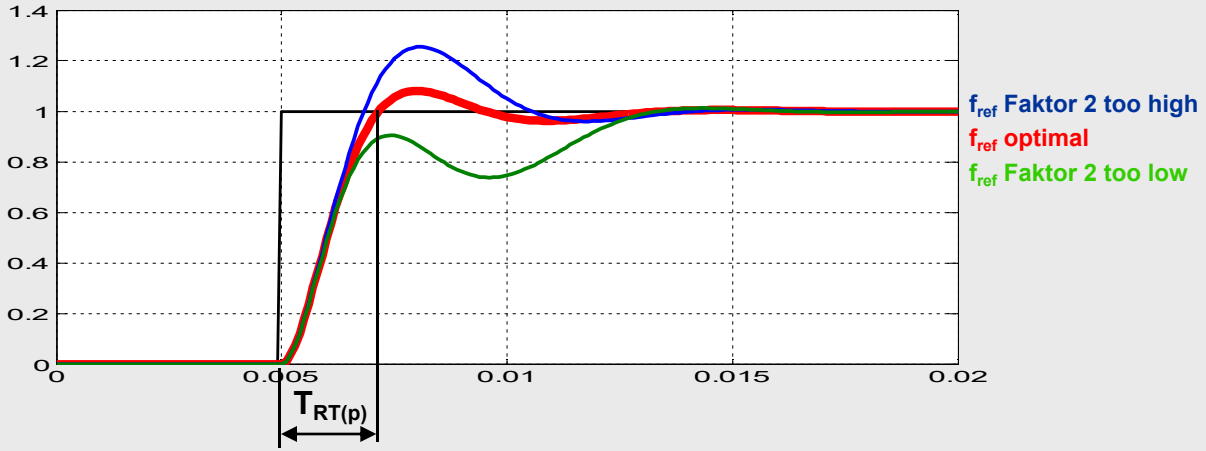
“Reference Model(参考模型)”功能原理， 带参考模型

SIEMENS

PI-Controller with Reference model



Step response:
PI-controlled closed Speed Controller with Reference model



Freq. Resp. of Closed Speed Controller Including Current Setpoint Filters: Tn Reduced

带电流设定点滤波器的闭环速度控制频率响应， 减小Tn

SIEMENS

Kp = 1,4 Nms/rad	Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Tn = 8 ms	Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz

Freq. Resp. of Closed Speed Controller Including Current Setpoint Filters: Tn Reduced With Reference Model 150 Hz

带电流设定点滤波器的闭环速度控制频率响应， 减小Tn+参考模型150Hz

SIEMENS

Kp = 1,4 Nms/rad
Tn = 8 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
Reference model = 150 Hz

Freq. Resp. of Closed Speed Controller Including Current Setpoint Filters: Tn Reduced With Reference Model 80 Hz

带电流设定点滤波器的闭环速度控制频率响应， 减小Tn+参考模型80Hz

SIEMENS

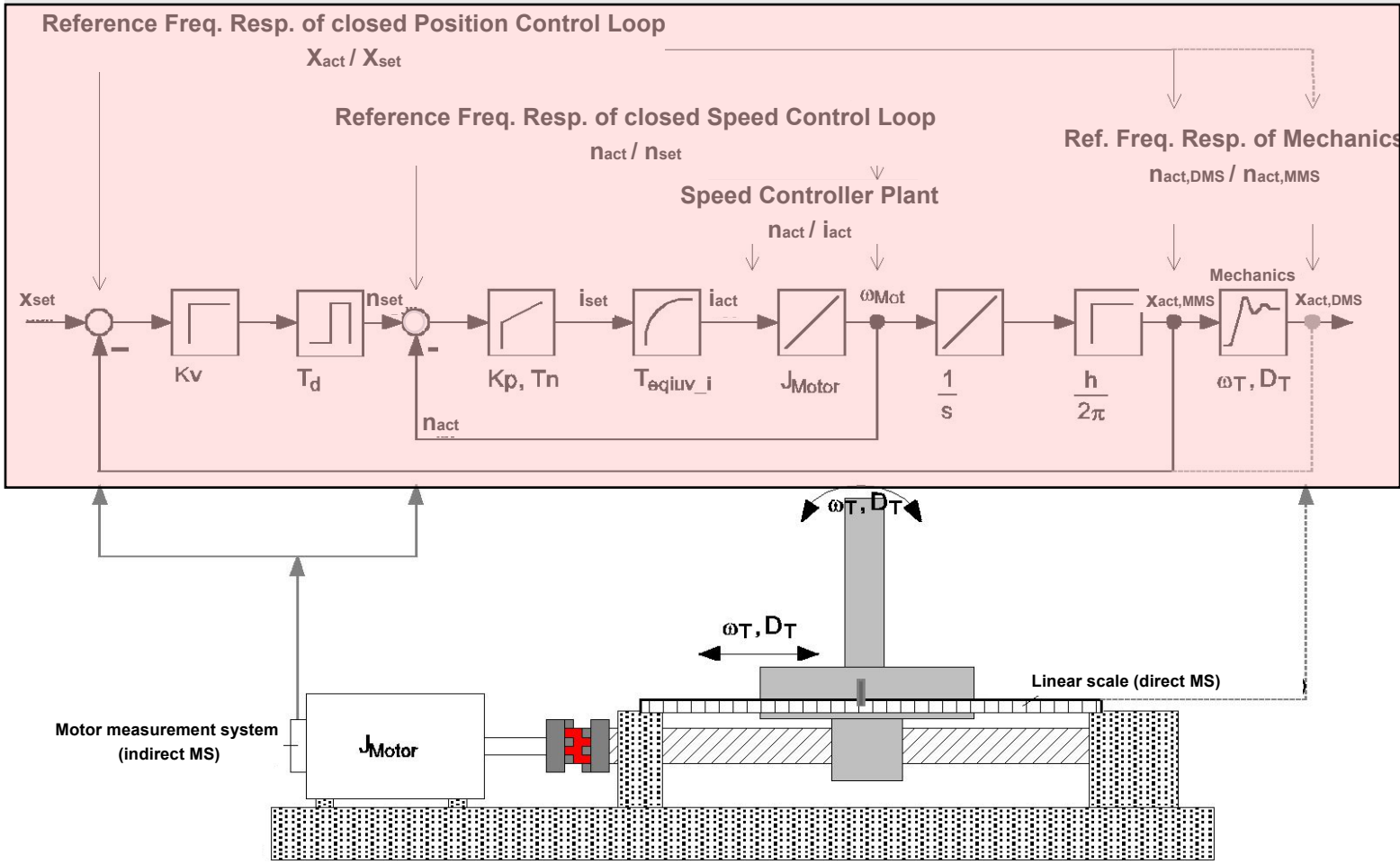
Kp = 1,4 Nms/rad
Tn = 8 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
Reference model = 80 Hz

Freq. Resp. of the Closed Position Controller
闭环位置控制的频率响应

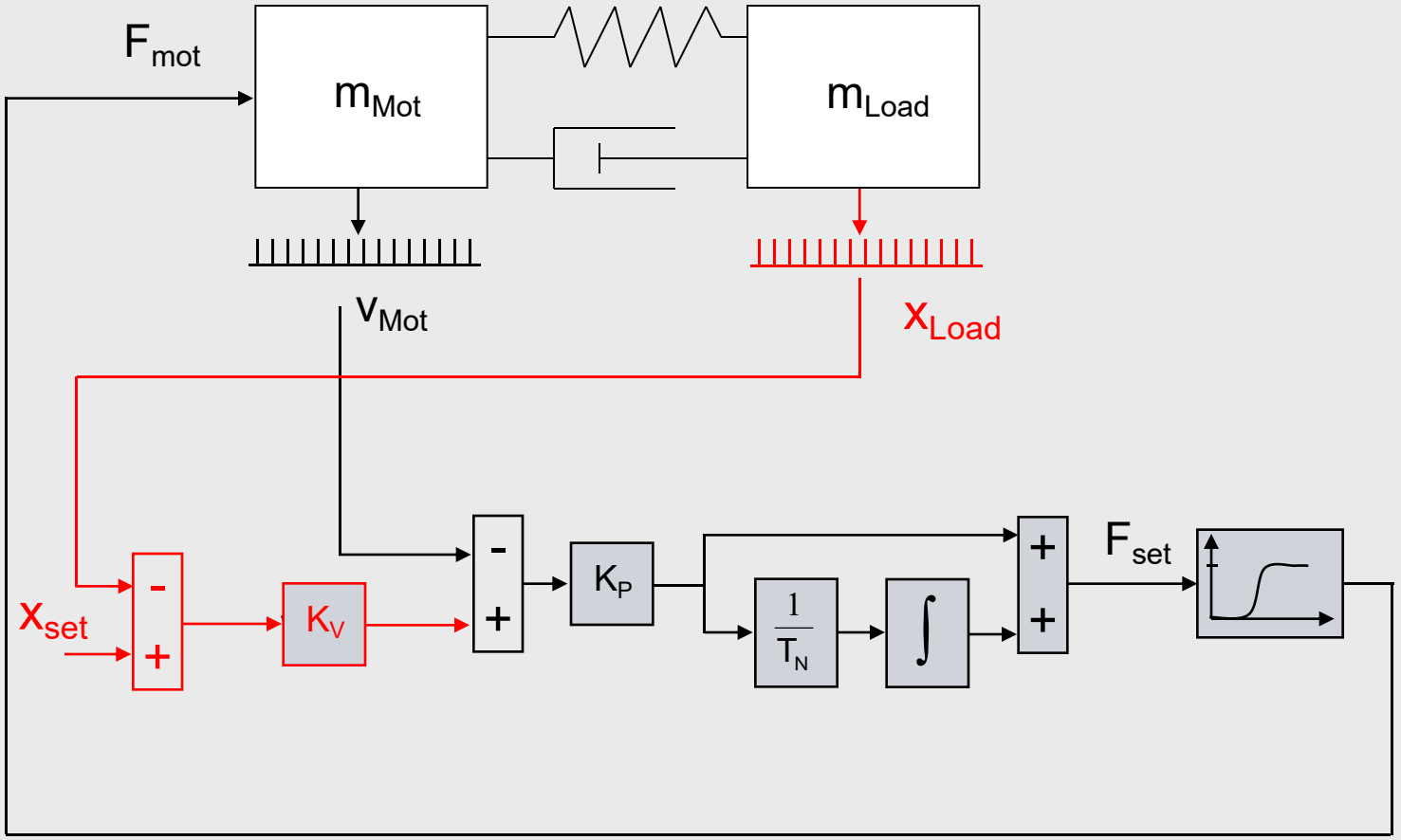
SIEMENS

active actual Position
commanded position

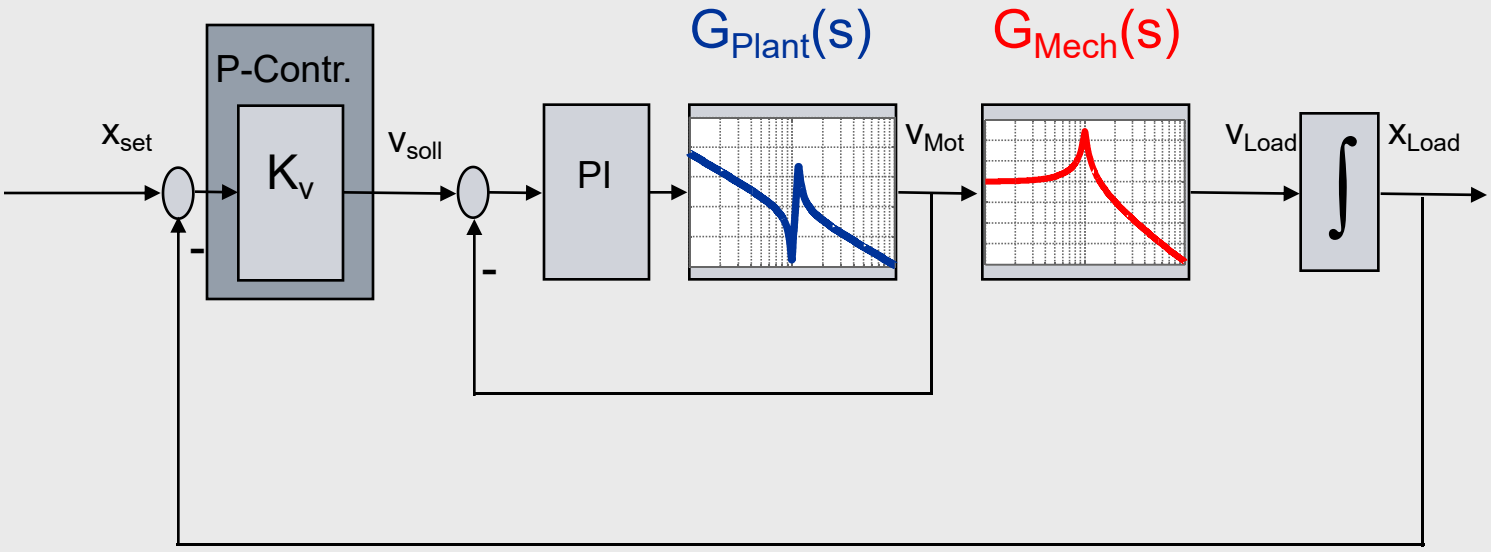


Speed and Position Controller
速度和位置控制器

SIEMENS



	Disturbance optimization		Damping optimization
Kp	10	10	2
Tn	6	6	30
Reference model	60	0	0
Kv	0.8	0.4	1.5



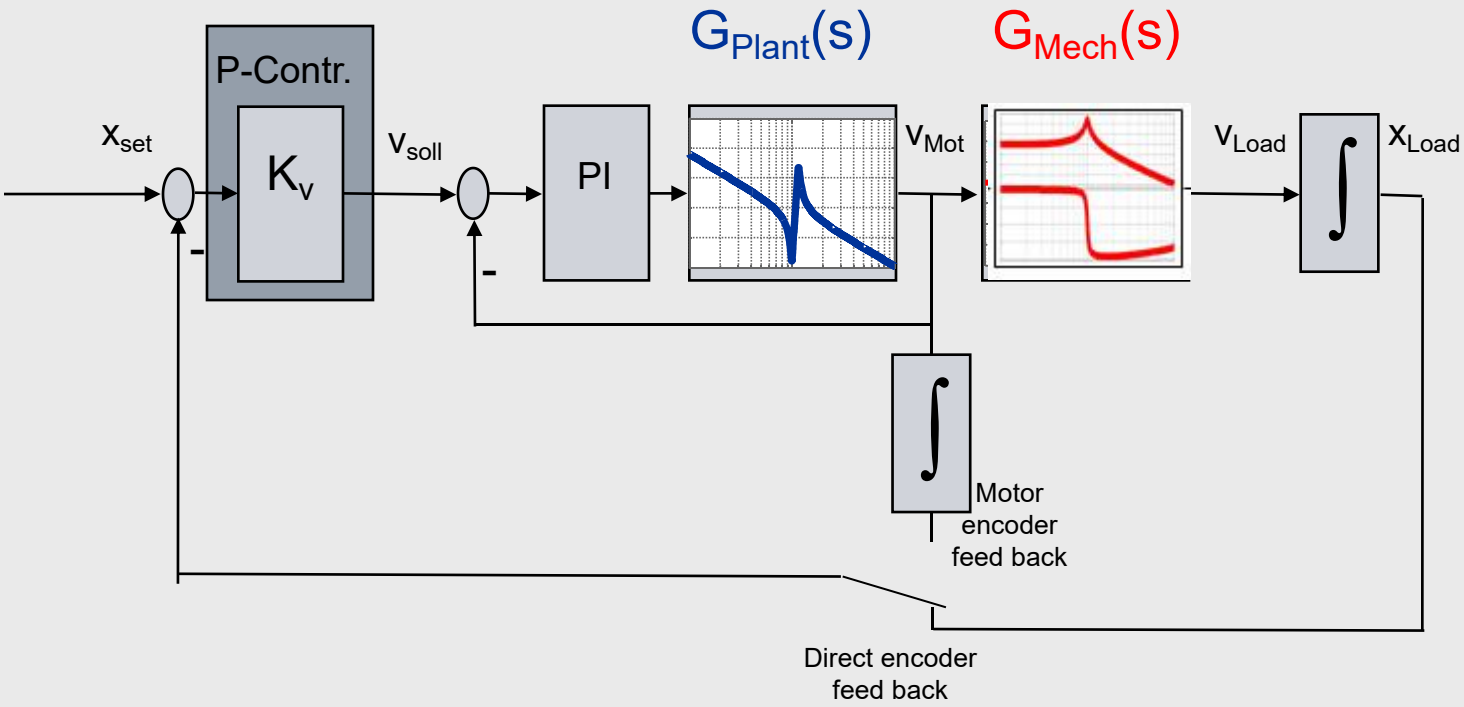
机械系统的伯德图与前面速度环的伯德图叠加,如果正好下凹与尖峰幅值相同,则在**0dB**,这是**damping optimization**的速度环设定.如果传动部件自锁,则无法实现,这时需要用**APC**,利用直接反馈将速度/加速度反馈回速度环

如果使用**damping optimization**，可将**Kp**降低 5 倍，**Tn**增加**5**倍，进行测试。

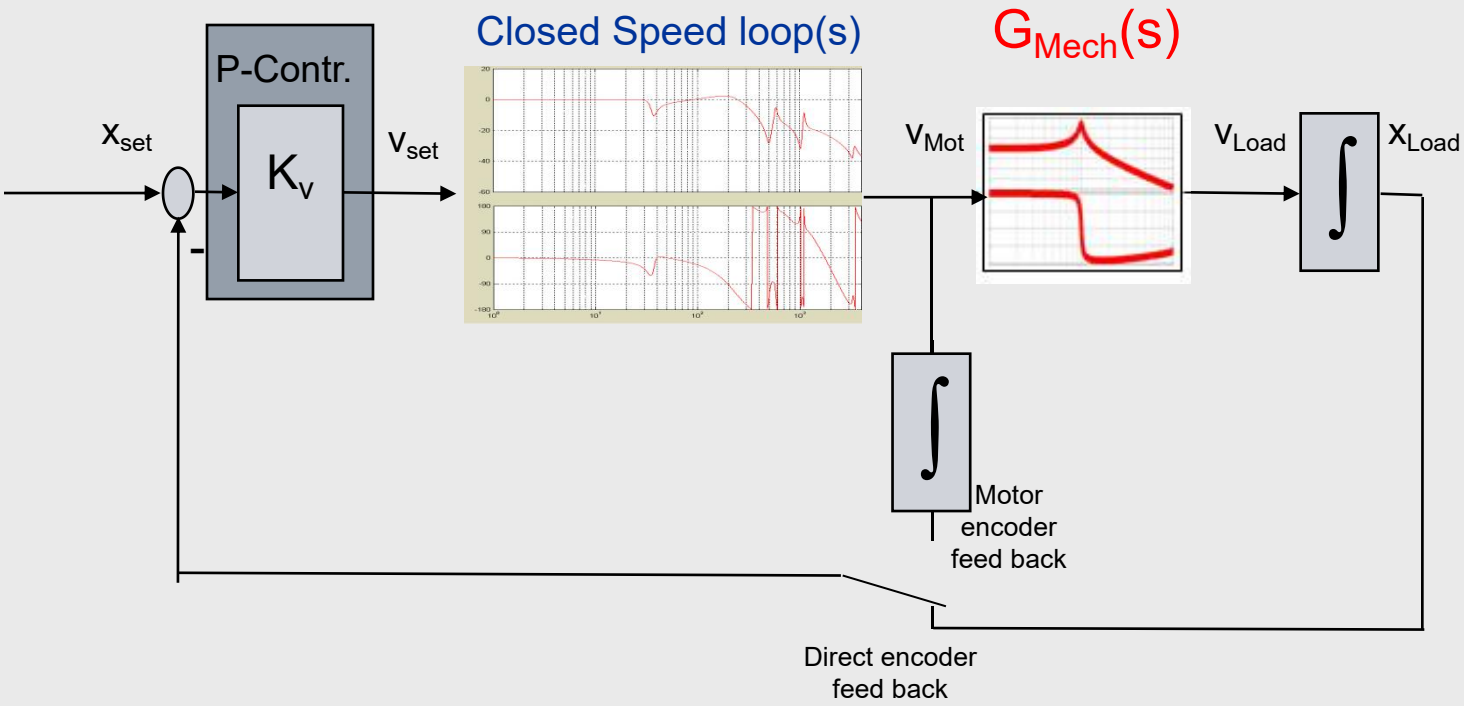
两种选择：**Disturbance optimization** 大**Kp**小**Kv** ; **Damping optimization** 小**Kp**大**Kv**

如果有干扰靠近电机侧**Damping optimization**可能不合适；另外也要看其它轴是否能匹配。

Speed and Position Controller

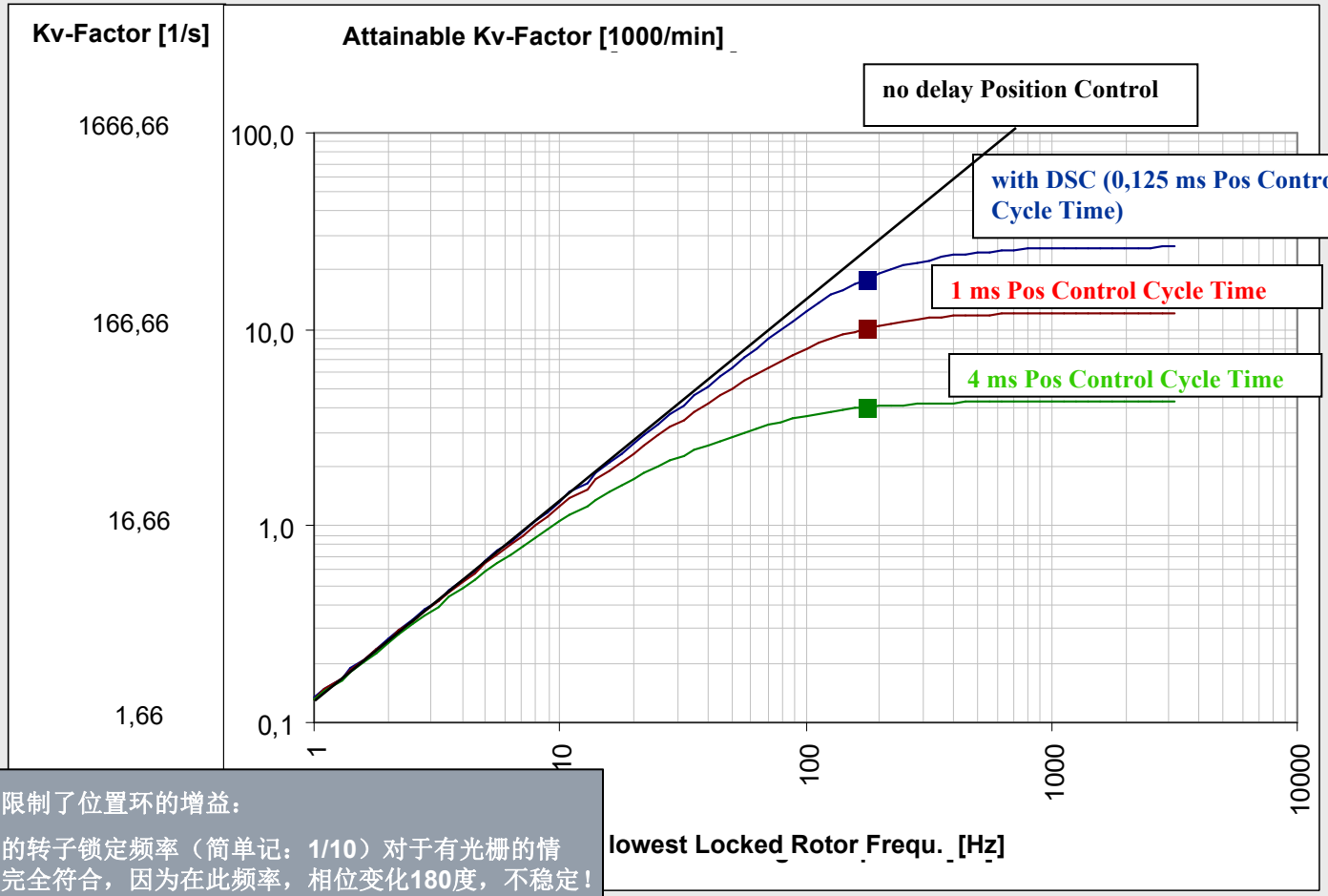


Speed and Position Controller



Relationship Between Kv-Factor and Lowest Locked Rotor Freq.
Kv系数和最低Locked Rotor Frequency的关系

SIEMENS



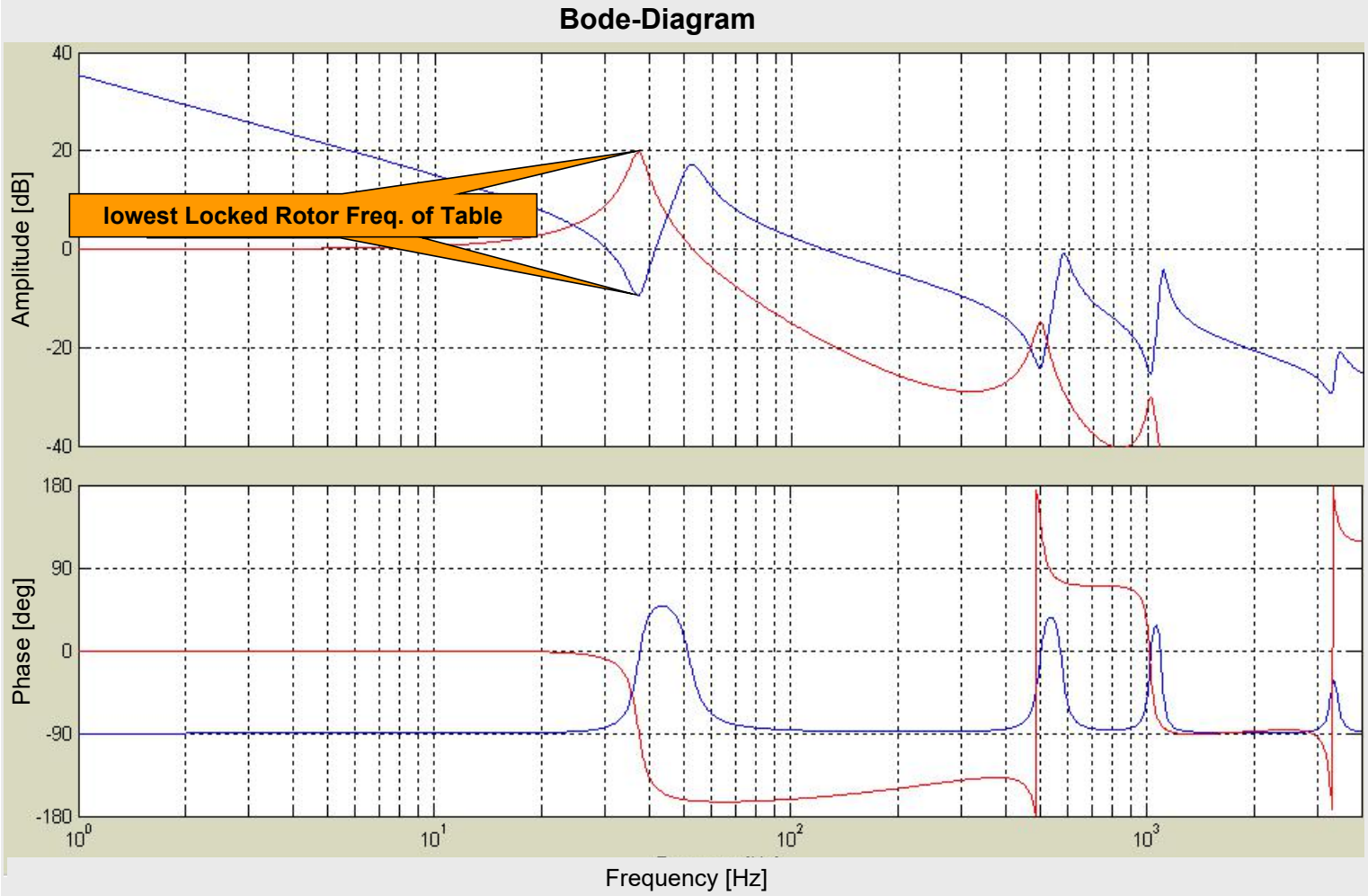
两点限制了位置环的增益：

最低的转子锁定频率（简单记：1/10）对于有光栅的情况，完全符合，因为在此频率，相位变化180度，不稳定！

位置环控制周期，由控制周期导致的相位变化。

Freq. Resp. of the Speed Controller Plant and of the Mechanics: Multiple Body System (Multi Mass Oscillator)
Speed Controller Plant的和Mechanics的频率响应（多质量振荡器）

SIEMENS



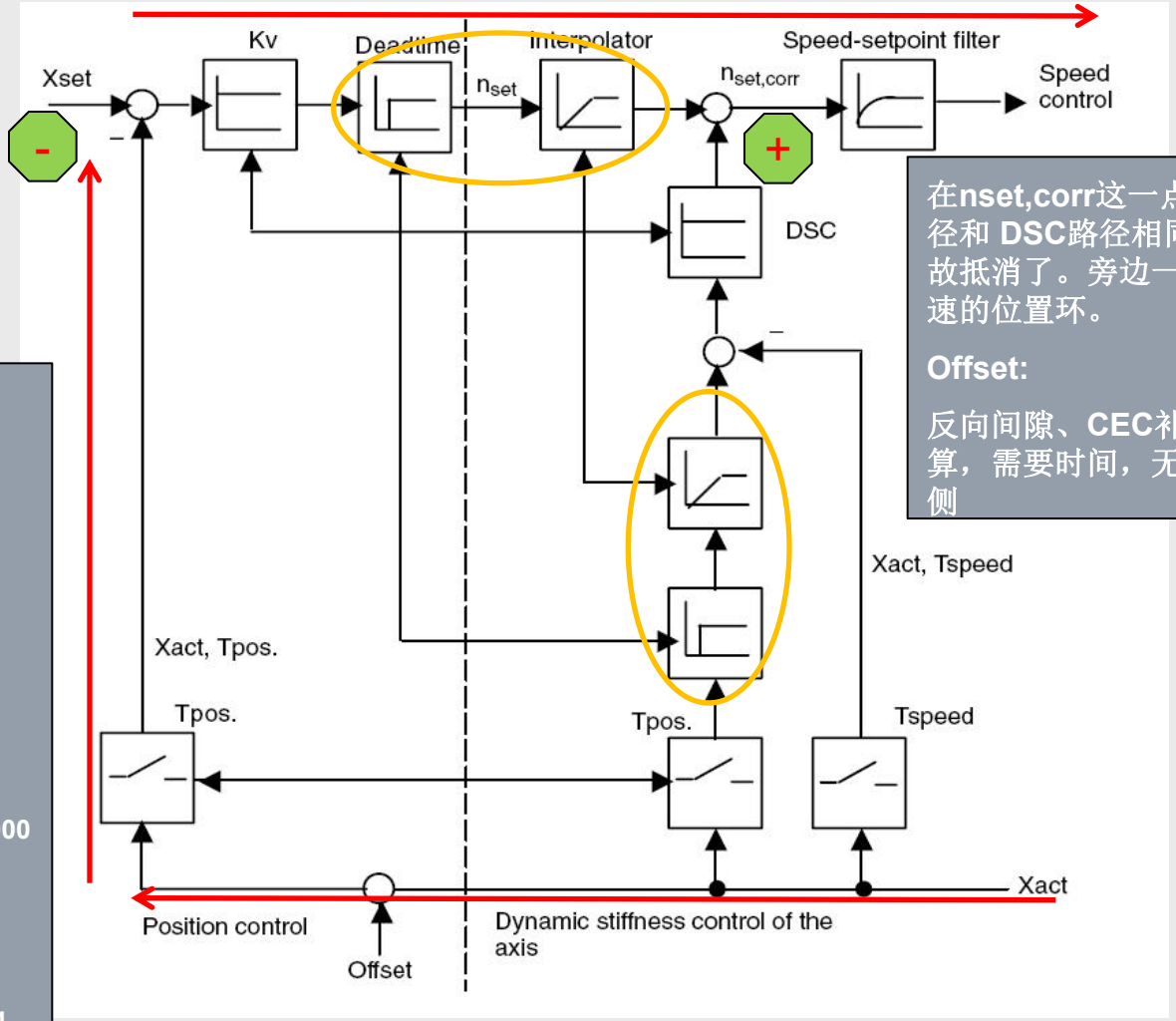
DSC (Dynamic Stiffness Control)
A Quasi Position Controller Implemented in the 611D
DSC（动态刚性控制）在611D上实现类似的位置控制器

SIEMENS

Introduction to mechanical System Dynamics

Speed and Position Controller

速度和位置控制器



在nset,corr这一点，正常路径和 DSC路径相同，值相反，故抵消了。旁边一路可保证快速的位置环。

Offset:

反向间隙、CEC补偿、需要计算，需要时间，无法放到驱动侧

对于840Dpl官方只能用于电机编码器。

驱动使用电机编码器，位置使用光栅。

但可以：

系统负责最后的精度，驱动负责动态性能。

这样在840Dsl上也这么用。

官方：可选择

转换系数：

电机编码器：2048 p/rev

传动比：MD31050=951869 MD31060=100000

丝杠螺距：1mm

光栅尺栅距： 0.04mm

则：电机一圈：2048pulse

对应光栅尺的脉冲数：951869/100000*1/0.04

系数=2048/（9.51869/0.04）

Dynamic Stiffness Control is activated by MD 32640 : STIFFNESS_CONTROL_ENABLE

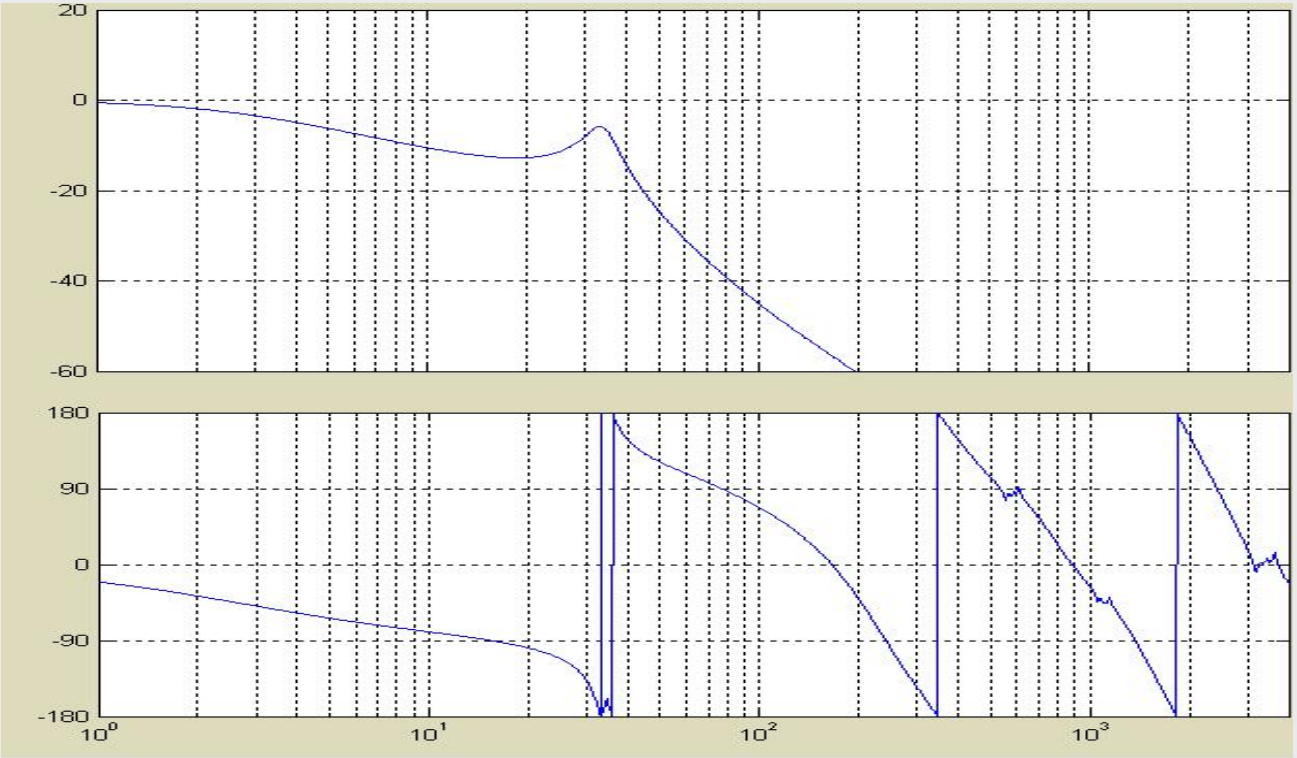
DSC 840Dsl

注意转换系数

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters: Without Reference Model
带电流设定点滤波器的位置闭环控制的频率响应：不带参考模型

SIEMENS

Bode-Diagram



Kv = 1 m/min/mm (Position Controller Cycle Time 1ms)

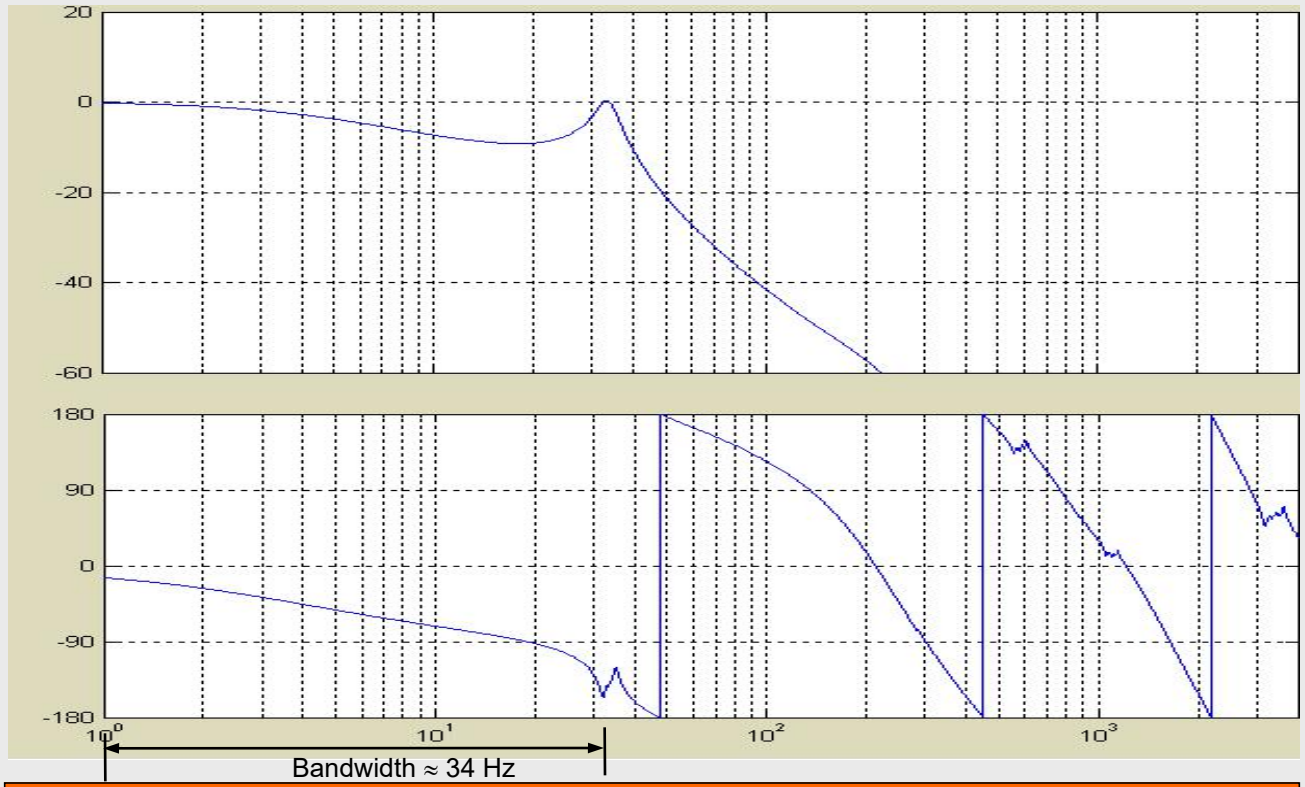
Kp = 1,4 Nms/rad
Tn = 8 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters: Kv Increased

带电流设定点滤波器的位置闭环控制的频率响应：提高Kv

SIEMENS



Kv = 1,5 m/min/mm (Position Controller Cycle Time 1ms)

Kp = 1,4 Nms/rad
Tn = 8 ms

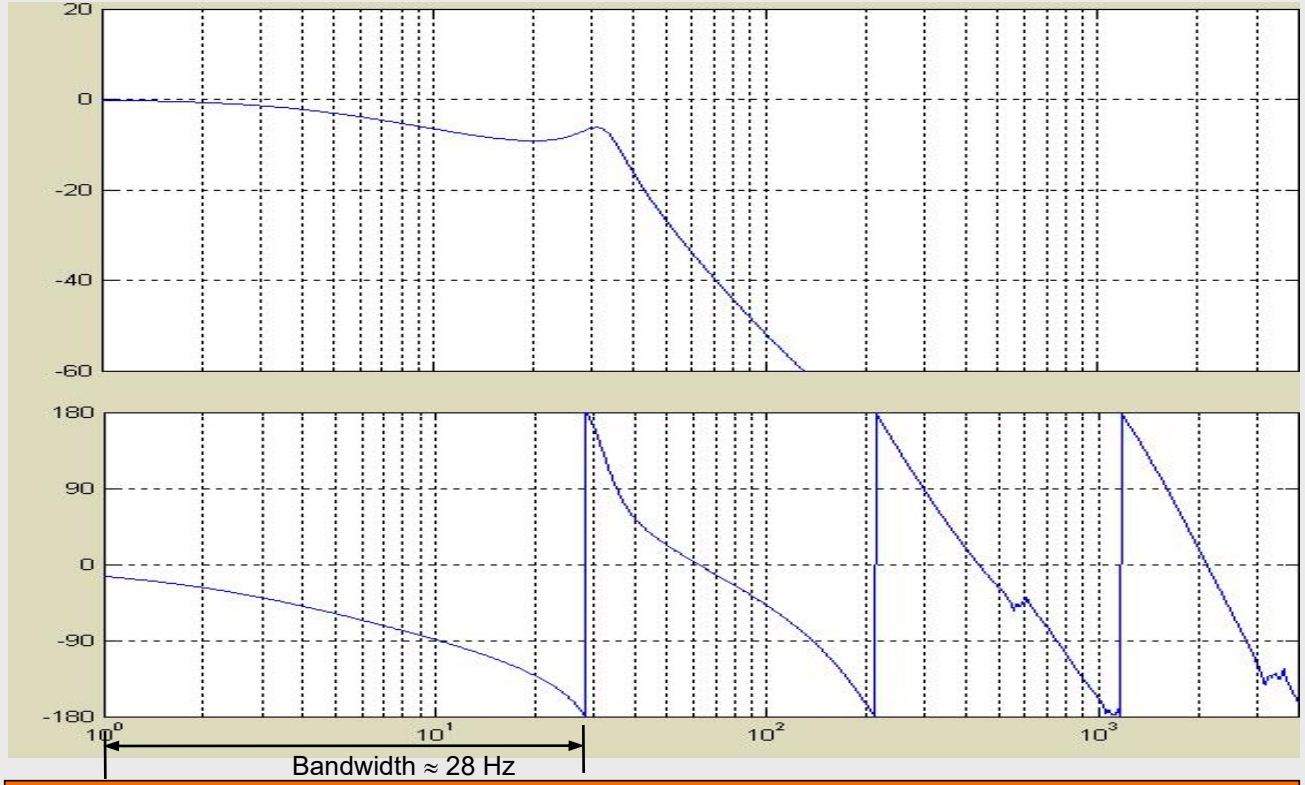
Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters: With Speed Filter

带电流设定点滤波器的位置闭环控制的频率响应：带速度滤波器

SIEMENS

Bode-Diagram



Kv = 1,5 m/min/mm **with Speed filter 5ms** (Position Controller Cycle Time 1ms)

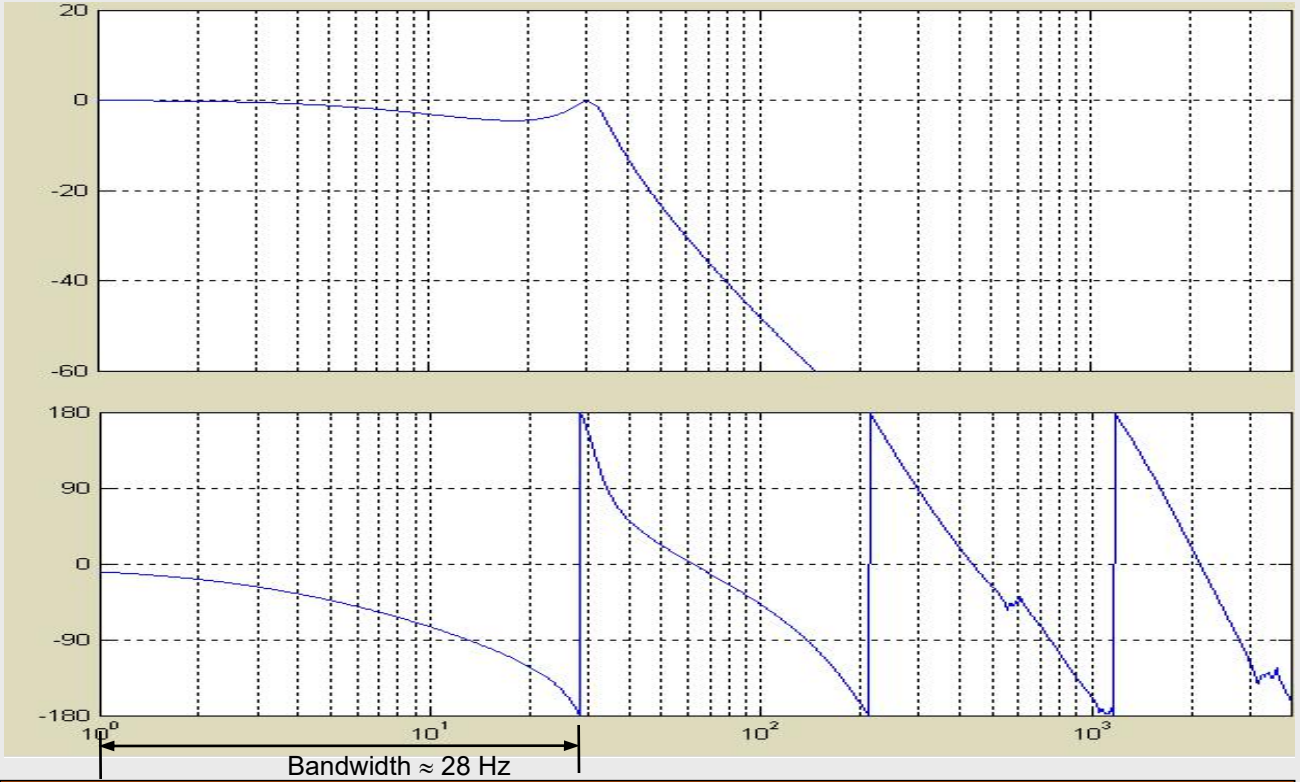
Kp = 1,4 Nms/rad
Tn = 8 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters and Speed filters: Kv Increased
带电流设定点滤波器的位置闭环控制的频率响应：提高Kv

SIEMENS

Bode-Diagram



Kv = 2,3 m/min/mm **with Speed filter 5ms** (Position Controller Cycle Time 1ms)

Kp = 1,4 Nms/rad
Tn = 8 ms

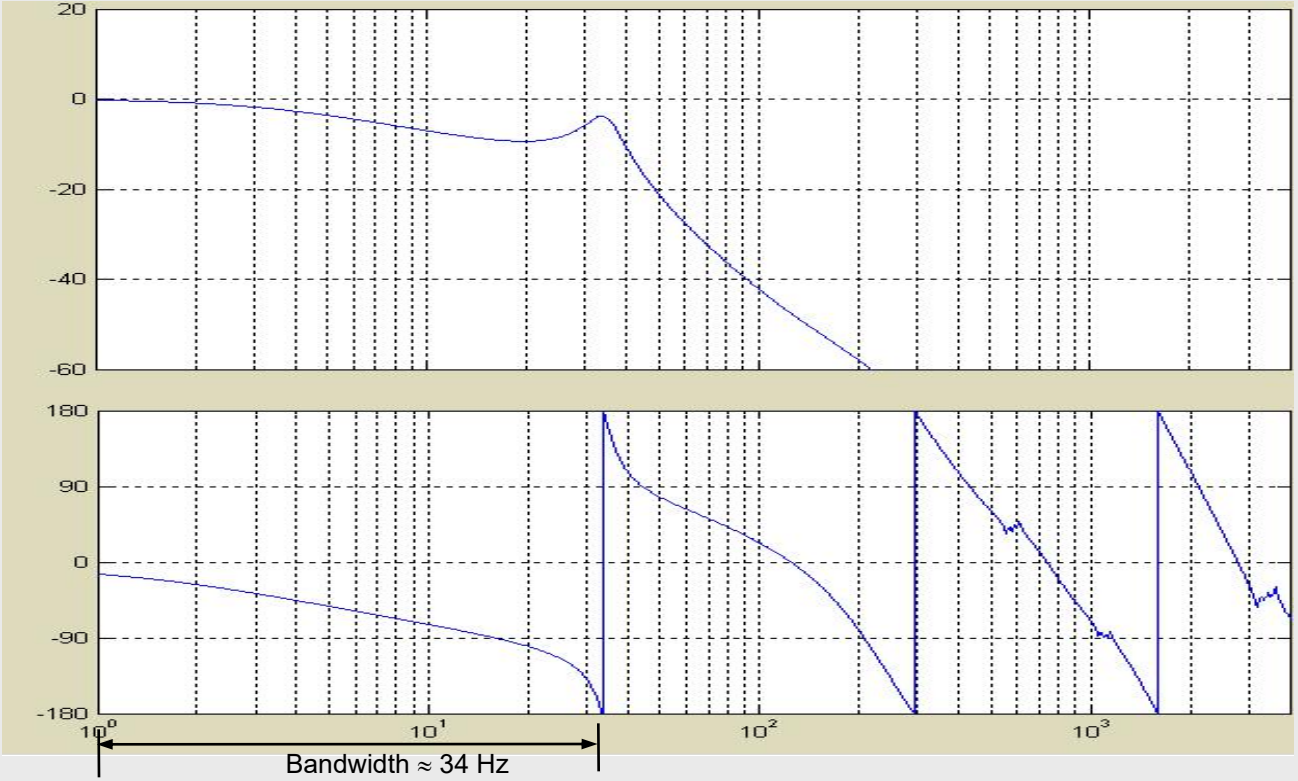
Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters: Tn Increased

带电流设定点滤波器的位置闭环控制的频率响应：延长Tn

SIEMENS

Bode-Diagram



Kv = 1,5 m/min/mm	(Position Controller Cycle Time 1ms)
Kp = 1,4 Nms/rad **Tn = 20 ms**	Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters : Tn Increased and Kp Reduced

带电流设定点滤波器的位置闭环控制的频率响应：延长Tn，降低Kp

SIEMENS

Bode-Diagram

Kv = 1,5 m/min/mm (Position Controller Cycle Time 1ms)

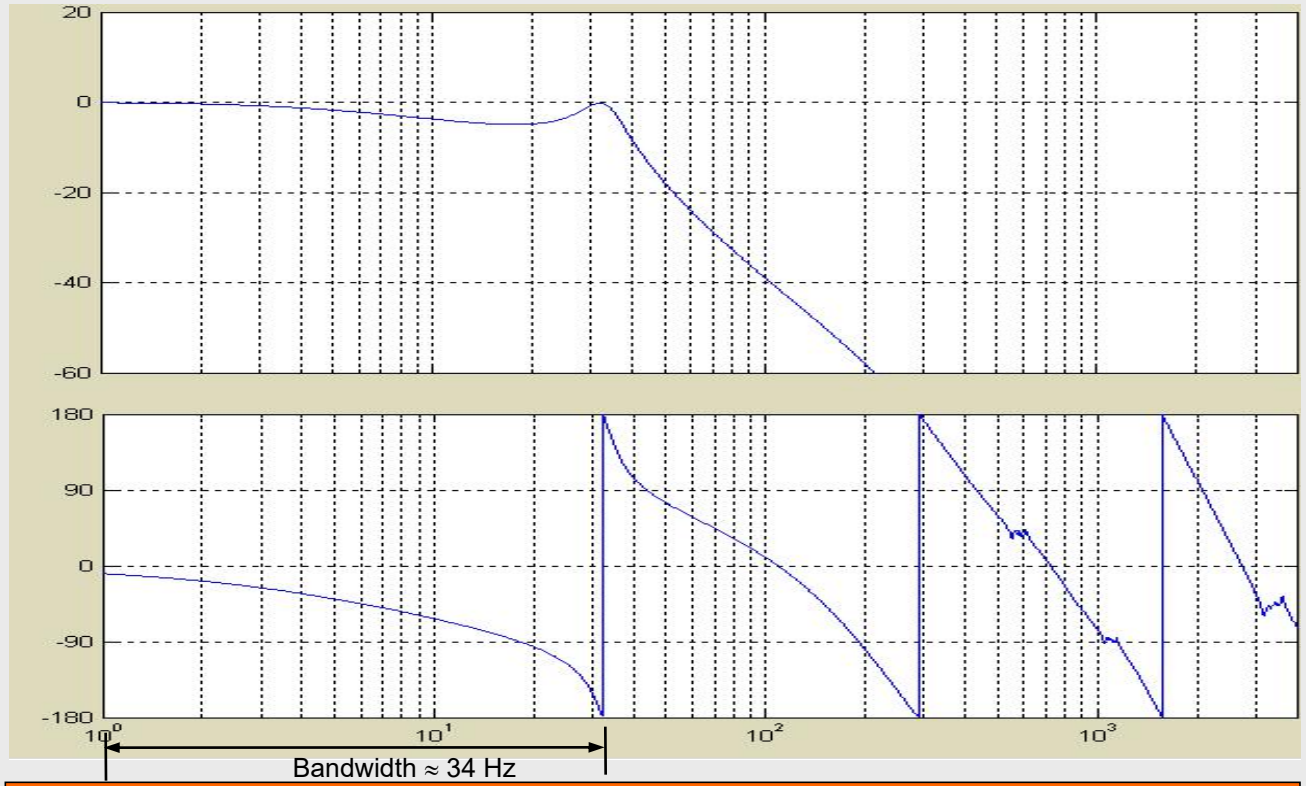
Kp = 1 Nms/rad
Tn = 20 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference modell

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters : Kv Increased
带电流设定点滤波器的位置闭环控制的频率响应：提高Kv

SIEMENS

Bode-Diagram



Kv = 2,3 m/min/mm (Position Controller Cycle Time 1ms)

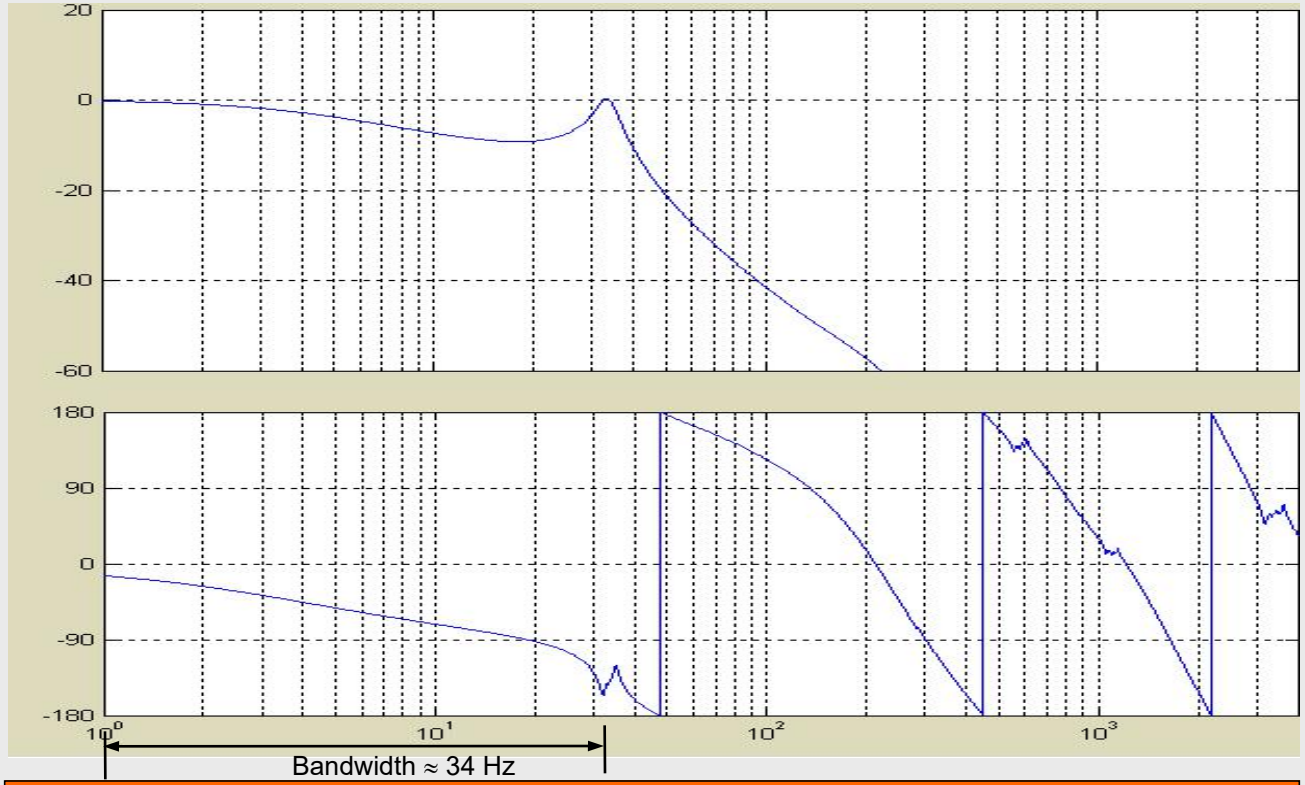
Kp = 1 Nms/rad
Tn = 20 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller
→ Start of a New Optimization Strategy (ref model)
带电流设定点滤波器的位置闭环控制的频率响应：启用新的优化策略（参考模型）

SIEMENS

Bode-Diagram



Kv = 1,5 m/min/mm (Position Controller Cycle Time 1ms)

Kp = 1,4 Nms/rad
Tn = 8 ms

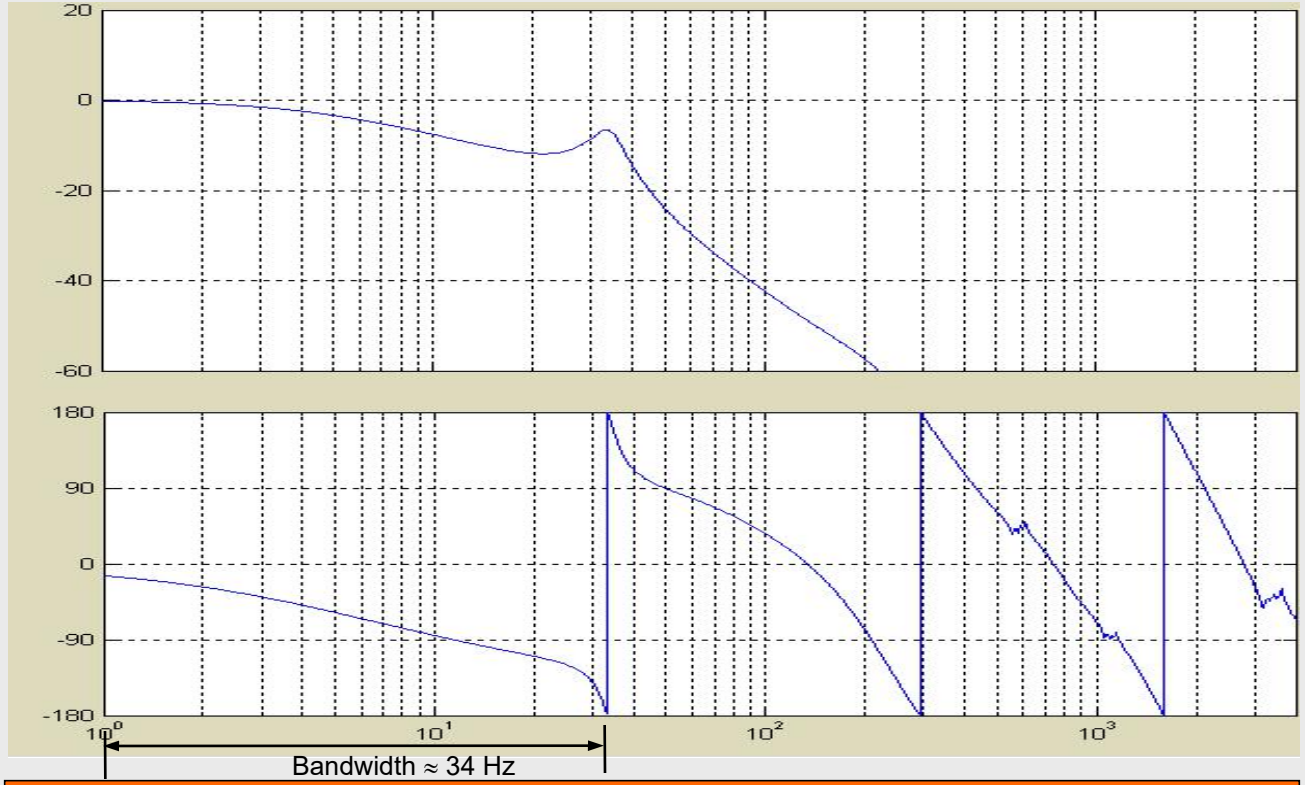
Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
without Reference model

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters : With Reference Model

带电流设定点滤波器的位置闭环控制的频率响应：带参考模型

SIEMENS

Bode-Diagram



Kv = 1,5 m/min/mm (Position Controller Cycle Time 1ms)

Kp = 1,4 Nms/rad
Tn = 8 ms

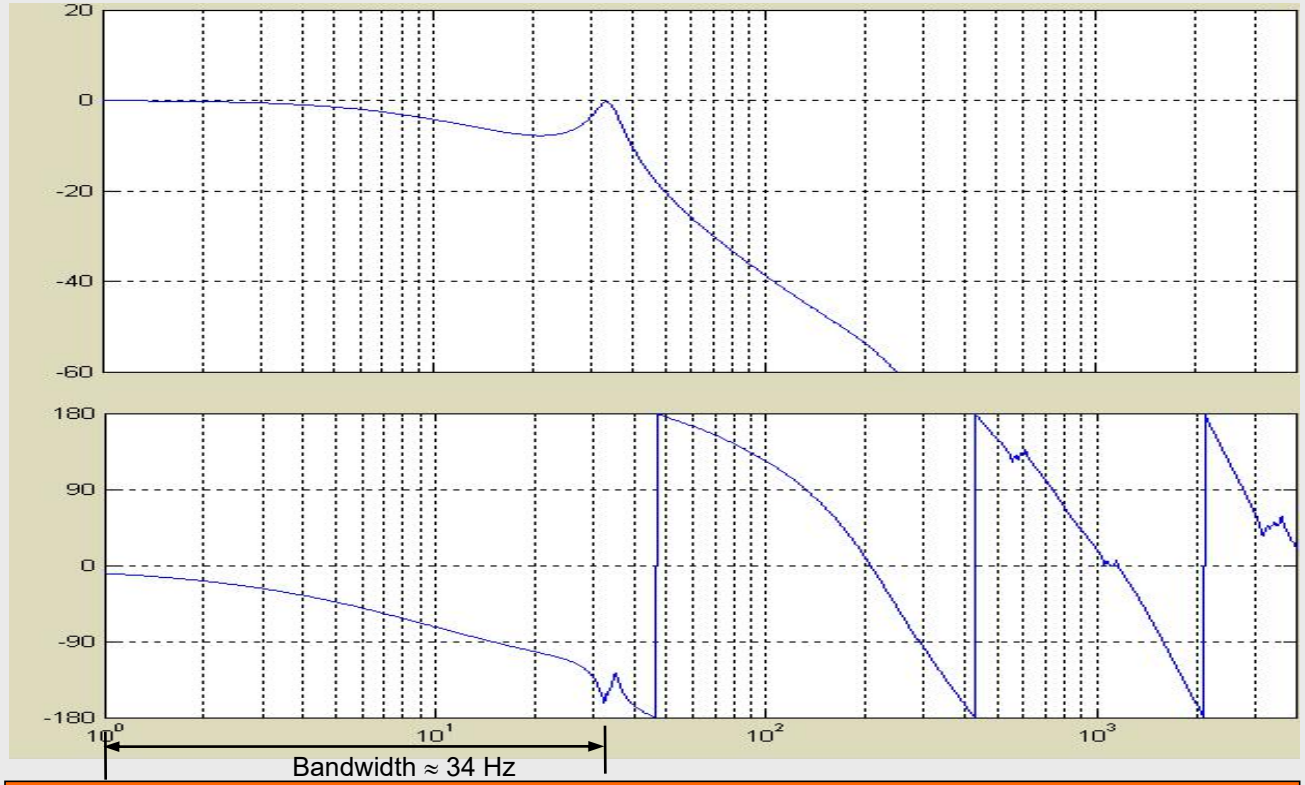
Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
Reference model = 80 Hz

Freq. Resp. of the Closed Position Controller With Current Setpoint Filters: With Reference Model Kv Increased

带电流设定点滤波器的位置闭环控制的频率响应：带参考模型，提高Kv

SIEMENS

Bode-Diagram



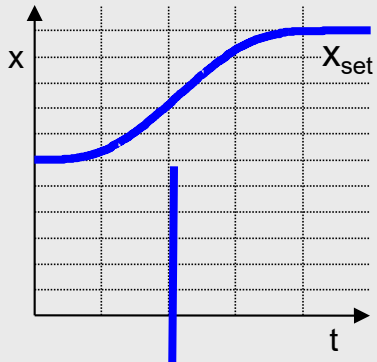
Kv = 2,3 m/min/mm (Position Controller Cycle Time 1ms)

Kp = 1,4 Nms/rad
Tn = 8 ms

Band stop 1: f = 590 Hz, BW = 590 Hz, BW_num = 200 Hz
Band stop 2: f = 1100 Hz, BW = 1100 Hz, BW_num = 400 Hz
Reference model = 80 Hz

Position Controller without Speed Feed Forward
不带速度前馈的位置控制器

SIEMENS

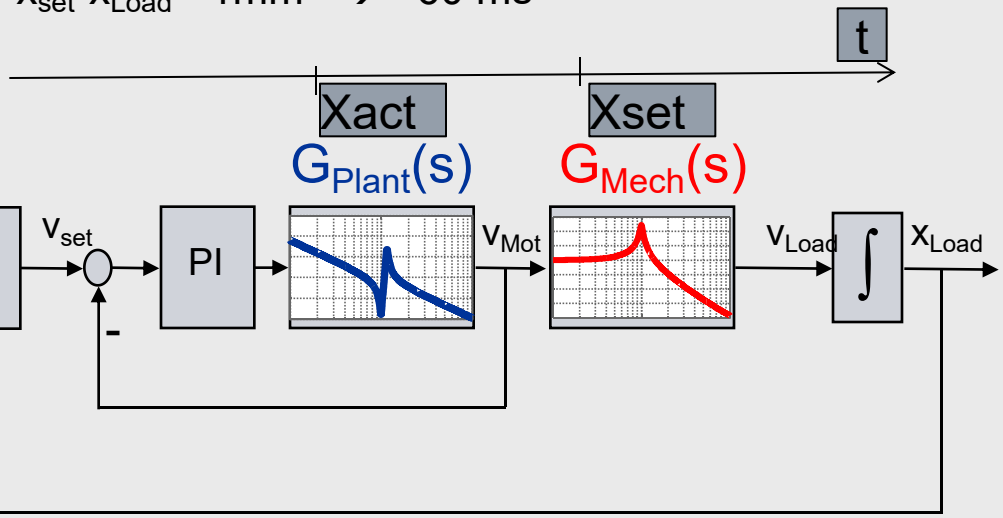


At constant Velocity v:

Following error $\Delta x = x_{set} - x_{Load} = v/Kv$

e.g. Kv=1(m/min)/mm, v=1m/min =>

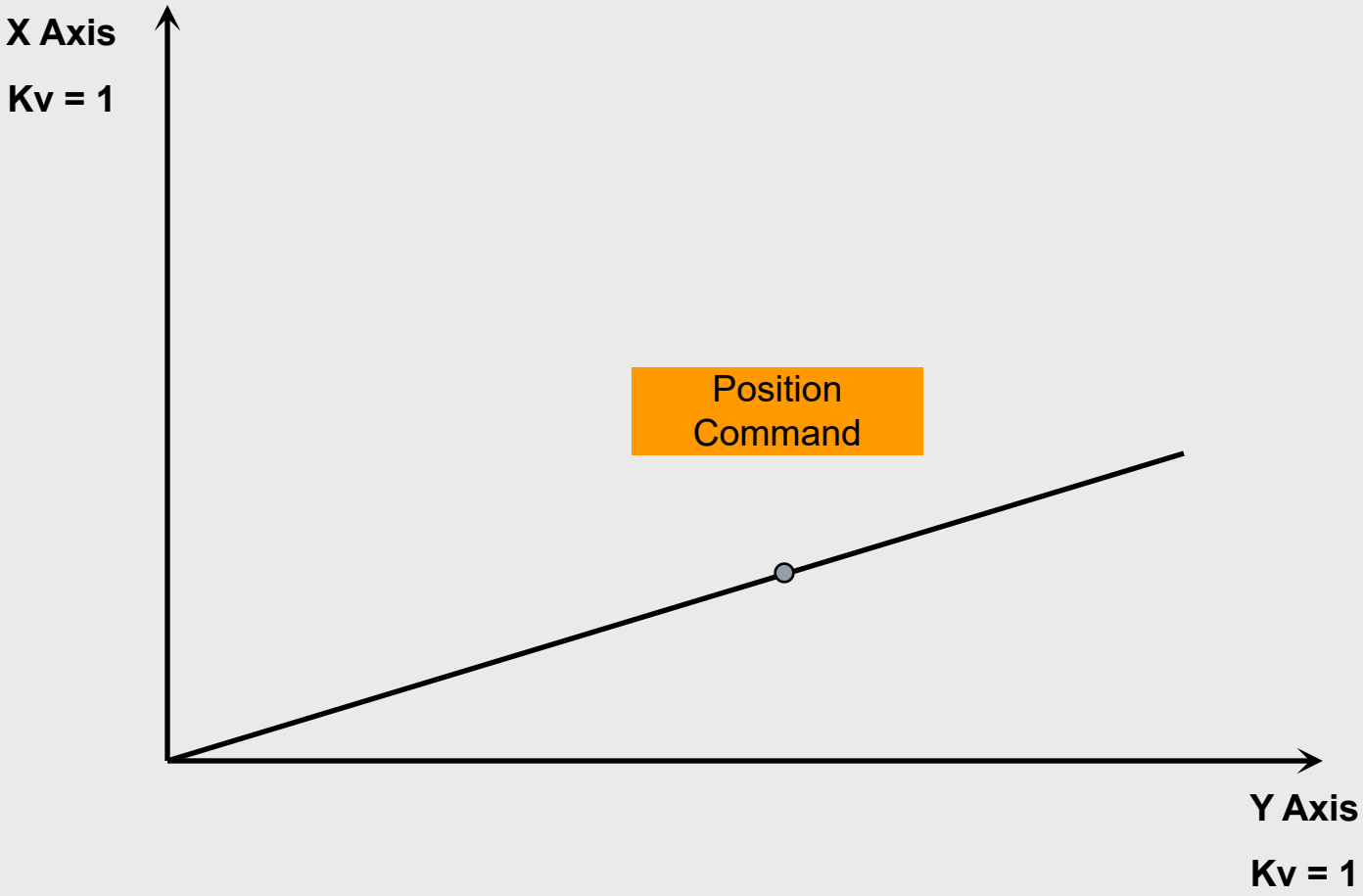
$x_{set} - x_{Load}$= 1mm → 60 ms



For Interpolation K_v of all axes has to be at same value!

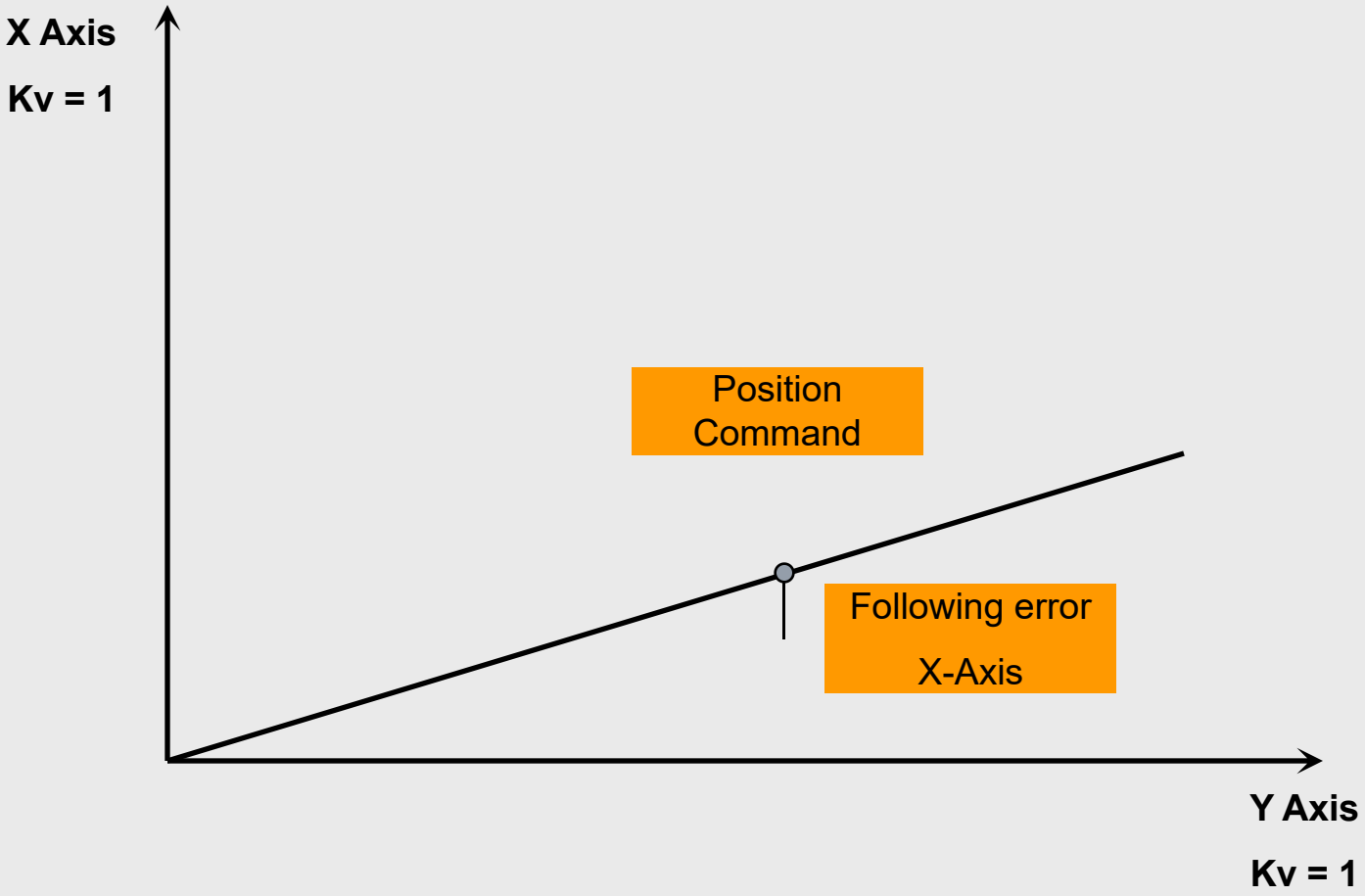
Position Controller without Speed Feed Forward
不带速度前馈的位置控制器

SIEMENS



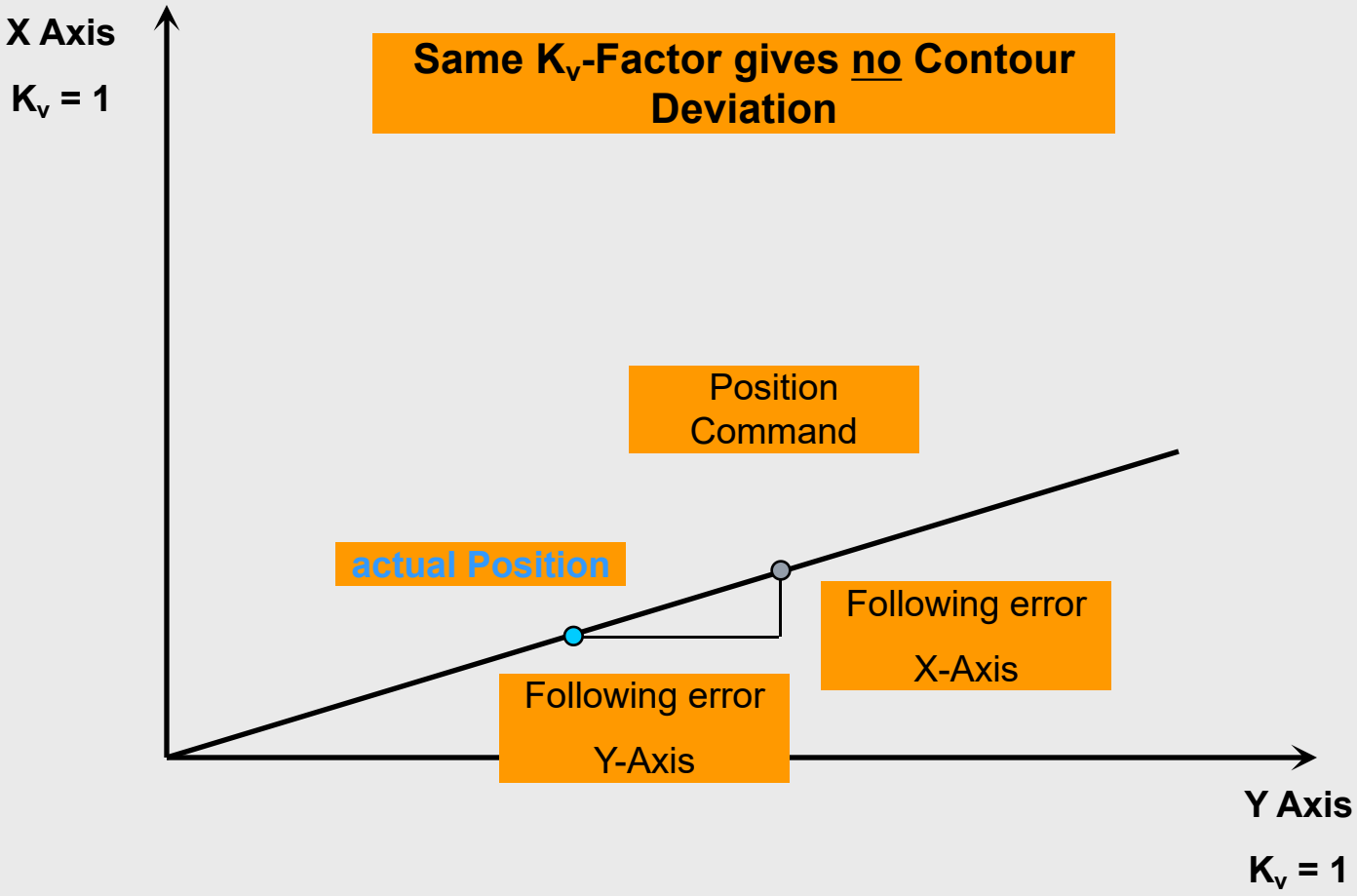
Position Controller without Speed Feed Forward
不带速度前馈的位置控制器

SIEMENS



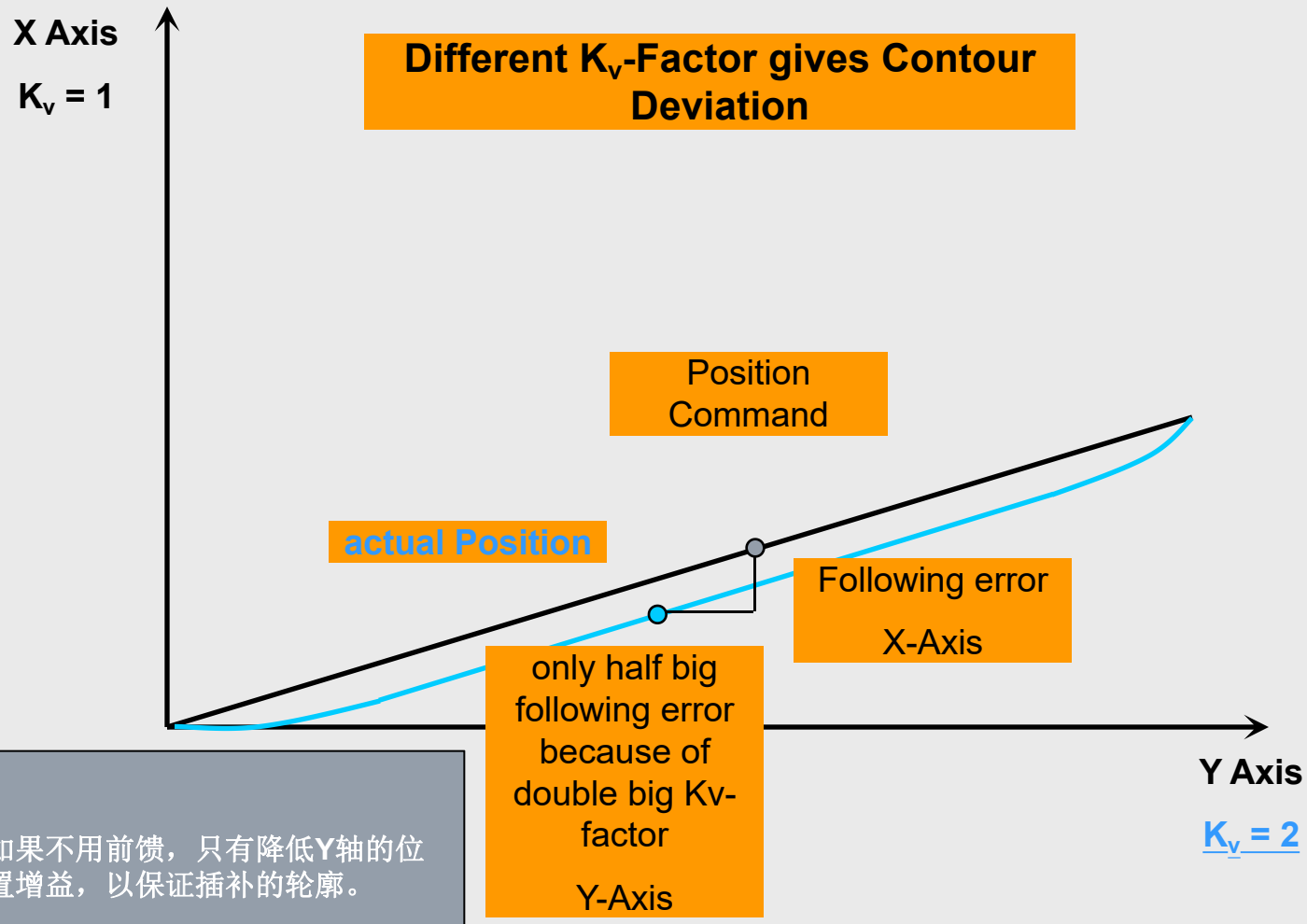
Position Controller without Speed Feed Forward
不带速度前馈的位置控制器

SIEMENS



Position Controller without Speed Feed Forward
不带速度前馈的位置控制器

SIEMENS

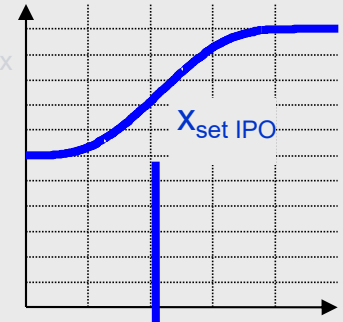


如果不用前馈，只有降低Y轴的位置增益，以保证插补的轮廓。

Position Controller without Feed Forward

Commanded-Kv [1000/min] =

$$\frac{0{,}06\ [s]}{(0{,}06/\text{disturbance-Kv}[1000/\text{min}])+\text{Jerk time}[s]+\text{dyn match time}[s]+\text{desval delay time}[s]}$$



Remark:

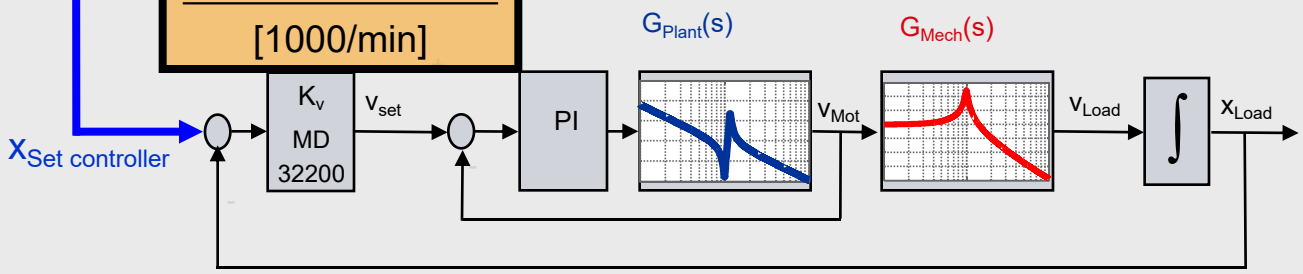
If Jerk Mode MD32402=2 (moving averaging)
Jerk time / 2 (only half time constant)

Jerk time [s] MD32400 MD32402 MD32410

Dynamic match time [s] MD32900 MD32910

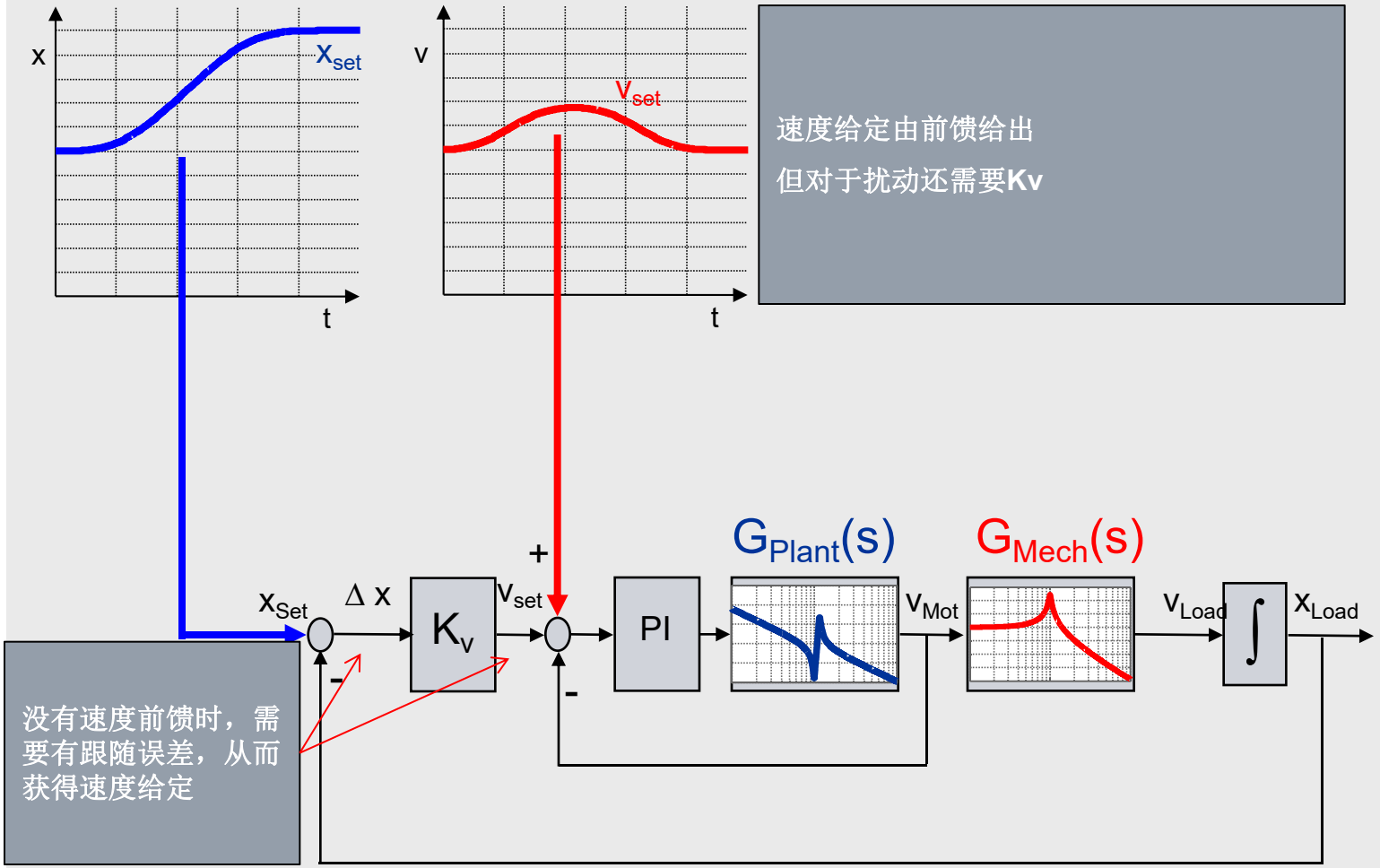
Desval delay time[s] MD32890 MD32895

Disturbance-Kv
[1000/min]



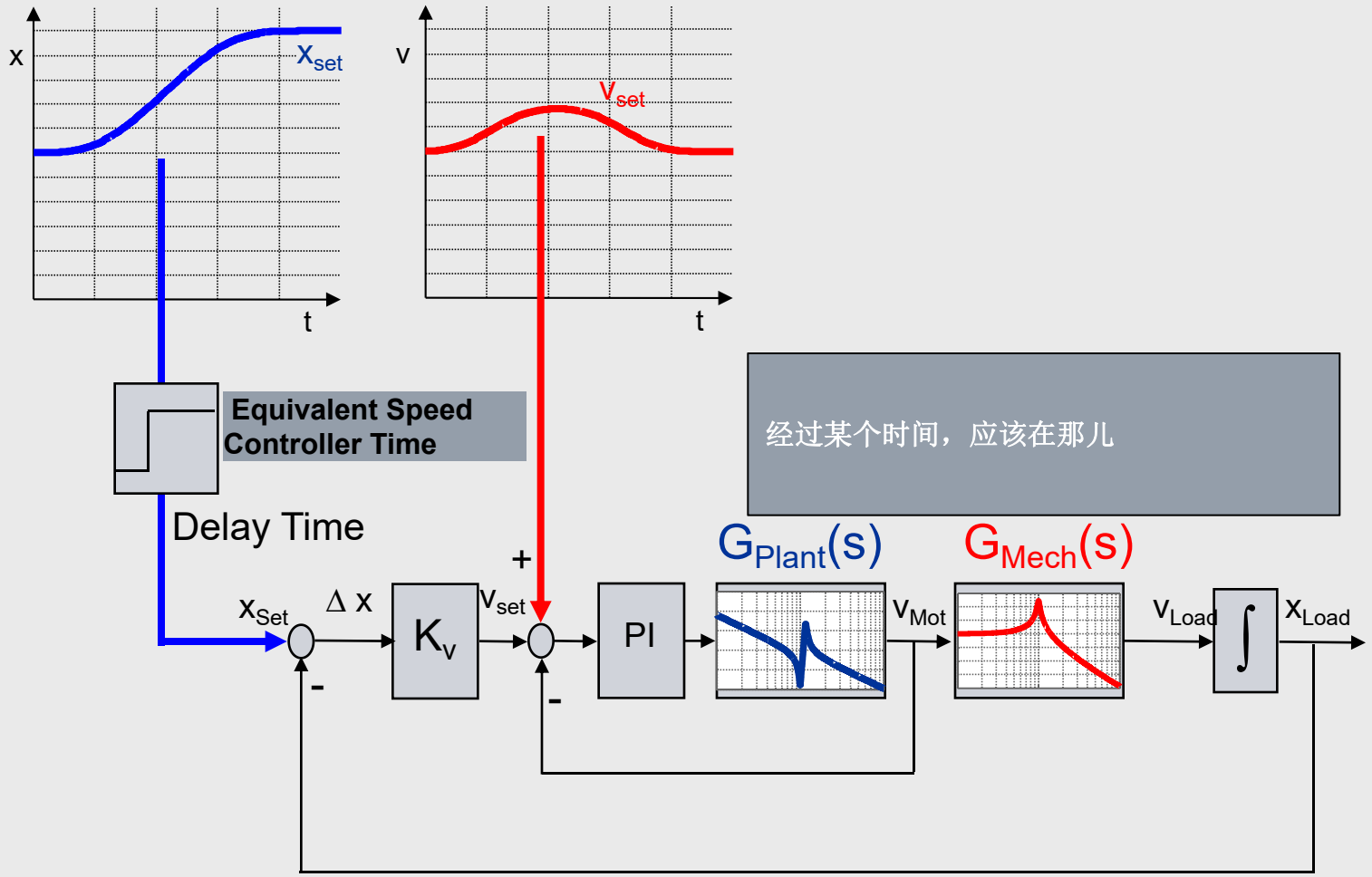
Position Controller with Speed Feed Forward
带速度前馈的位置控制器

SIEMENS



Position Controller with Speed Feed Forward
带速度前馈的位置控制器

SIEMENS

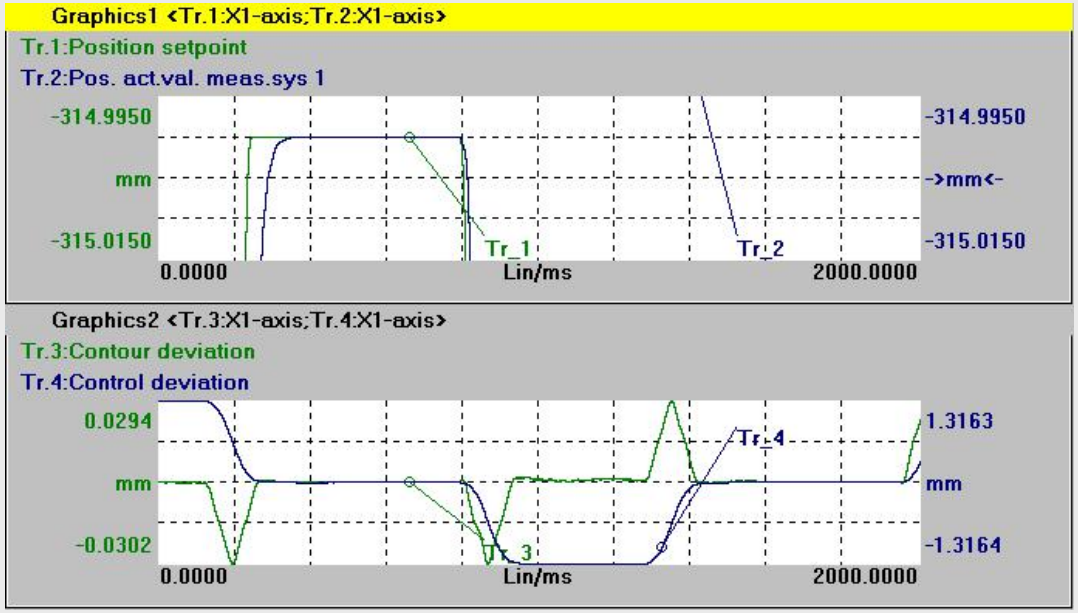


使用前馈就要使用Jerk限制

Speed Feed Forward FFW Mode 0 OFF: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式0 OFF: 定位响应（跟踪功能）

SIEMENS

Positioning behavior without FFW



Adjusted Parameters:

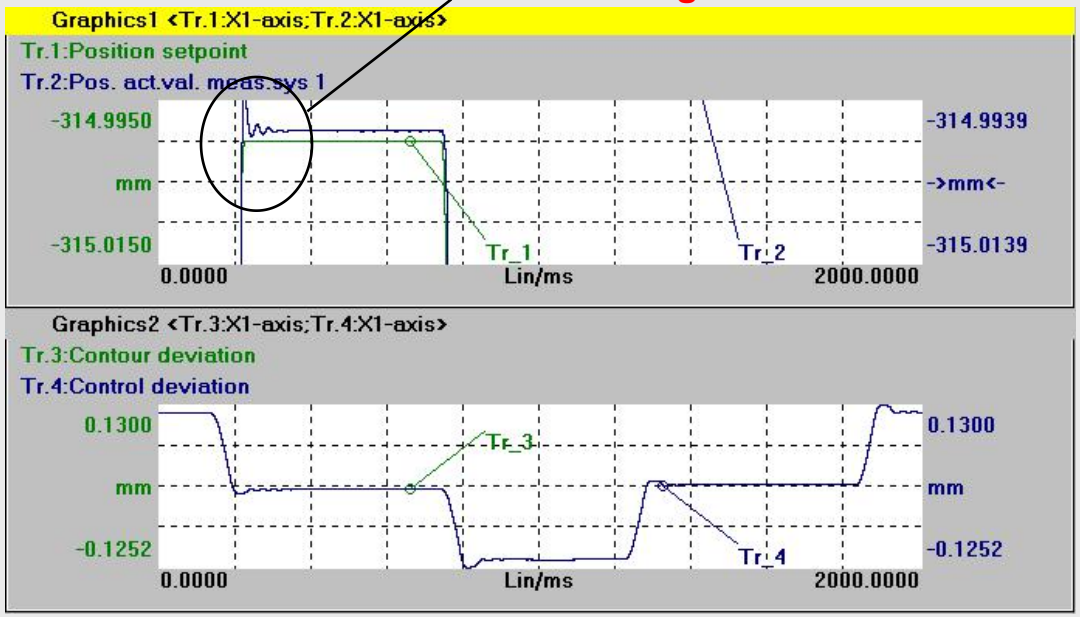
32200	POSCTRL_GAIN	3.80
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	**FFW_MODE**	**0**
32810	EQUIV_SPEEDCTRL_TIME	0.0
32431	MAX_AX_JERK	80

Speed Feed Forward FFW Mode 3: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式3 OFF: 定位响应（跟踪功能）

SIEMENS

Positioning behavior with FFW : Without Position Controller

Jerk too high!!



Adjusted Parameters:

32200	**POSCTRL_GAIN**	**0**
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	FFW_MODE	3
32810	EQUIV_SPEEDCTRL_TIME	0.002
32431	**MAX_AX_JERK**	**150 m/s³**

Speed Feed Forward FFW Mode 3: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式3 OFF: 定位响应（跟踪功能）

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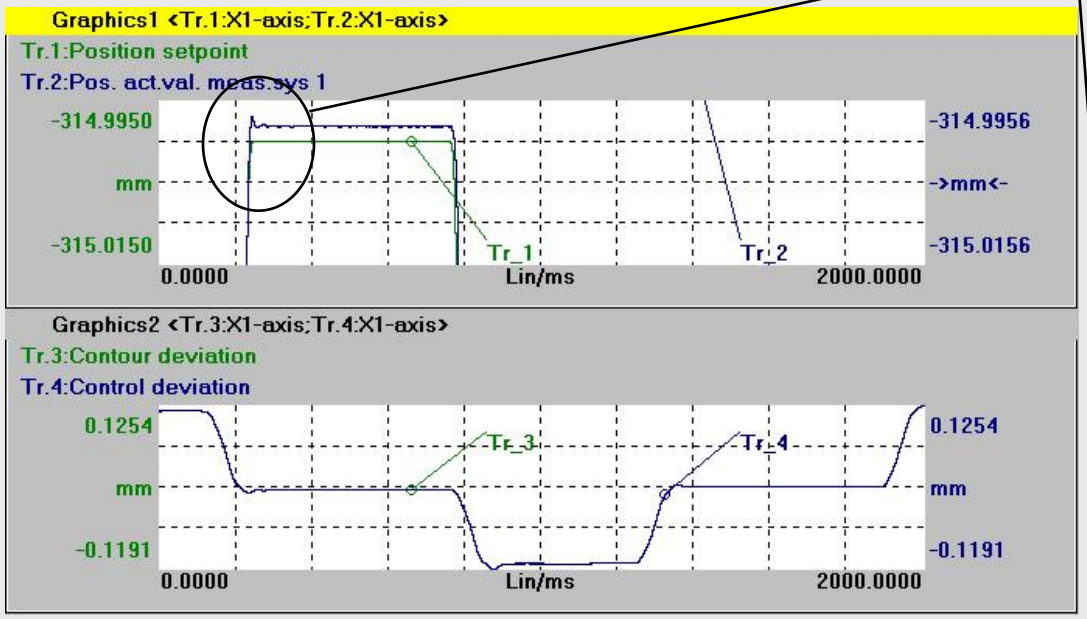
Positioning behavior with FFW : Without Position Controller
Equivalent Speed Controller Time has no Influence!!



Adjusted Parameters:

32200	**POSCTRL_GAIN**	**0**
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	FFW_MODE	3
32810	EQUIV_SPEEDCTRL_TIME	0.002
32431	**MAX_AX_JERK**	**80 m/s³**

Speed Feed Forward FFW Mode 3: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式3 OFF: 定位响应（跟踪功能）

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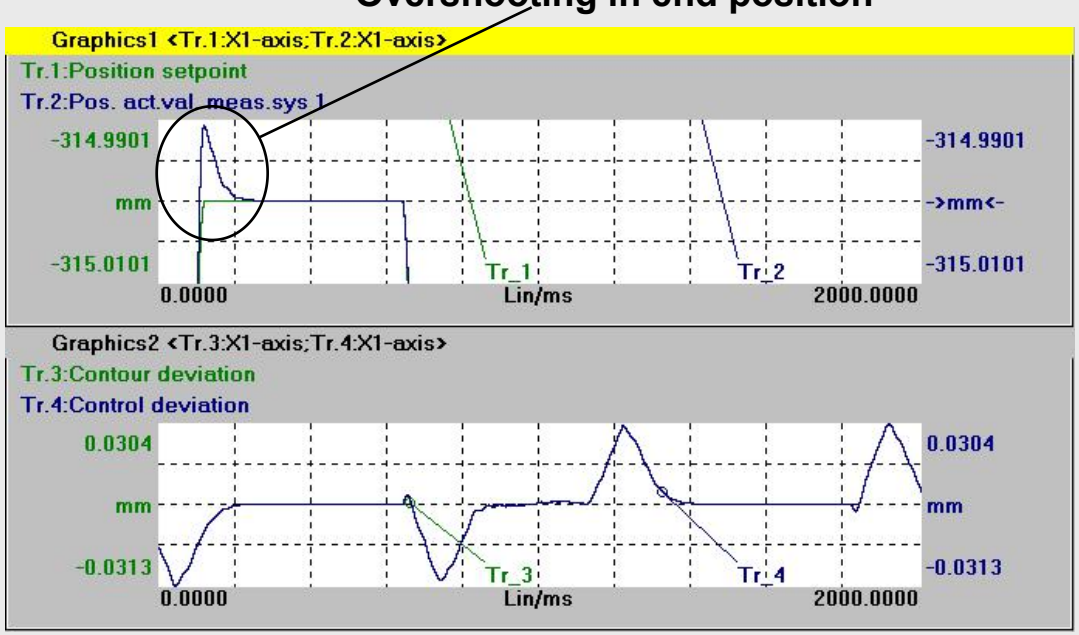
Positioning behavior with FFW : Equivalent Speed Controller (MD32810) too short!!
Overshooting in end position



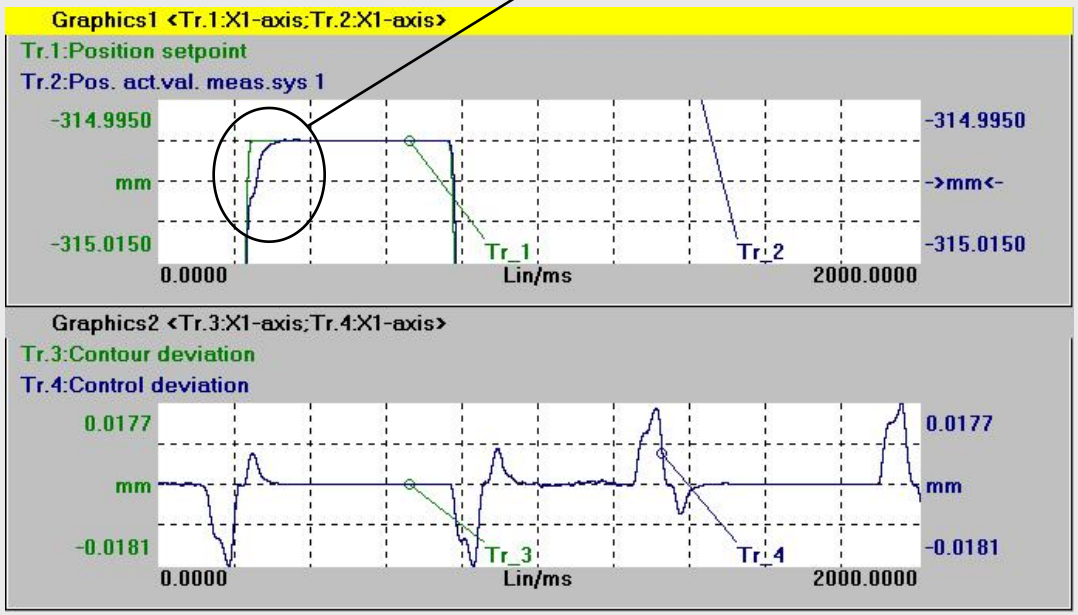
Adjusted Parameters:

32200	POSCTRL_GAIN	3.80
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	**FFW_MODE**	**3**
32810	**EQUIV_SPEEDCTRL_TIME**	**0.002**
32431	MAX_AX_JERK	80

Speed Feed Forward FFW Mode 3: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式3 OFF: 定位响应（跟踪功能）

SIEMENS

Positioning behavior with FFW : Equivalent Speed Controller (MD32810) too long!!
Creeping in end position



Adjusted Parameters:

32200	POSCTRL_GAIN	3.80
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	**FFW_MODE**	**3**
32810	**EQUIV_SPEEDCTRL_TIME**	**0.003**
32431	MAX_AX_JERK	80

Speed Feed Forward FFW Mode 3: Evaluation With Positioning Behavior (Trace-Function)
速度前馈 FFW模式3 OFF: 定位响应（跟踪功能）

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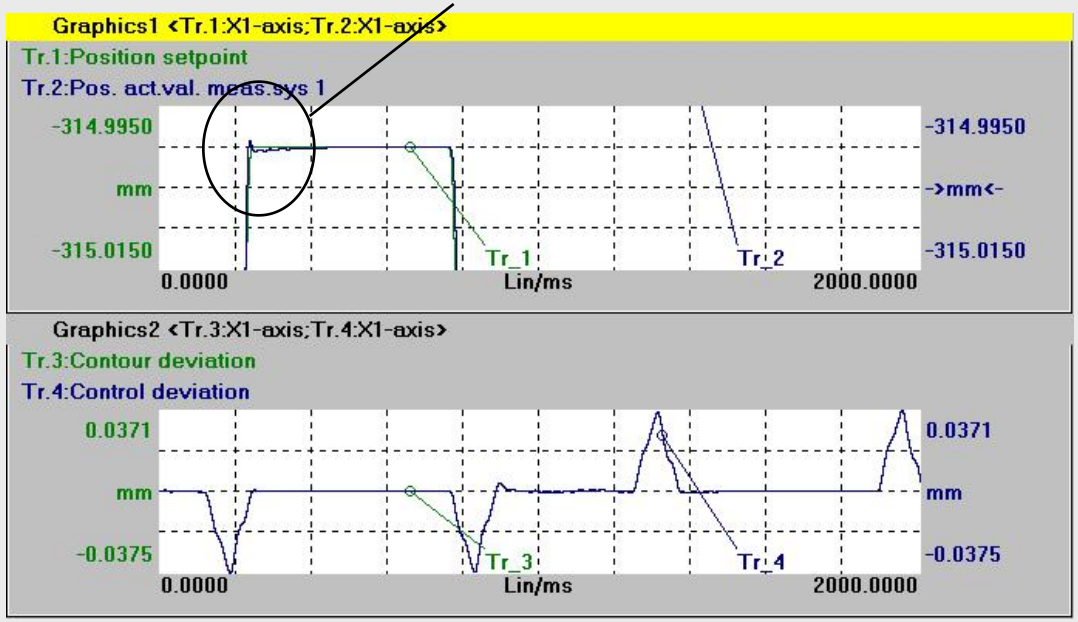
Positioning behavior with FFW : With Position Controller Jerk optimal and Equivalent Speed Controller Time optimal



Adjusted Parameters:

32200	POSCTRL_GAIN	3.80
1407	SPEEDCTRL_GAIN_1	5.50
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	0.0
1500	NUM_SPEED_FILTERS	0
32610	VELO_FFW_WEIGHT	1.0
32620	FFW_MODE	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025
32431	MAX_AX_JERK	80

Position Controller with Speed Feed Forward
带速度前馈的位置控制器

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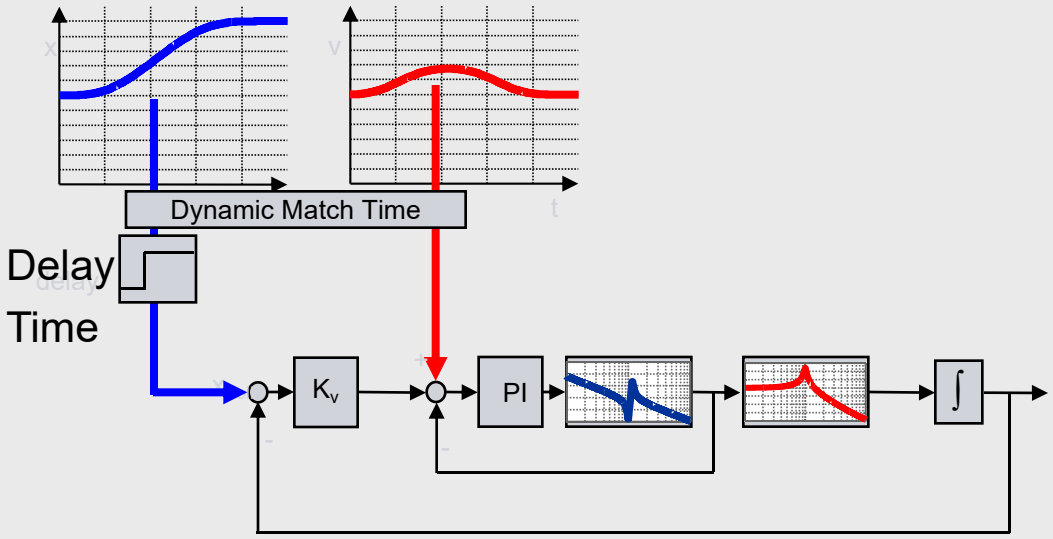
Axis with constant velocity v:

$\Delta x = x_{set} - x_{Load} = v * \text{Delay Time}$

Leading K_v = 1/Delay Time

Example:
Delay Time = 4ms, v = 1m/min => $\Delta x = x_{set} - x_{Load}$ = 66,7µm
Leading K_v=1/4ms=1/0.004s * 60s/min*m/1000mm=15 [1000/min]

For interpolation the axes can have different Disturbance-K_v.
But all the axes must have same Leading-K_v (delay time)!

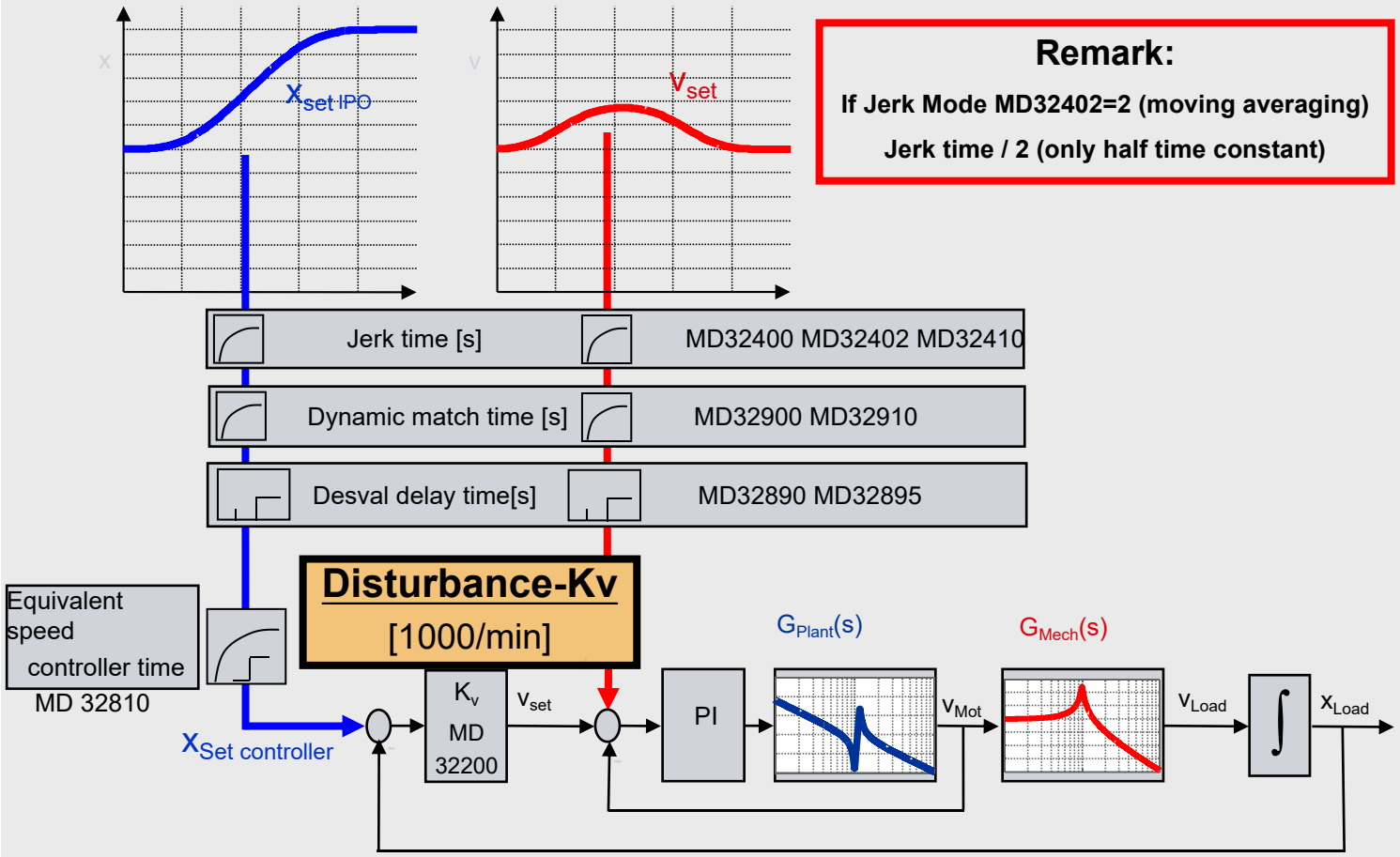


Position Controller with Speed Feed Forward

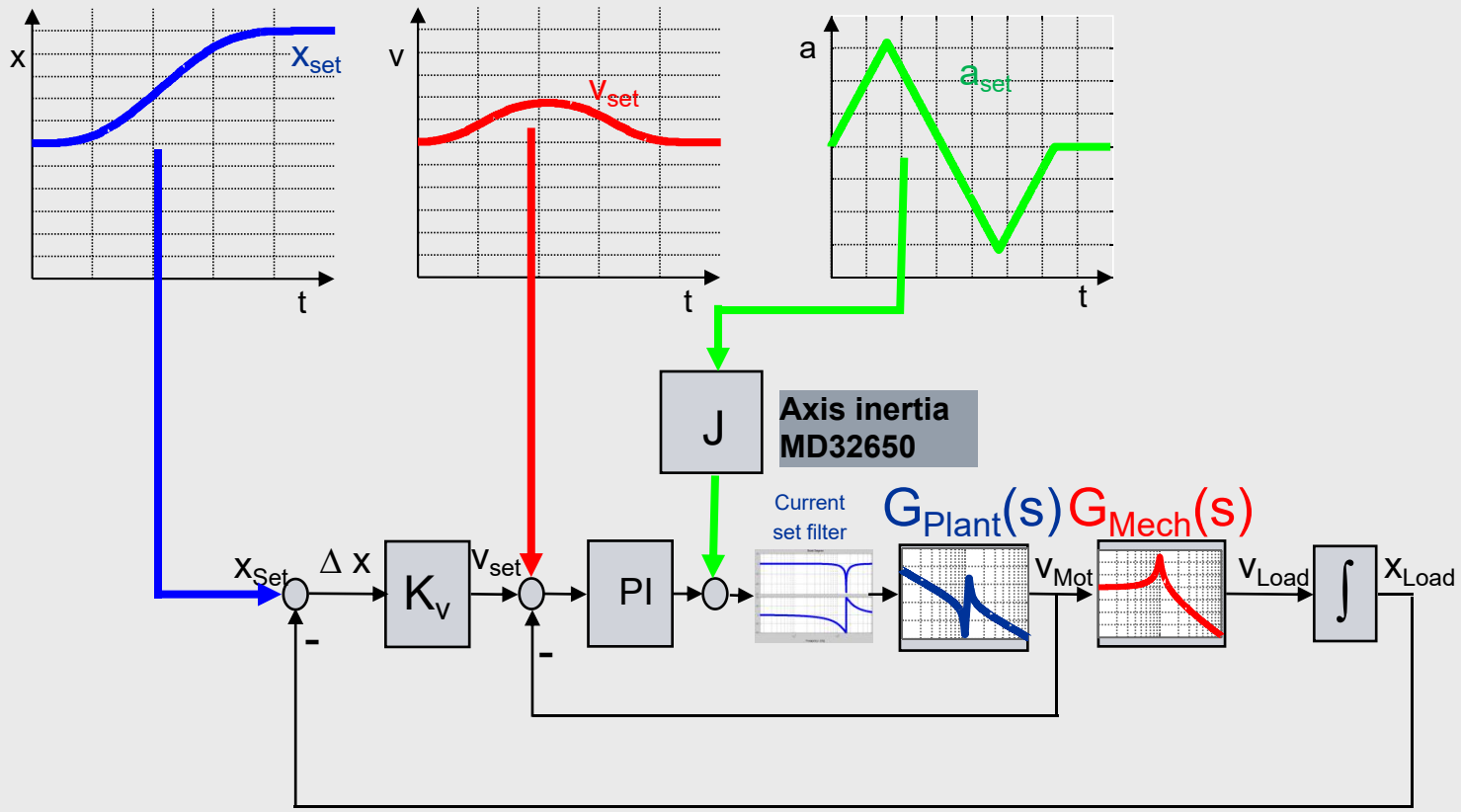
Commanded-Kv [1000/min] =

0,06 [s]

Equiv. speed controller time [s] + Jerk time[s] + dyn. match time[s] + desval delay [s]

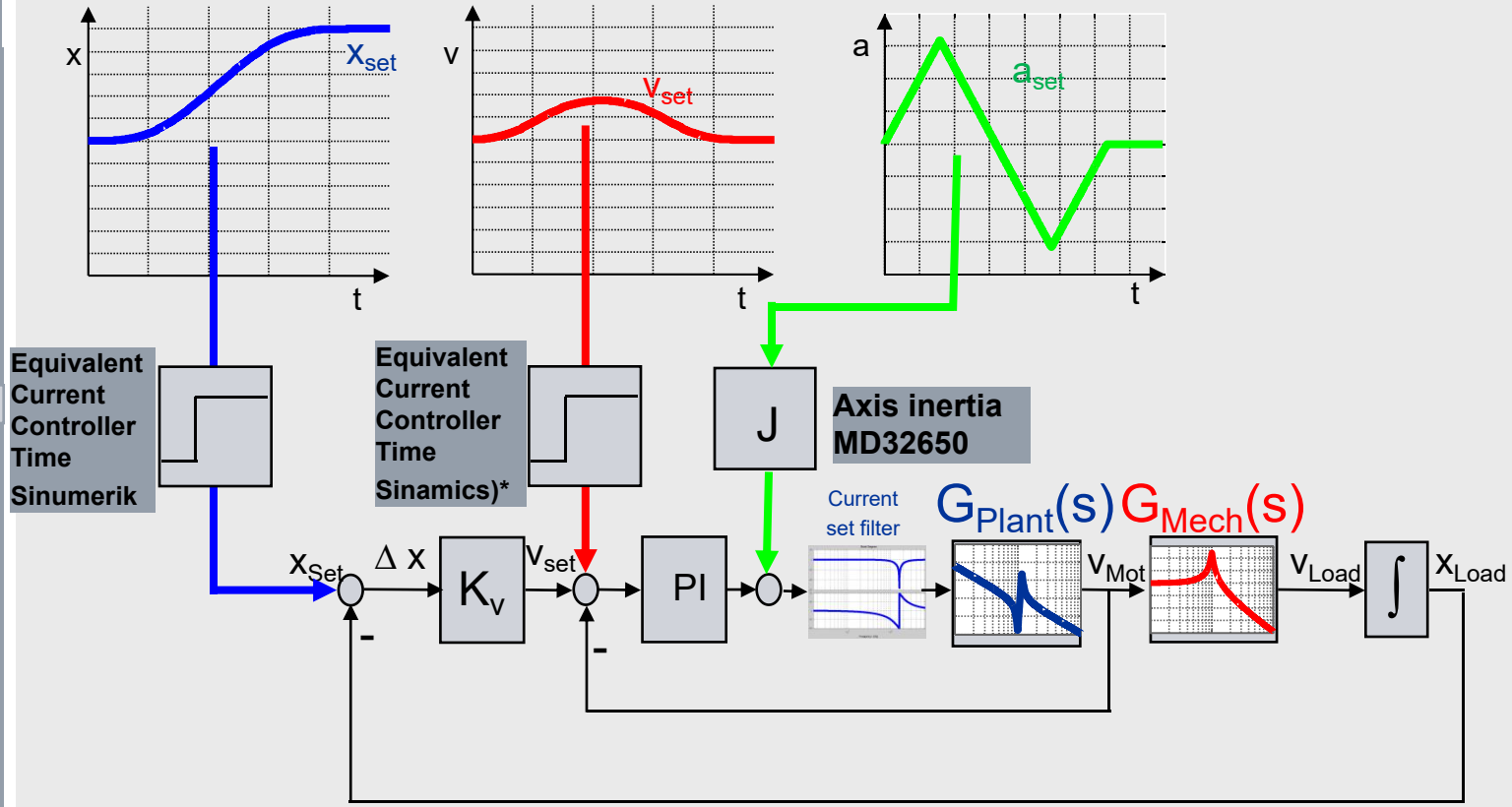


Position Controller with Torque Feed Forward



Since the torque feed forward signal does not result in a movement in zero time, this structure would result in an overshoot in position. To overcome this effect, the setpoints for speed and position have to be delayed. The delay basically fits to the time that is needed to build the real motor current including current setpoint filter delay time.

Position Controller with Torque Feed Forward

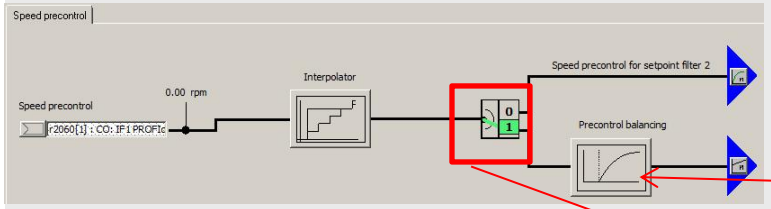


***A standard delay is already considered within Sinamics. In most applications, an additional delay has not to be defined.**

If an additional delay is necessary (if a wide current filter setting is done) please use drive parameter p1429.

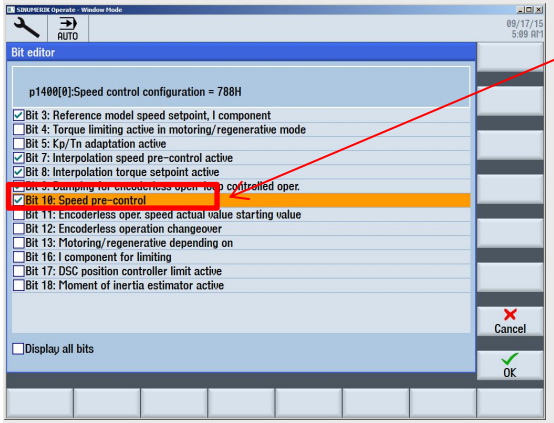
Position Controller with Torque Feed Forward

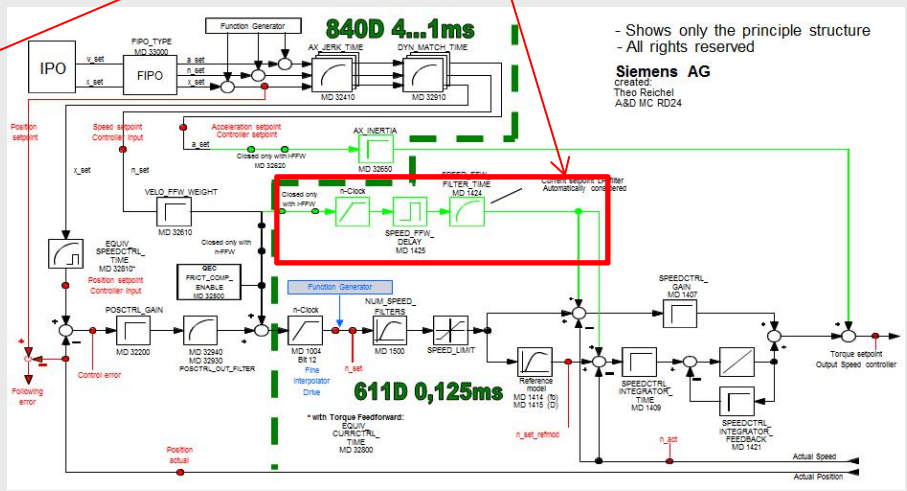
Change over speed precontrol path for torque feed forward



418	p1400		Speed control configuration				
419	p1400[0]	D	Speed control configuration	788H		Operation	2
420	p1400[0].3	D	Reference model speed setpoint I component	ON		Operation	2
421	p1400[0].4	D	Torque limiting active in motoring/regenerative mode	No		Operation	2
422	p1400[0].5	D	Kp/Tn adaptation active	No		Operation	2
423	p1400[0].7	D	Interpolation speed pre-control active	Yes		Operation	2
424	p1400[0].8	D	Interpolation torque setpoint active	Yes		Operation	2
425	p1400[0].9	D	Damping for encoderless open-loop controlled oper.	Yes		Operation	2
426	p1400[0].10	D	Speed pre-control	For balancing		Operation	2
427	p1400[0].11	D	Encoderless oper. speed actual value starting value	For setp_filter 2		Operation	2
428	p1400[0].12	D	Encoderless operation changeover	For balancing		Operation	2

p1400 Bit10 Speed pre-control =1





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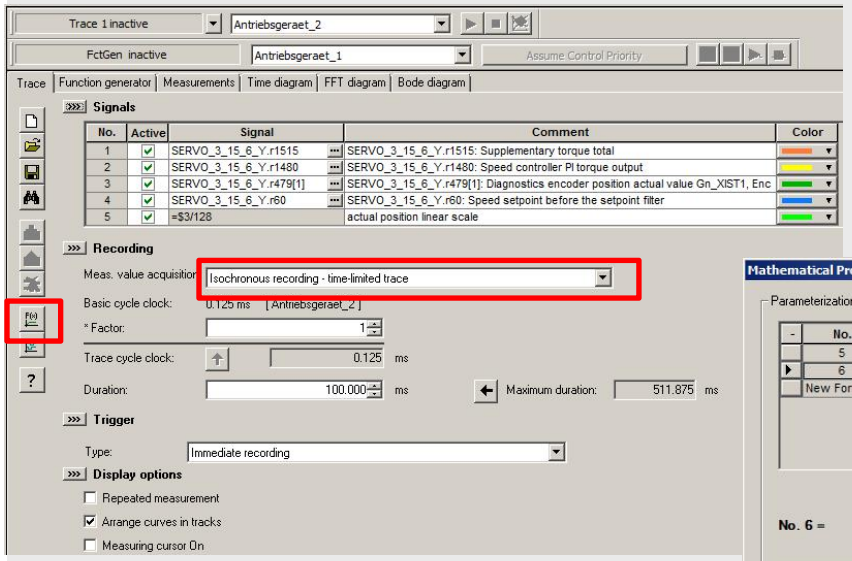
Position Controller with Torque Feed Forward

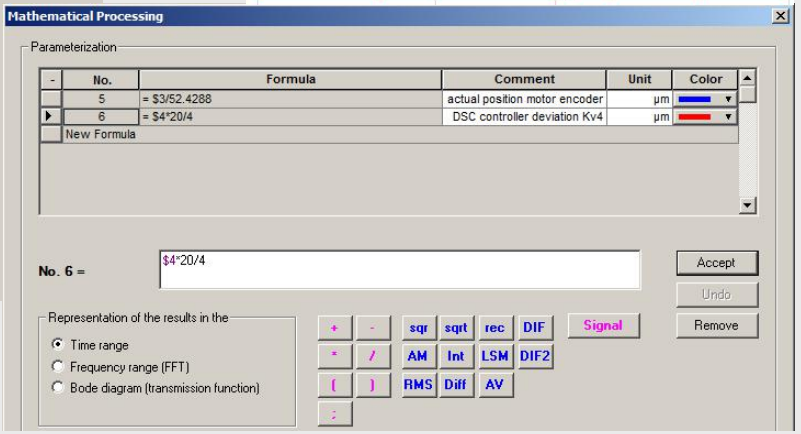
Starter settings

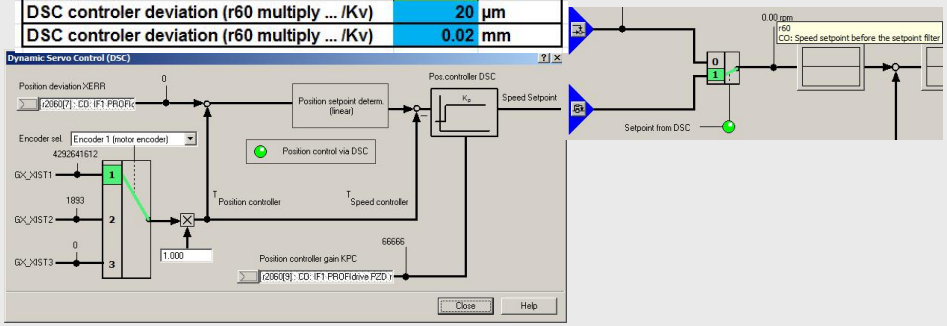
Linear scale		
Grid	16	µm
fine interpolation	2048	p418 =2^11
fine increment	0.0078125	µm
r479 devide by	128	gives position in µm

linear axis with rotating motor encoder		
Encoder pulses / rev.	512	Imp / rev. p408
fine interpolation	2048	p418 =2^11
fine increments / rev.	1048576	Ink / rev,
gear ratio	1	MD31060 /MD31050
ball screw pitch	20	mm
r479 devide by	52.4288	gives position in µm

linear axis with a rotating motor		
Gearbox 32060 numerator	1	
Gearbox 32050 denumberator	1	
Gear ratio i	1	
screew pitch	20	mm
DSC controler deviation (r60 multiply ... /Kv)	20	µm
DSC controler deviation (r60 multiply ... /Kv)	0.02	mm

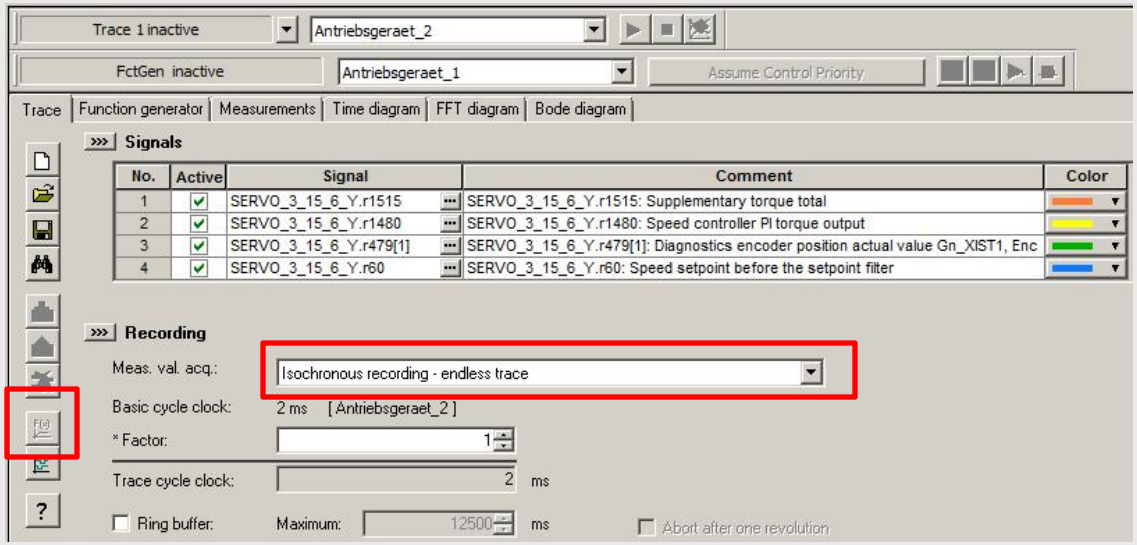






Position Controller with Torque Feed Forward

Starter settings for measurement



Position Controller with Torque Feed Forward

Check the formulas by moving the axis without feed forward FFW_MODE = 0

```
soft¶
ANF: ¶
G90 G64 G01 y0 F15000¶
G4 F1¶
NEUCONF¶
y200¶
G4 F1¶
NEUCONF¶
Gotob anf¶
m30¶
```

moving distance 200 mm

v = 15 [m/min]

Kv = 1,7 [(m/min)/mm]

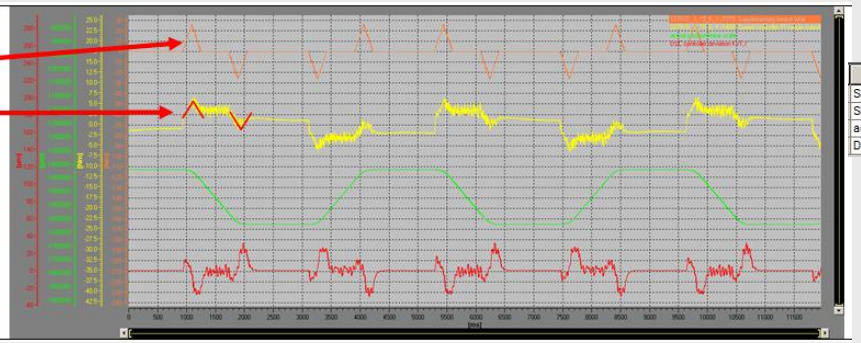
Controller deviation 15 / 1,7 = 8.823 [mm]

Comment	Unit	
SERVO_3_15_6_Y.r1515: Supplementary torque total	Nm	
SERVO_3_15_6_Y.r1480: Speed controller PI torque output	Nm	
actual position linear scale	µm	
DSC controller deviation Kv1,7	µm	

Position Controller with Torque Feed Forward

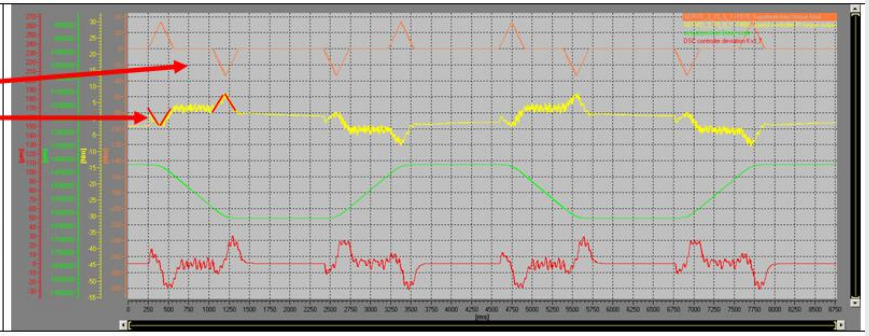
Check and optimize MD 32650 AX_INERTIA (total inertia)
FFW_MODE = 4

Acceleration profile is visible in signal „r1480: Speed controller PI torque output“ →
MD 32650
AX_INERTIA = 0,0105 kgm²
too small

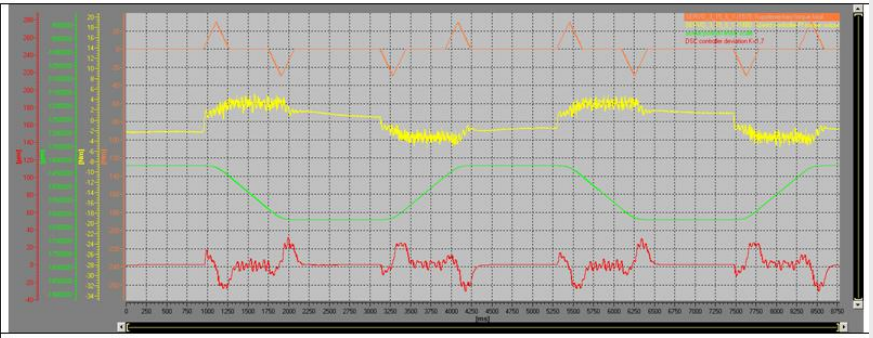


Comment	Unit
SERVO_3_15_6_Y.r1515: Supplementary torque total	Nm
SERVO_3_15_6_Y.r1480: Speed controller PI torque output	Nm
actual position linear scale	µm
DSC controller deviation Kv1,7	µm

Inverse acceleration profile is visible in signal „r1480: Speed controller PI torque output“ →
MD 32650
AX_INERTIA = 0,0135 kgm² too big



Acceleration profile is not visible in signal „r1480: Speed controller PI torque output“ →
MD 32650
AX_INERTIA = 0,012 kgm²
at optimum value



Position Controller with Torque Feed Forward

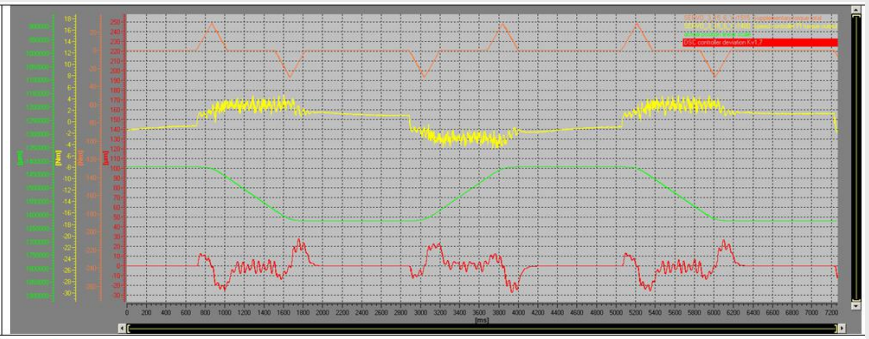
Check and optimize MD 32800 $MA_EQUIV_CURRCTRL_TIME und p1429 Speed pre-control balancing time constant FFW_MODE = 4

MD32800 =
1,5 ms

p1429 =
0,36 ms

Controller deviation is not conform with jerk profile →

time constants too long

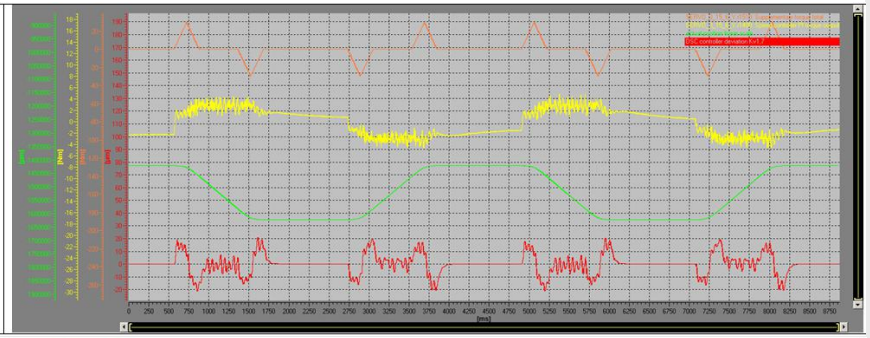


MD32800 =
1,2 ms

p1429 =
0,36 ms

Controller deviation is very conform with jerk profile →

time constants match very well together

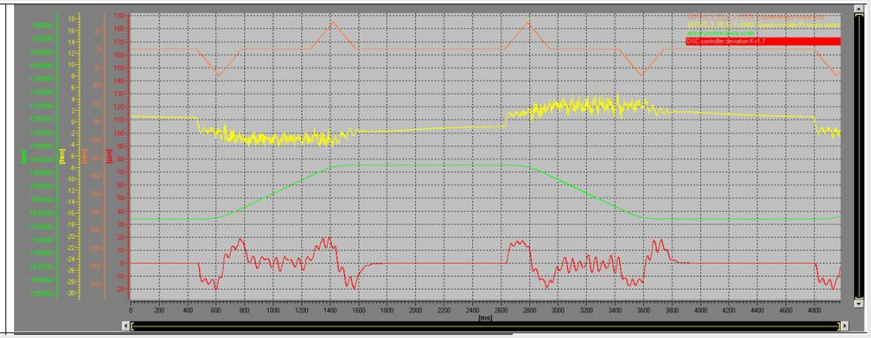


MD32800 =
0,8 ms

p1429 =
0 ms

Controller deviation is very conform with jerk profile and bigger commanded Kv-factor →

time constants at optimum values



Comment	Unit	
SERVO_3_15_6_Y.r1515: Supplementary torque total	Nm	
SERVO_3_15_6_Y.r1480: Speed controller PI torque output	Nm	
actual position linear scale	µm	
DSC controller deviation Kv1,7	µm	

Position Controller with Torque Feed Forward

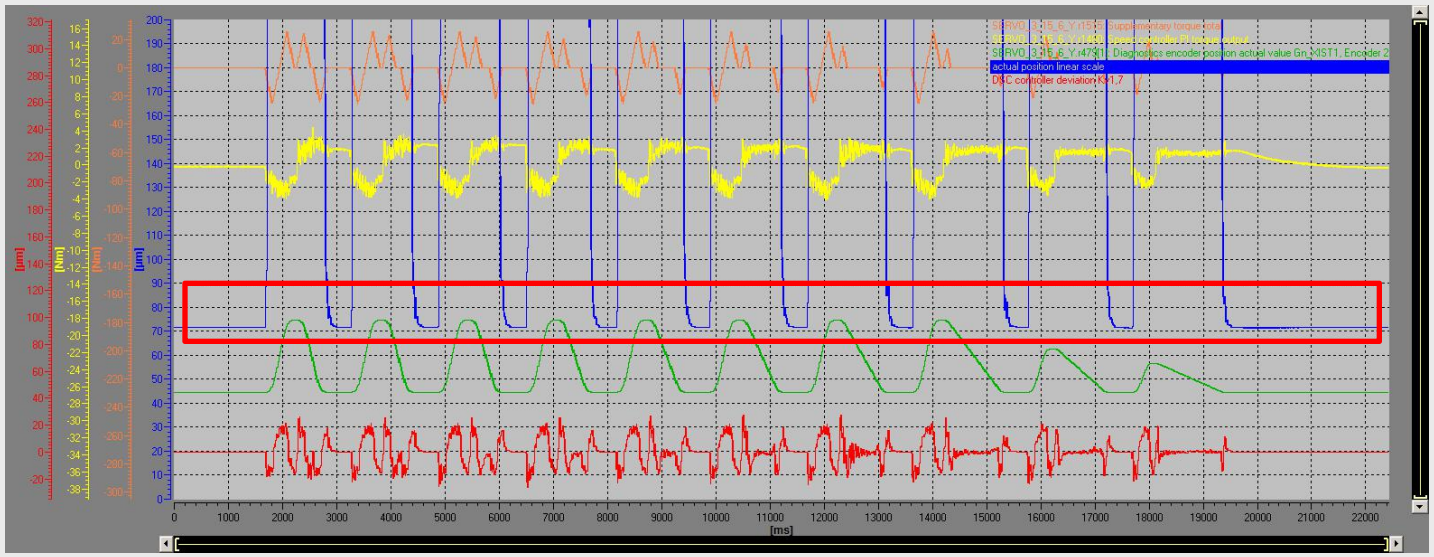
Positioning behavior at direct scale with different speeds

```
ffuon¶
SOFT¶
G90 G54¶
NEUCONF¶
ANF: ¶
M0¶
$AA_SCTRACE[Y]=1¶
NEUCONF¶
G90 G00 Y00¶
G91¶
G01 Y50 F10000¶
G04 F0.4¶
G0 Y-50 ¶
¶
G01 Y50 F9000¶
G04 F0.4¶
G0 Y-50¶
¶
G01 Y50 F8000¶
```

```
G04 F0.4¶
G0 Y-50¶
¶
G01 Y50 F7000¶
G04 F0.4¶
G0 Y-50 ¶
¶
G01 Y50 F6000¶
G04 F0.4¶
G0 Y-50 ¶
¶
G01 Y50 F5000¶
G04 F0.4¶
G0 Y-50 ¶
¶
G01 Y50 F4000¶
G04 F0.4¶
G0 Y-50 ¶
¶
G01 Y50 F3000¶
```

```
G04 F0.4¶
G0 Y-30 ¶
¶
G01 Y30 F2000¶
G04 F0.4¶
G0 Y-20¶
¶
G01 Y20 F1000¶
G04 F0.4¶
¶
GOTOB ANF¶
M30¶
¶
```

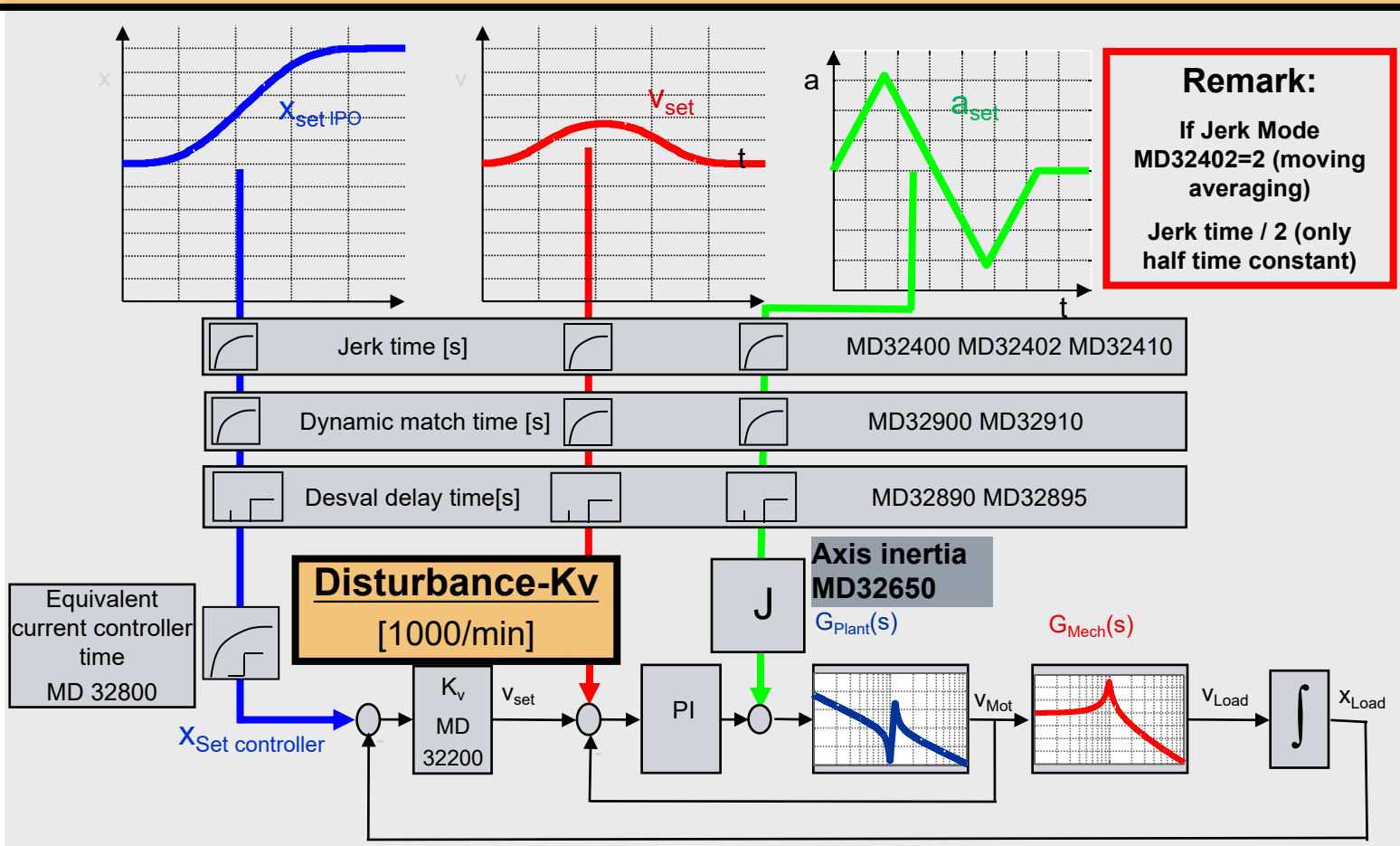
Comment	Unit
SERVO_3_15_6_Y.r1515: Supplementary torque total	Nm
SERVO_3_15_6_Y.r1480: Speed controller PI torque output	Nm
SERVO_3_15_6_Y.r479[1]: Diagnostics encoder position actual value Gn_XIST1, Encoder 2	-
actual position linear scale	µm
DSC controller deviation Kv1,7	µm



Position Controller with Torque Feed Forward

Commanded-Kv [1000/min] =

$$\frac{0{,}06\ [s]}{\text{Equiv. current controller time [s] + Jerk time[s] + dyn. match time[s] + desval delay [s]}}$$



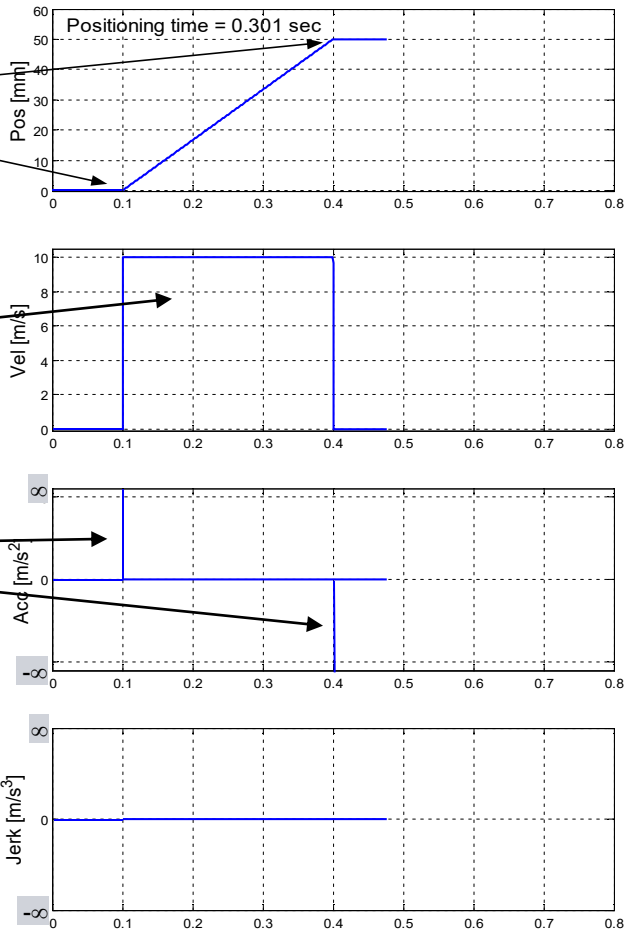
Positioning with Infinite Acceleration (a = ∞)
Only in Theory -> not Possible due to F = m*a
无加速度限制(a = ∞)的定位，理论曲线→不可能，因为F = m*a

SIEMENS

sharp Corners!

Velocity is a step Function

Acceleration is a Dirac-Impulse!



Positioning with Finite Acceleration (a = 4 m/s²) Without Jerk Limitation (r = ∞)
带加速度限制(a = 4 m/s²)的定位，没有Jerk限制(r = ∞)

SIEMENS

rounded Corners

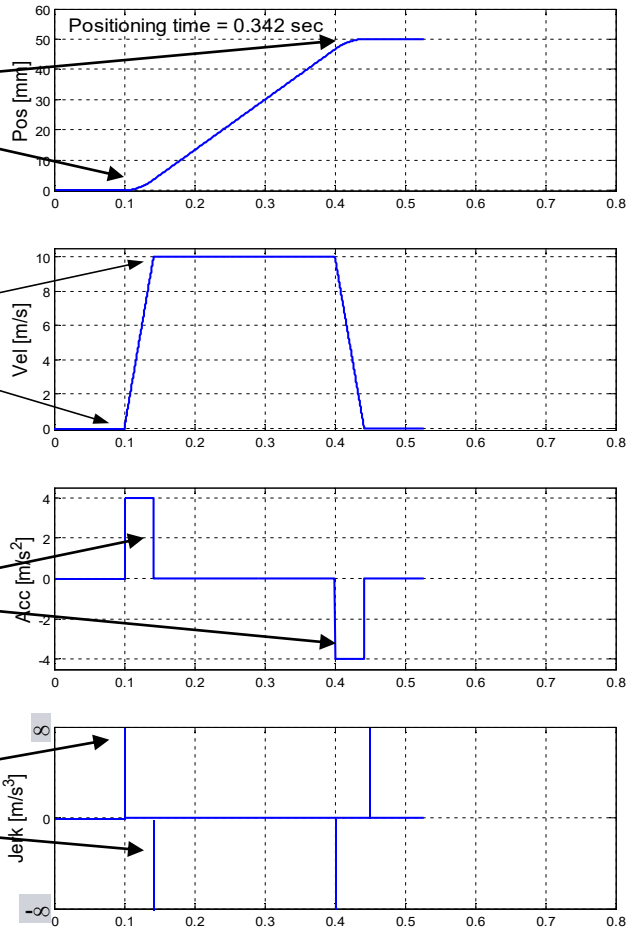
Velocity increases slowly

Sharp corners

Acceleration is a step function

a = 4 m/s²

Jerk is infinite!



Positioning with Finite Acceleration (a = 2 m/s²) Without Jerk Limitation (r = ∞)
带加速度限制(a = 2 m/s²)的定位，没有Jerk限制(r = ∞)

SIEMENS

rounded Corners

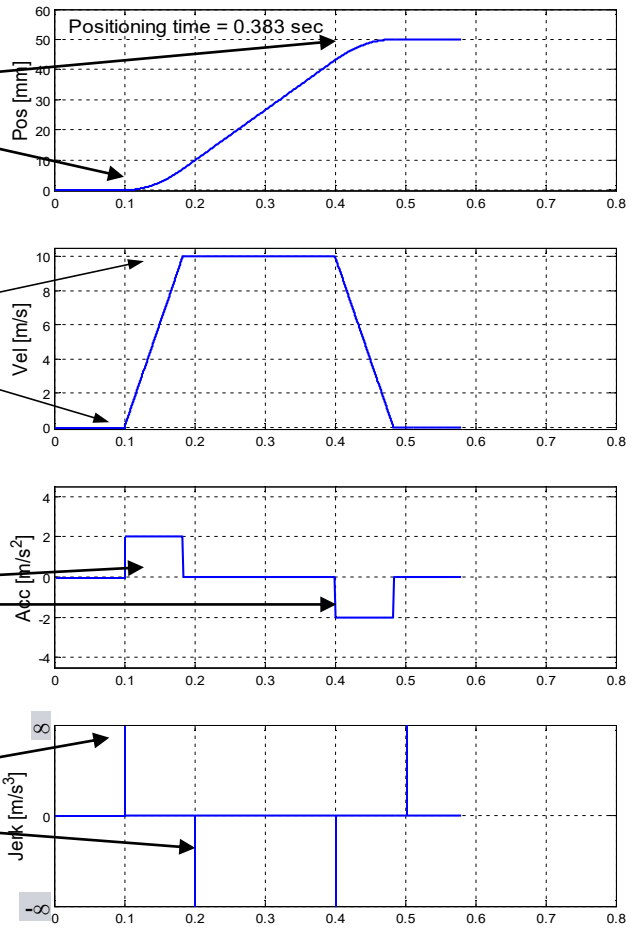
Velocity increases slowly

Sharp corners

Acceleration is a step function

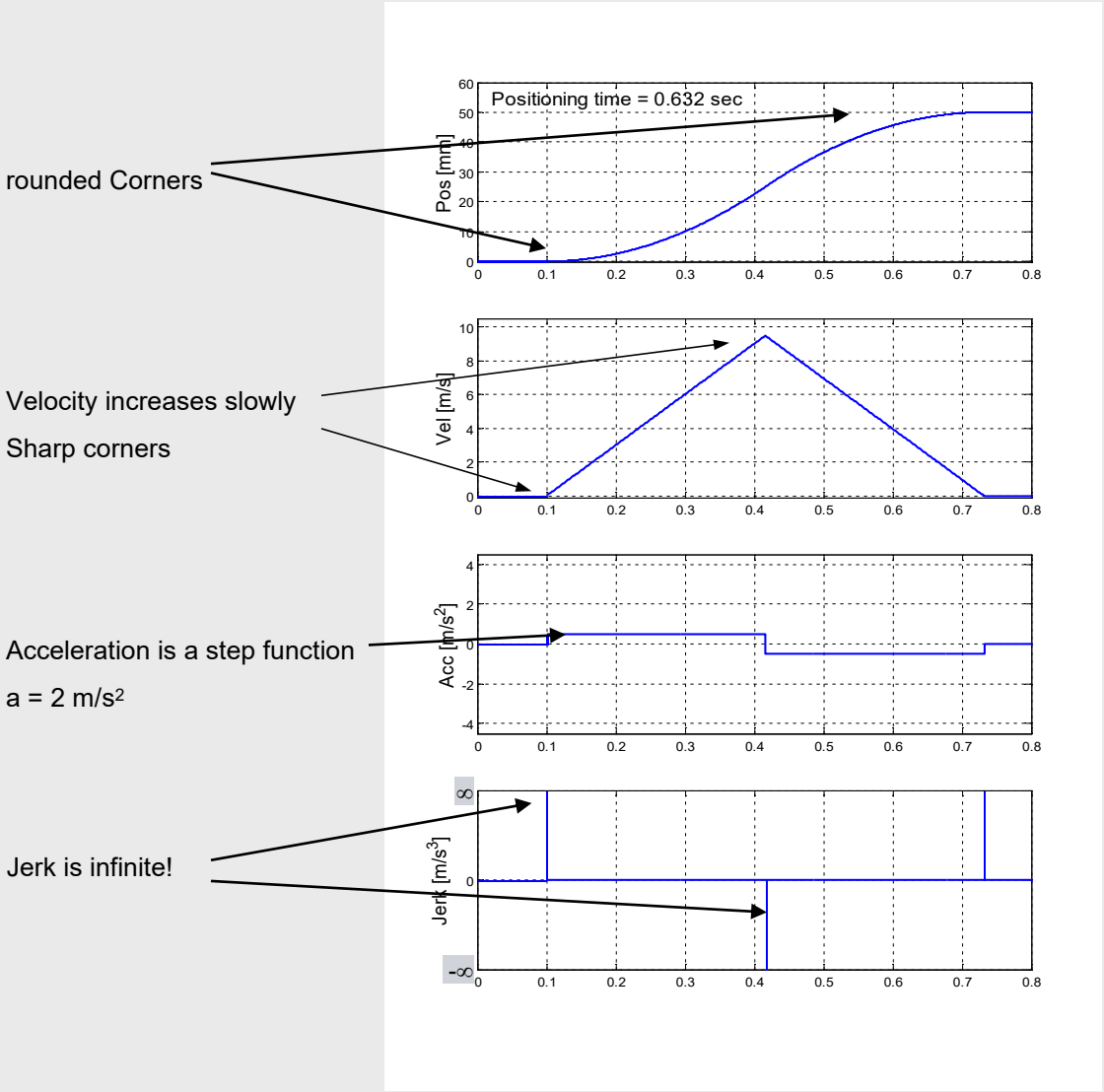
a = 2 m/s²

Jerk is infinite!



Positioning with Finite Acceleration (a = 0.5 m/s²) Without Jerk Limitation (r = ∞)
带加速度限制(a = 0.5 m/s²)的定位，没有Jerk限制(r = ∞)

SIEMENS



Positioning With Finite Acceleration (a = 4 m/s²) Without Jerk Limitation (r = ∞)
带加速度限制(a = 4 m/s²)的定位，没有Jerk限制(r = ∞)

SIEMENS

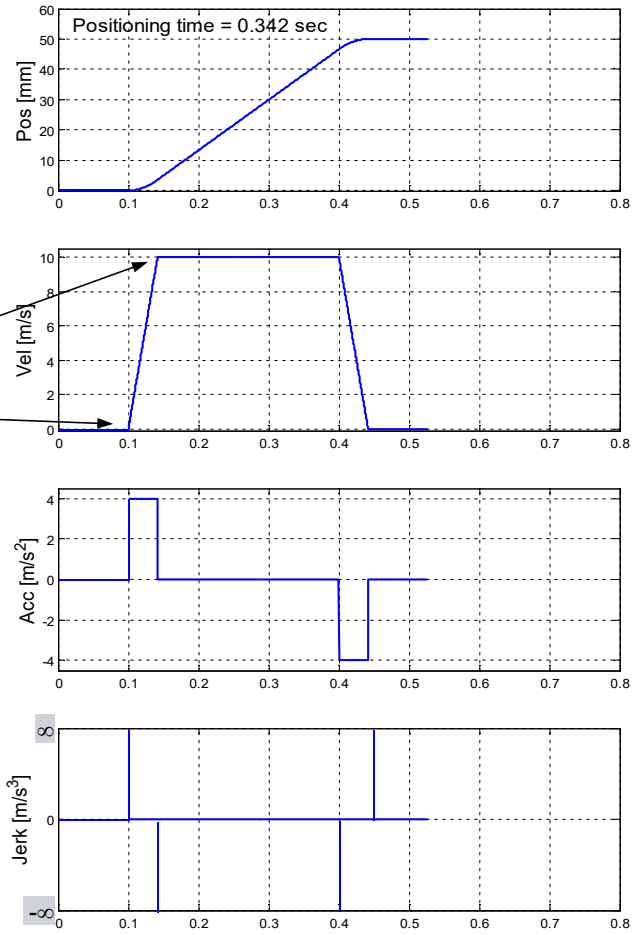
Rounded Corners

Velocity has a finite slope

Sharp Corners

Acceleration is a step function

a = 4 m/s²



Positioning With Finite Acceleration (a = 4 m/s²) With Jerk Limitation (r = 200 m/s³)

带加速度限制(a = 4 m/s²)的定位，有Jerk限制(r = 200 m/s³)

SIEMENS

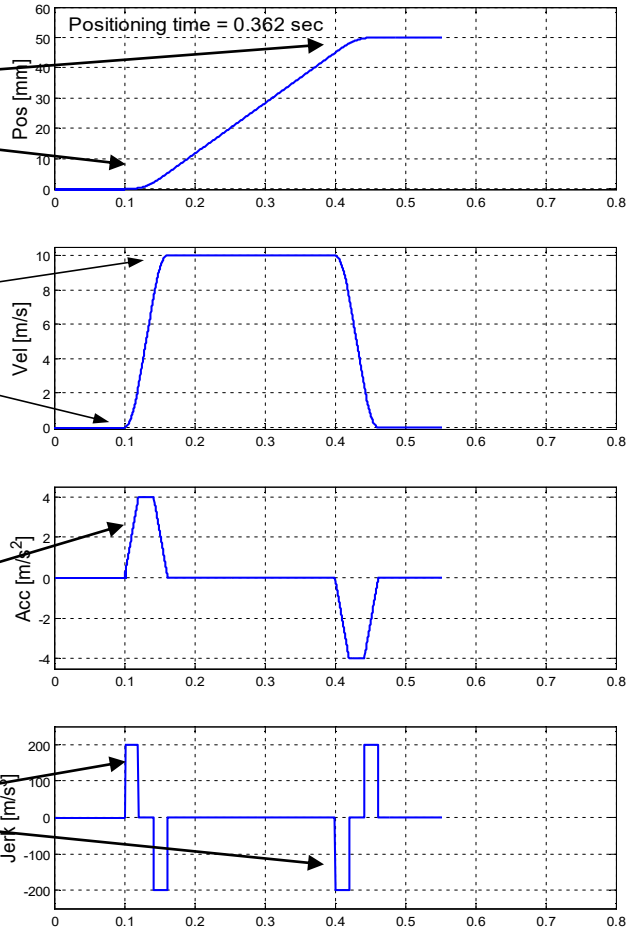
Very smooth

Rounded corners

Acceleration has a finite slope

Jerk is a step function

r = 200 m/s³



Positioning With Finite Acceleration (a = 4 m/s²) With Jerk Limitation (r = 50 m/s³)

带加速度限制(a = 4 m/s²)的定位，有Jerk限制(r = 50 m/s³)

SIEMENS

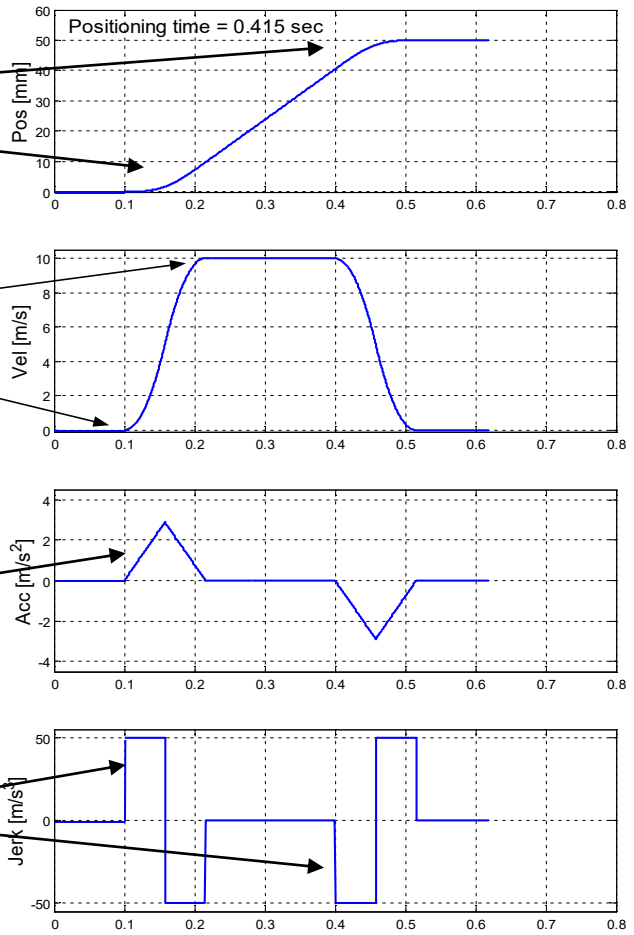
Very smooth

Rounded corners

Acceleration has a finite slope

Jerk is a step function

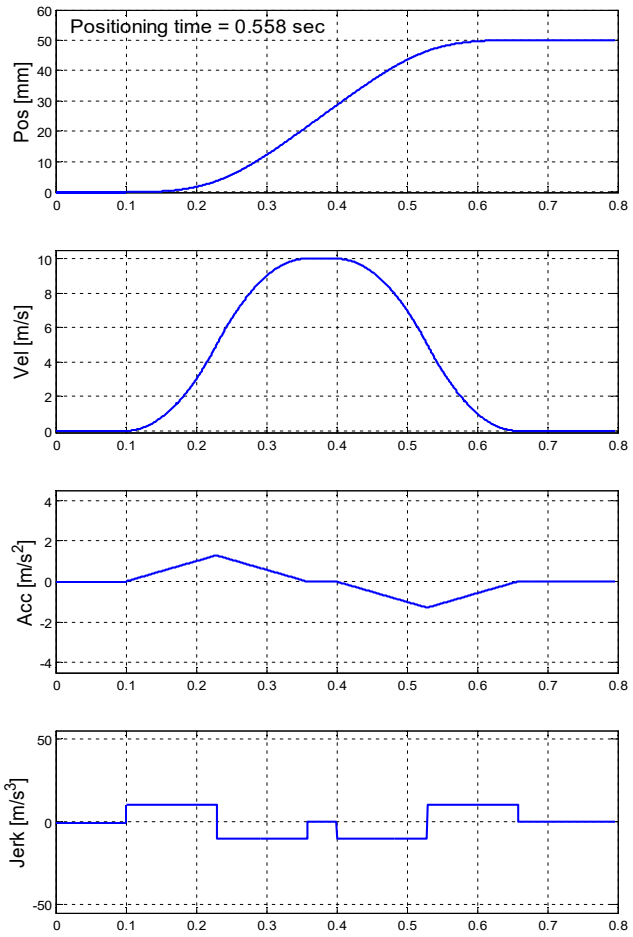
r = 50 m/s³

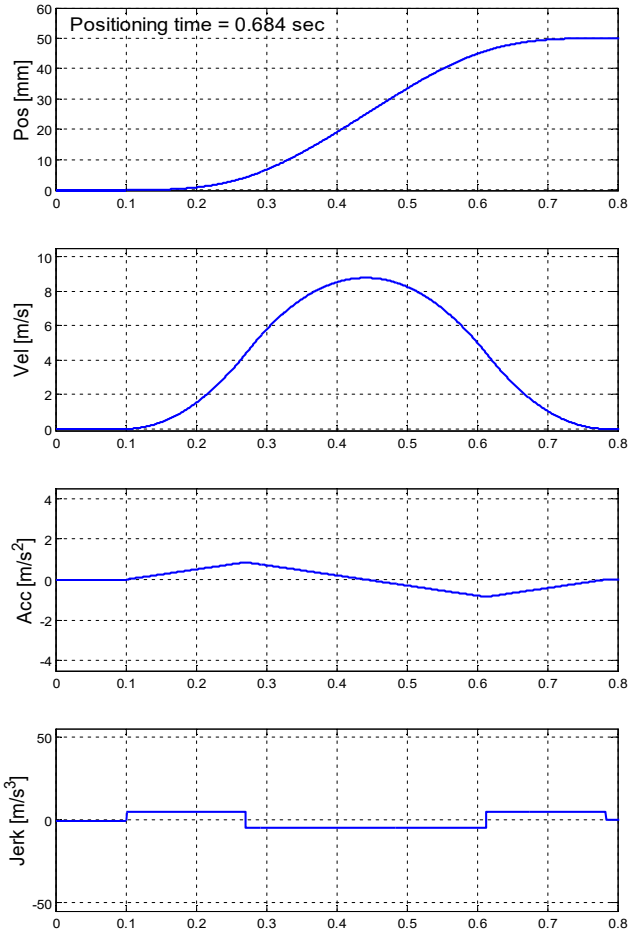


Positioning With Finite Acceleration (a = 4 m/s²) With Jerk Limitation (r = 10 m/s³) and (r = 5 m/s³)

带加速度限制(a = 4 m/s²)的定位，有Jerk限制(r = 10 m/s³)和(r = 5 m/s³)

SIEMENS

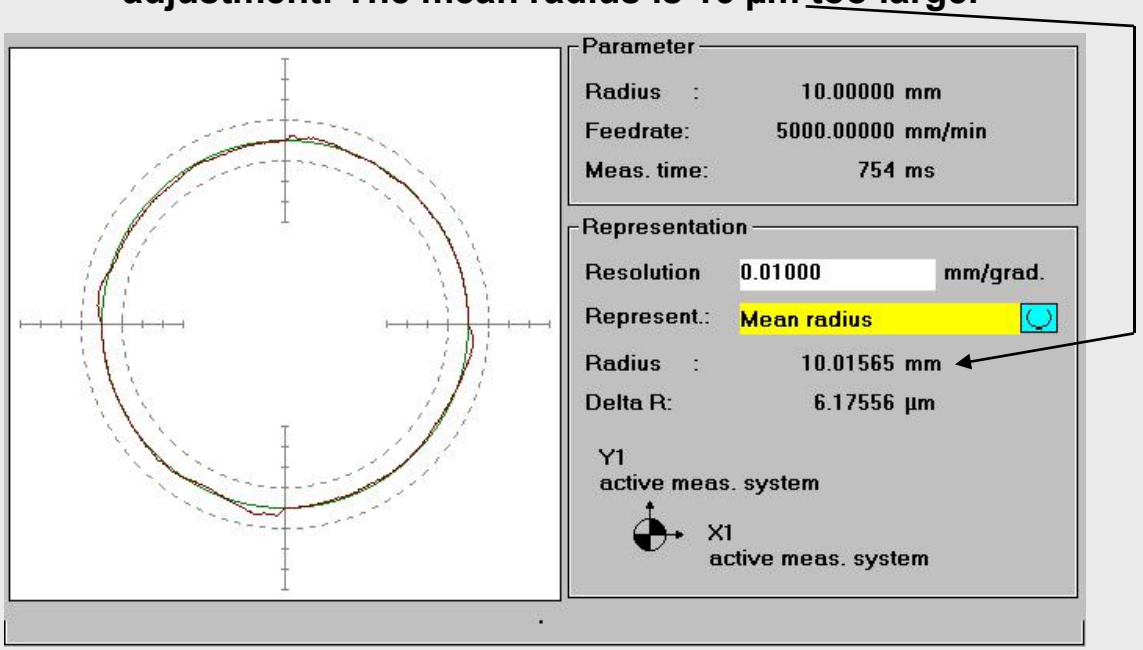




Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Circle with tuned Speed Feed Forward without any additional adjustment: The mean radius is 16 µm too large.

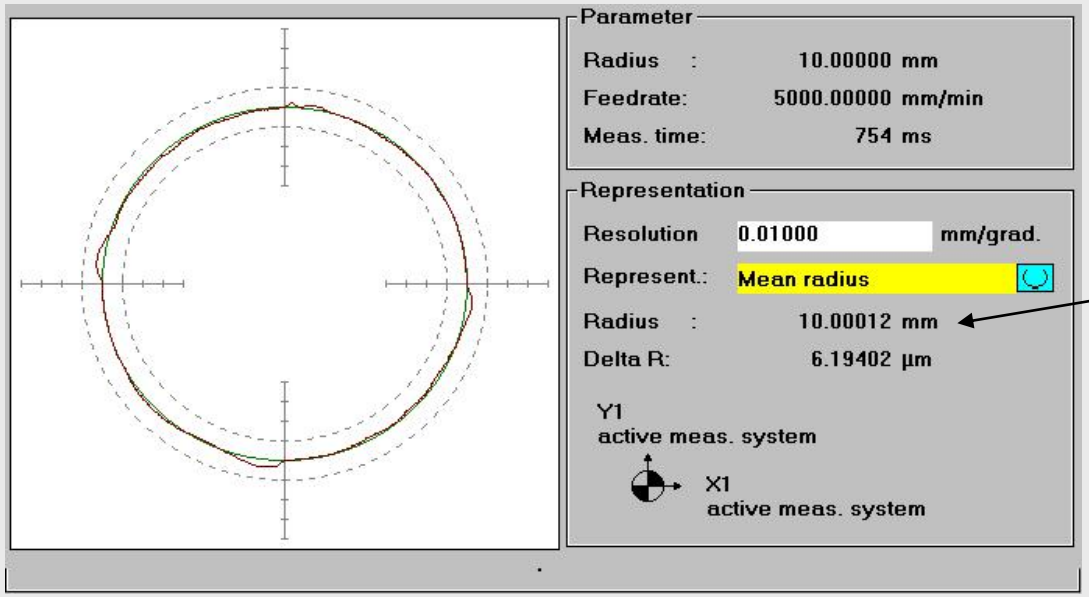


		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32900	DYN_MATCH_ENABLE	0	0
32400	AX_JERK_ENABLE	0	0

Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Circle corrected with machine data DYN_MATCH_TIME :
The mean radius is optimal (10,00012 µm)

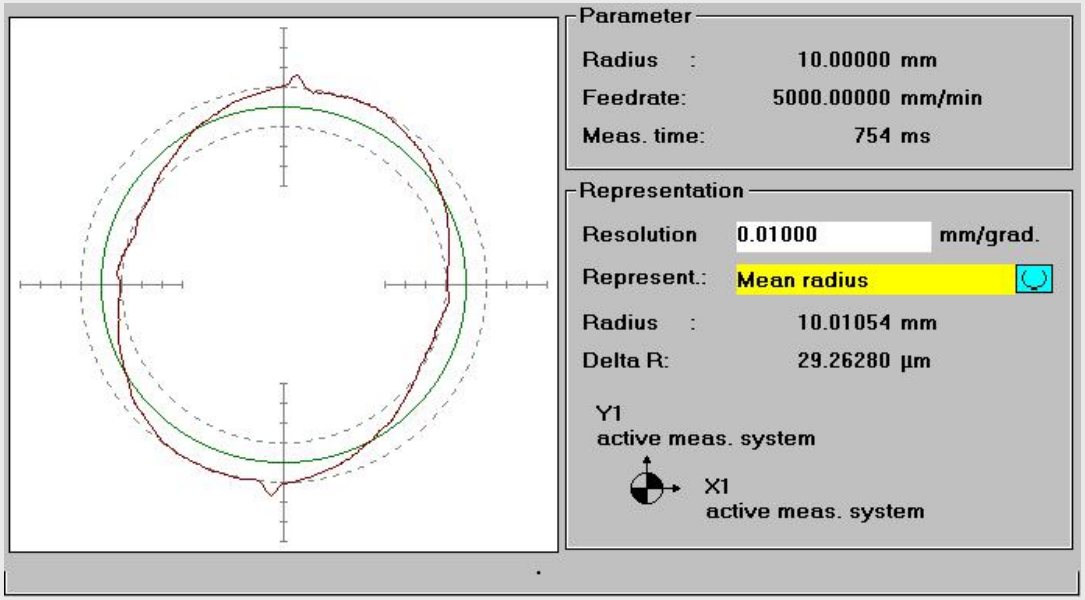


		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32910	**DYN_MATCH_TIME**	**0.0062**	**0.0062**
32900	**DYN_MATCH_ENABLE**	**1**	**1**
32400	AX_JERK_ENABLE	0	0

Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Circle with different time constants in the machine data
DYN_MATCH_TIME: Different Dynamics of the axes

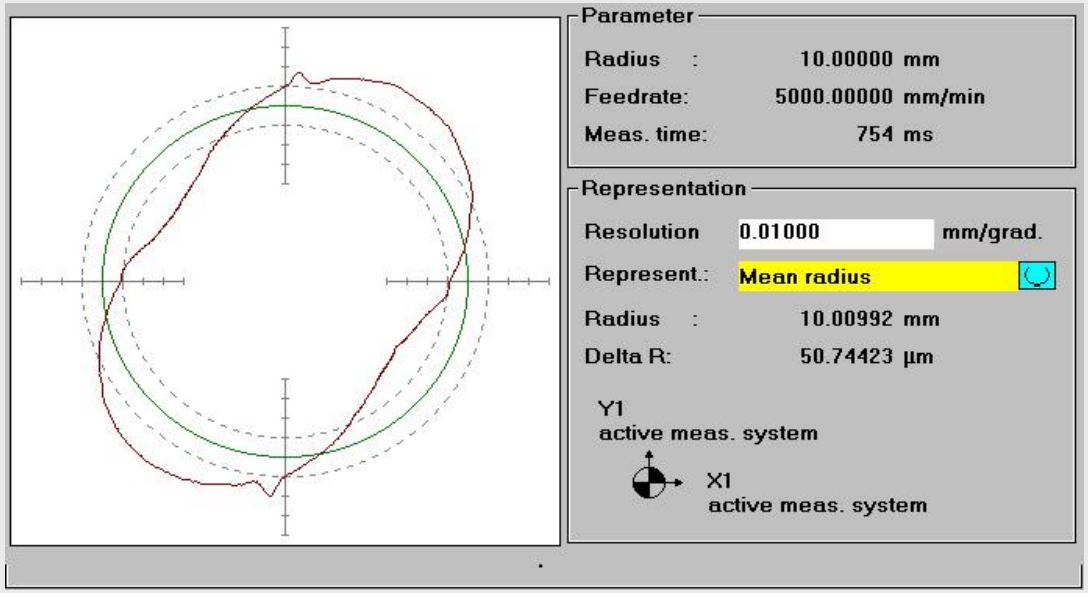


		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32910	**DYN_MATCH_TIME**	**0.0035**	**0.0036**
32900	DYN_MATCH_ENABLE	1	1
32400	AX_JERK_ENABLE	0	0

Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Circle with different time constants in the machine data
DYN_MATCH_TIME: Different Dynamics of the axes

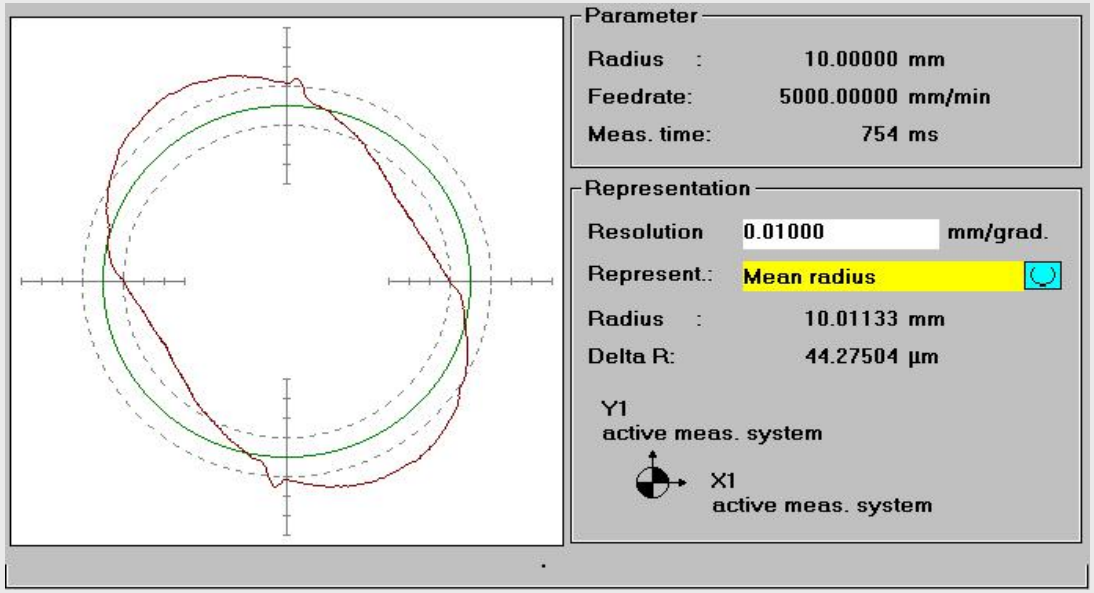


		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32910	**DYN_MATCH_TIME**	**0.0035**	**0.004**
32900	DYN_MATCH_ENABLE	1	1
32400	AX_JERK_ENABLE	0	0

Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Circle with different time constants in the machine data
DYN_MATCH_TIME: Different Dynamics of the axes

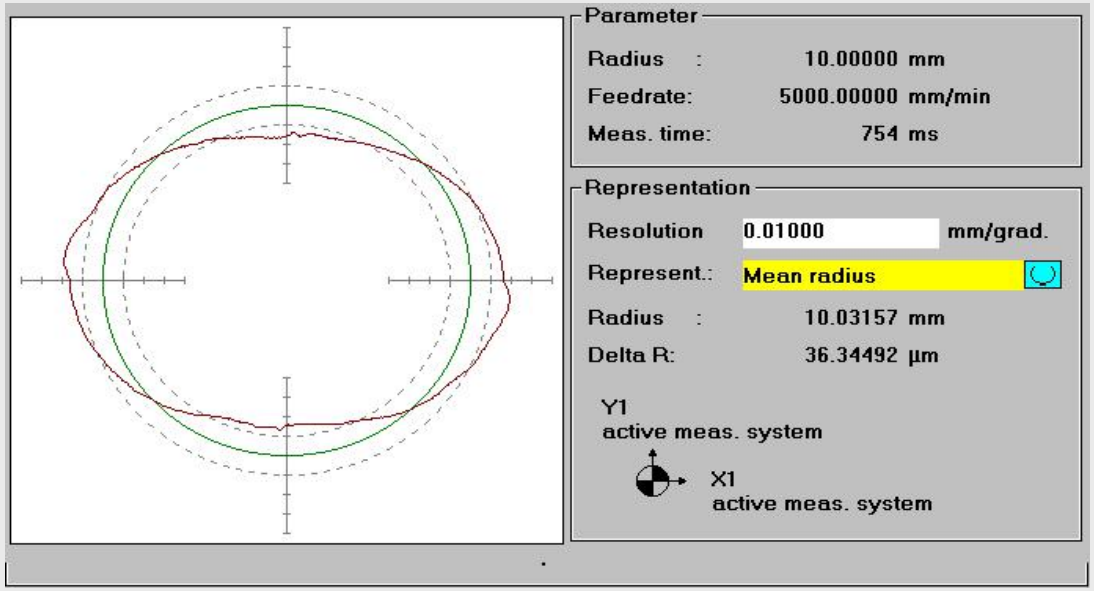


		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32910	**DYN_MATCH_TIME**	**0.0035**	**0.003**
32900	DYN_MATCH_ENABLE	1	1
32400	AX_JERK_ENABLE	0	0

Dynamic Behavior of Two Interpolating Axes: Assessment With the Circular Test
插补轴的动态响应：借助圆测试评估

SIEMENS

Impact of different Speed setpoint Filters. The same Effect is caused by different frequencies of the reference models



		Axis 1	Axis 2
32200	POSCTRL_GAIN	3.800	3.800
1407	SPEEDCTRL_GAIN_1	5.500	5.0
1409	SPEEDCTRL_INTEGRATOR_TIME_1	10.0	10.0
1414	SPEEDCTRL_REF_MODEL_FREQ	400.0	400.0
1500	NUM_SPEED_FILTERS	0	0
32610	VELO_FFW_WEIGHT	1.0	1.0
32620	FFW_MODE	3	3
32810	EQUIV_SPEEDCTRL_TIME	0.0025	0.0025
32910	**DYN_MATCH_TIME**	**0.0035**	**0.0035**
32900	DYN_MATCH_ENABLE	1	1
32400	AX_JERK_ENABLE	0	0
1500	**NUM_SPEED_FILTERS**	**2**	**0**
1503	**SPEED_FILTER_2_TIME**	**3.0**	**0.0**

Procedure of an Optimization
优化过程

SIEMENS

Presetting of different machine datas

Axis-MD 33000 FIPO_TYPE = **3** (Type of FIPO position setpoint)
Drive-MD 1004 CTRL_CONFIG = **1000H** (FIPO speed setpoint)

Measurements of the mechanical system

Ref. Frequency Response: **„Speed Controller Plant“**
Ref. Frequency Response: **„Mechanics“** (only possible with DMS)

Adjustment of Current Setpoint Filters

Ref. Freq. Resp. Of the closed speed controller (@ T_N = 10 ms K_p as high as possible)

Mayby use of other software to find optimal filter setting

Optimization of Speed Controller

Step Response or **Ref. Freq. Resp. Of the closed speed controller** (optimal values for K_p , T_N and f_{Refmod})

Optimization of Position Controller Parameters

Ref. Frequency Response of the closed position controller loop (find optimal value for Kv)

Activation and optimization of Speed Feed Forward

Positioning Behavior: **„SERVO TRACE“** (FFW_MODE = 3; find optimal Value for Equivalent Speed Controller Time

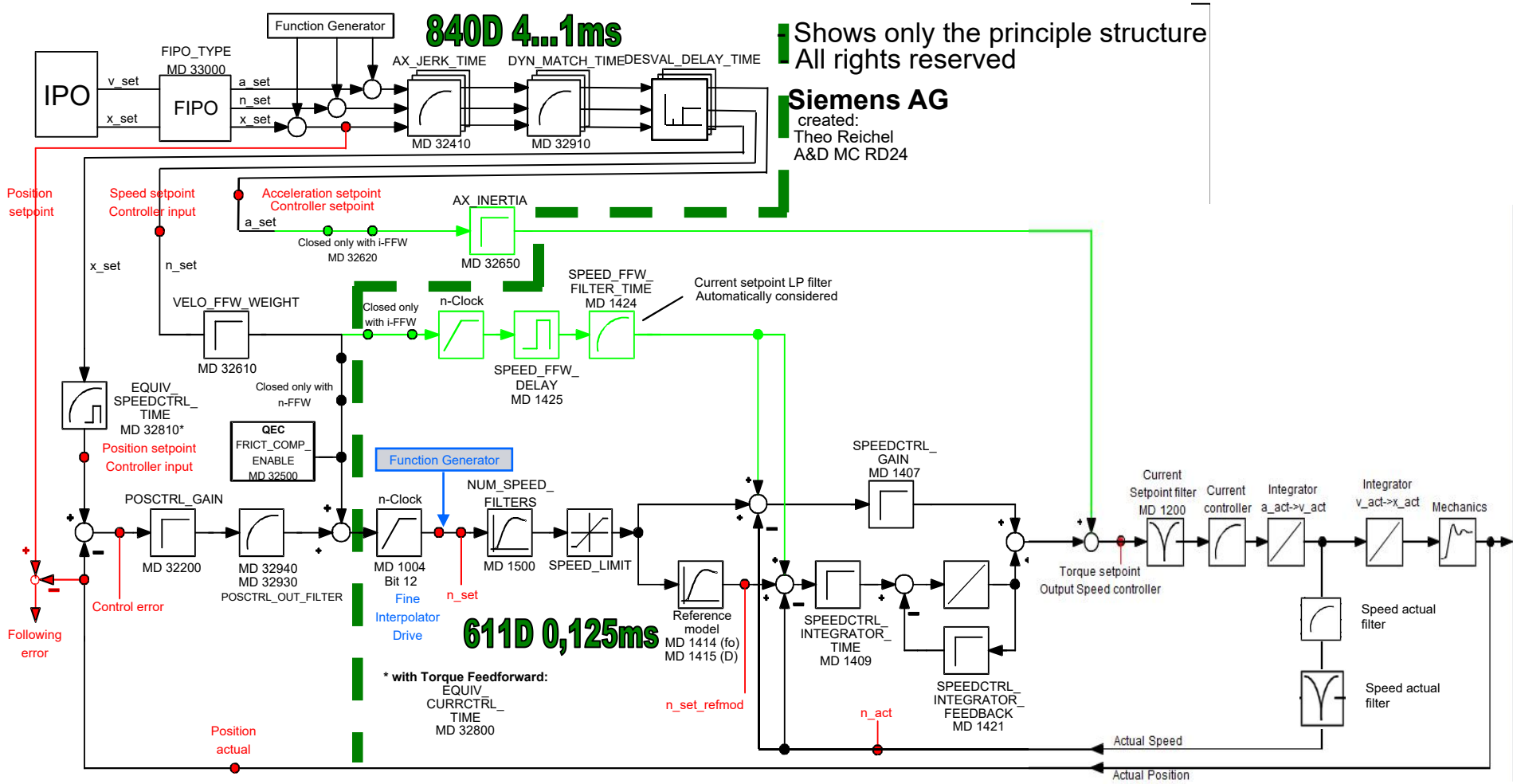
maybe finetuning with the Reference model)

Dynamics adjustment for different axes

„Circular Test“ (Mean Radius has to be the same as programed rafius; optimal roundness)

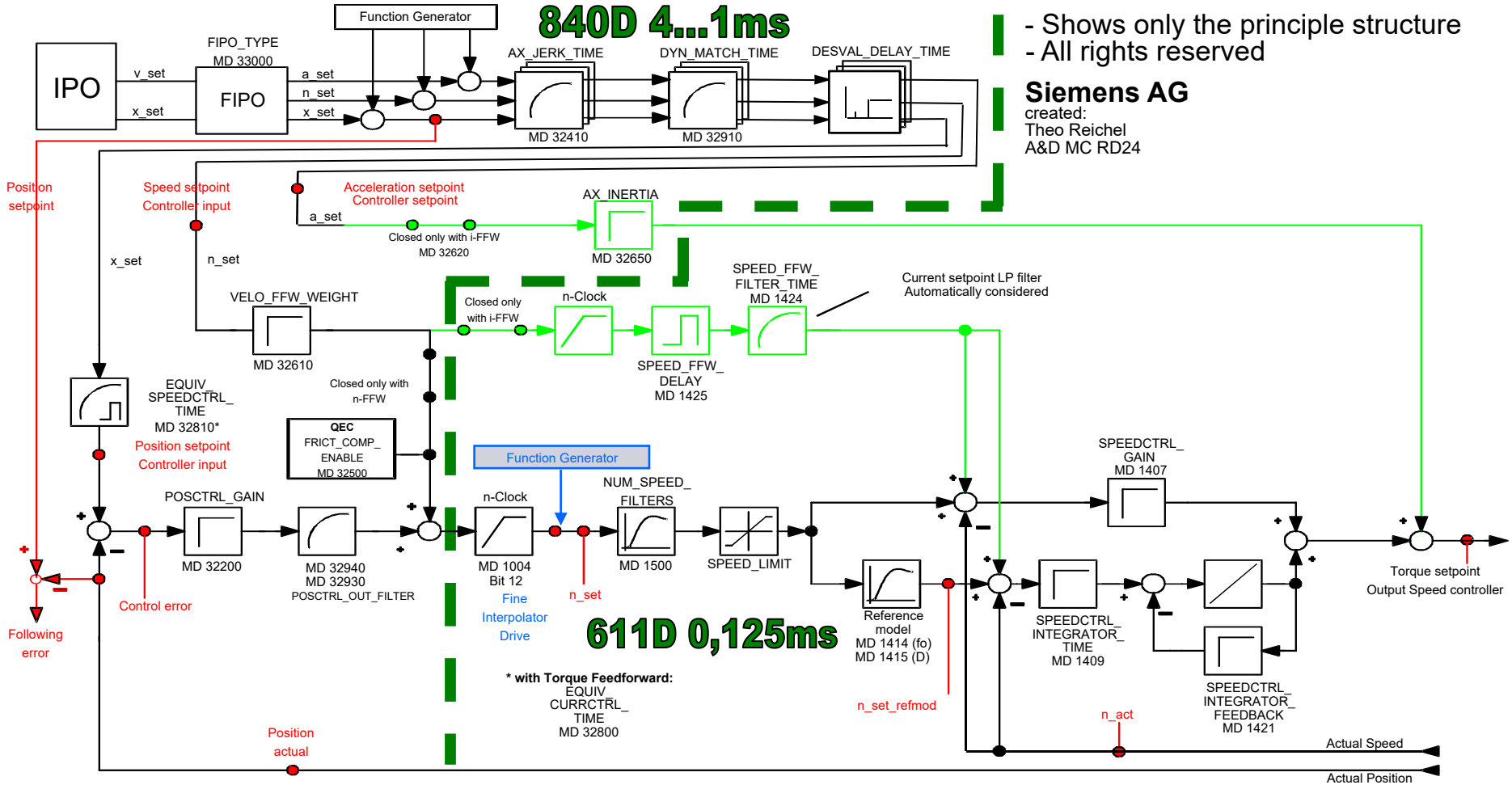
Fundamental Block Diagram of SINUMERIK 840D Servo and SIMODRIVE 611D (2)

SIEMENS



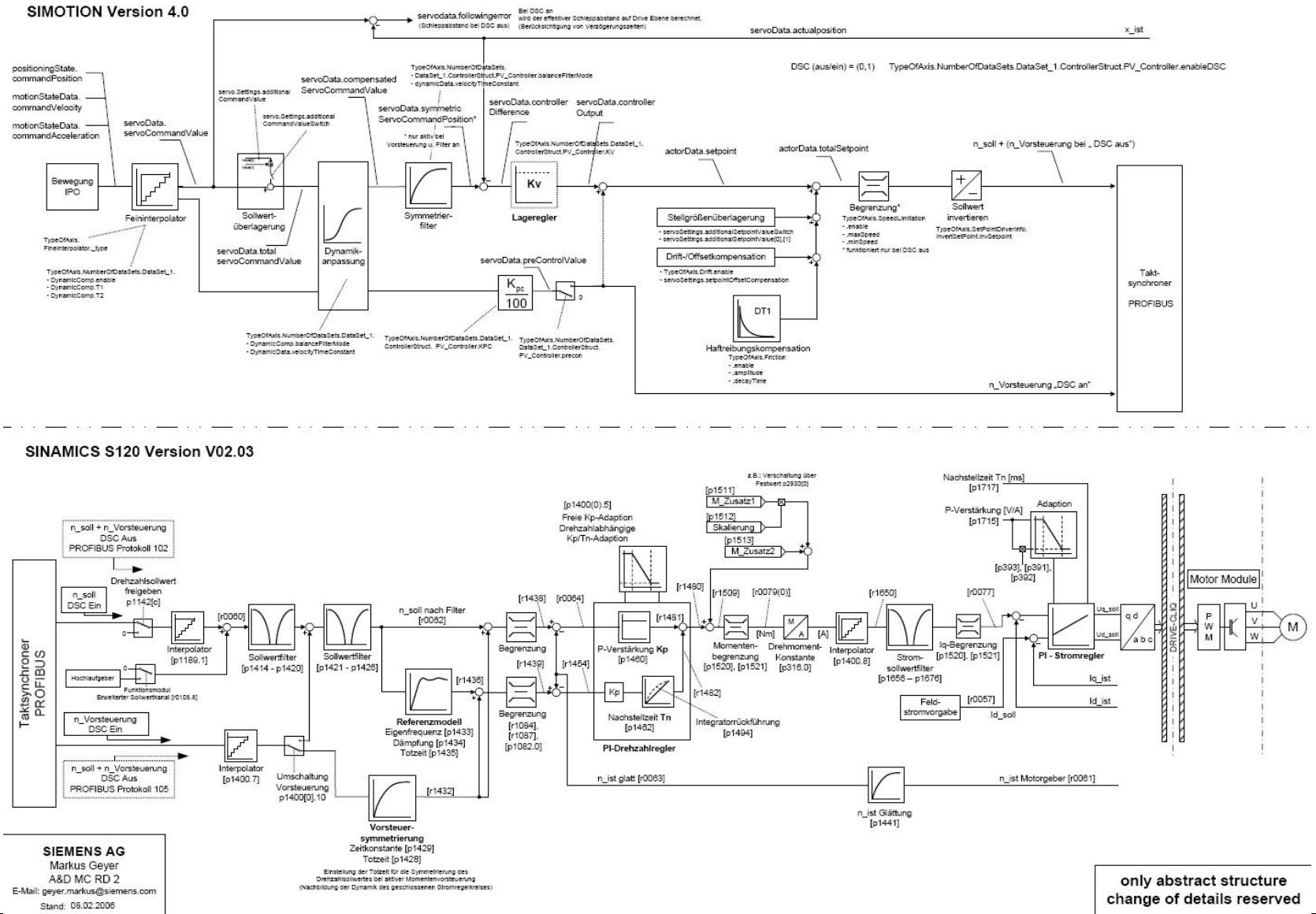
Fundamental Block Diagram of SINUMERIK 840D Servo and SIMODRIVE 611D (2)

SIEMENS



Fundamental Block diagram of SIMOTION V4.0 and SINAMICS S120 V02.03
SIMOTION V4.0和SINAMICS S120 V02.03的原理框图

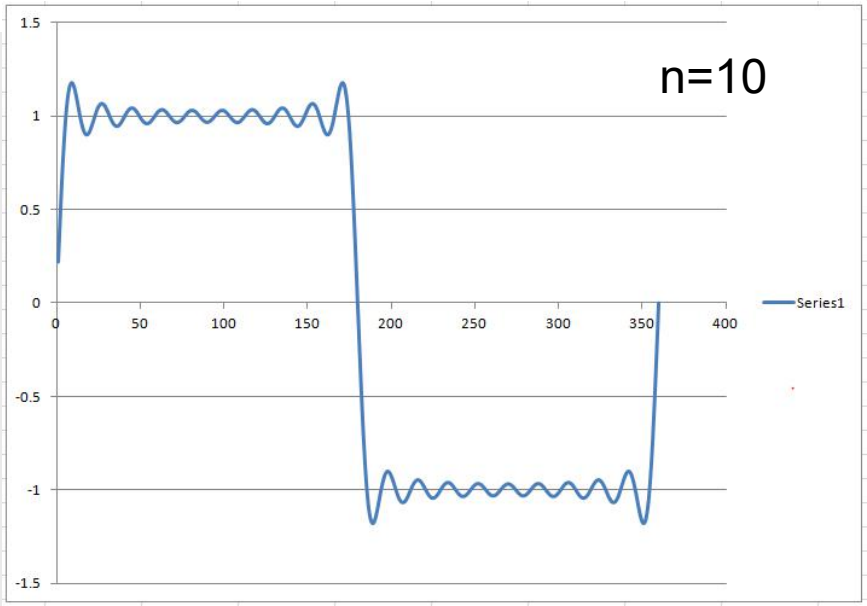
SIEMENS

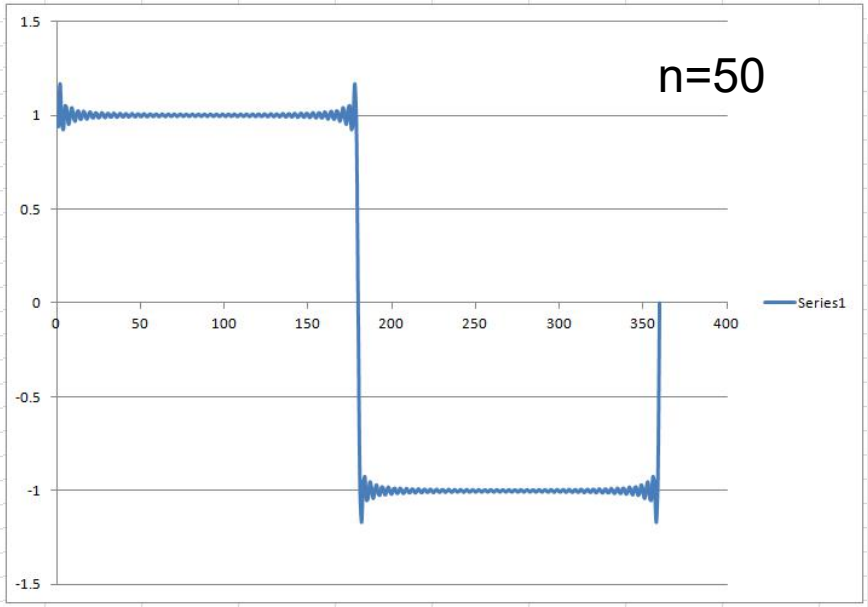


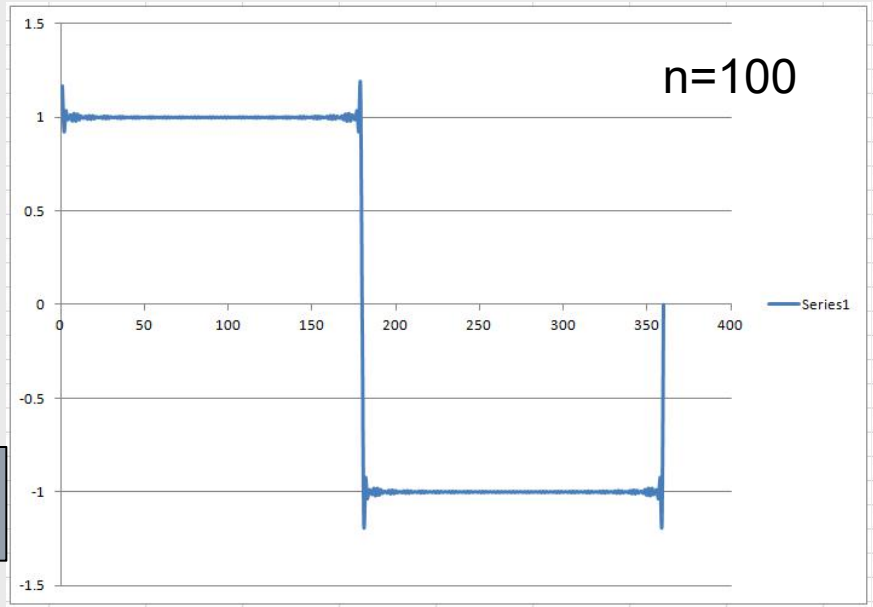
方波信号的富里叶级数

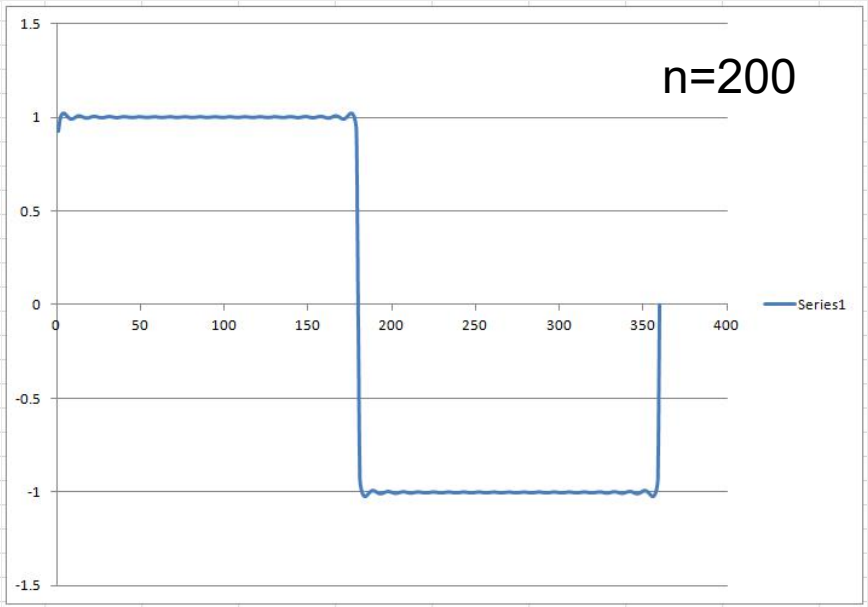
$$u(t) = \frac{4\hat{u}}{\pi}\left(sin(wt) + \frac{1}{3}sin(3wt) + \frac{1}{5}sin(5wt) + \ldots\right)$$

SIEMENS



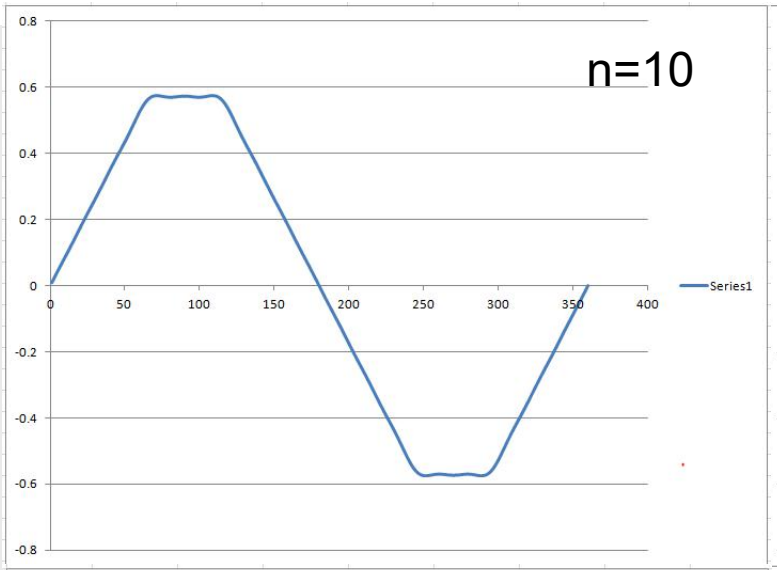


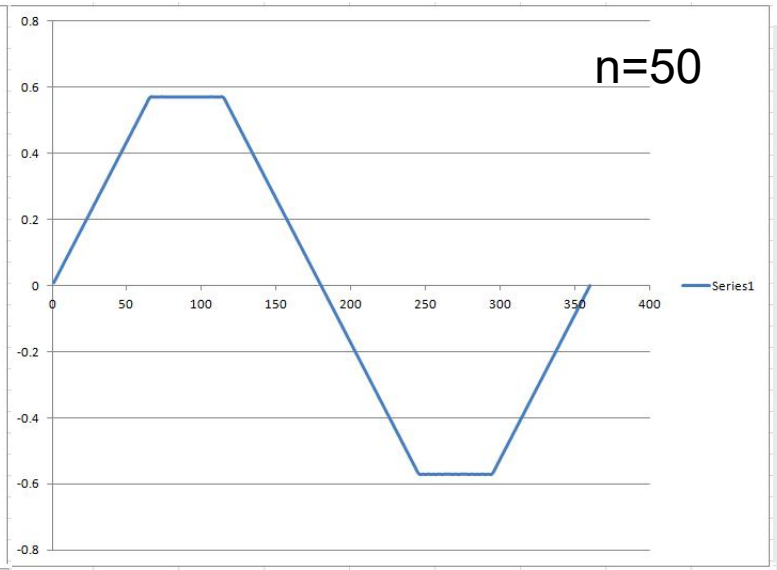


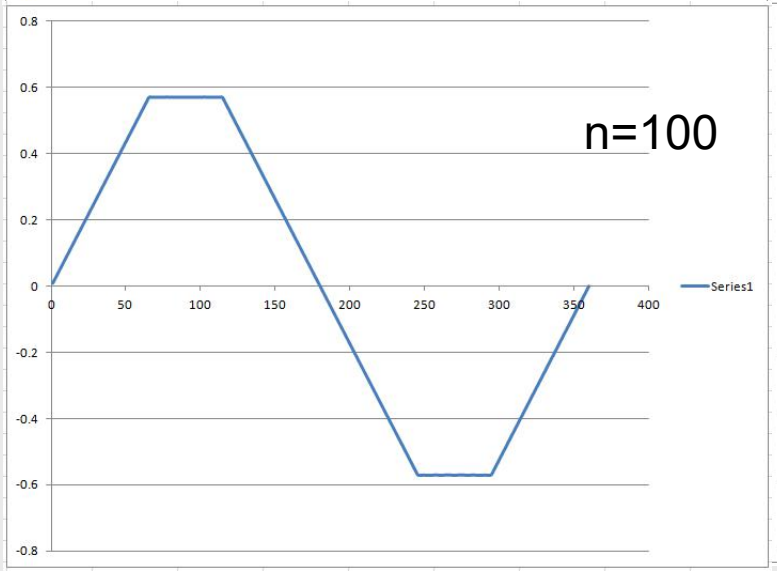


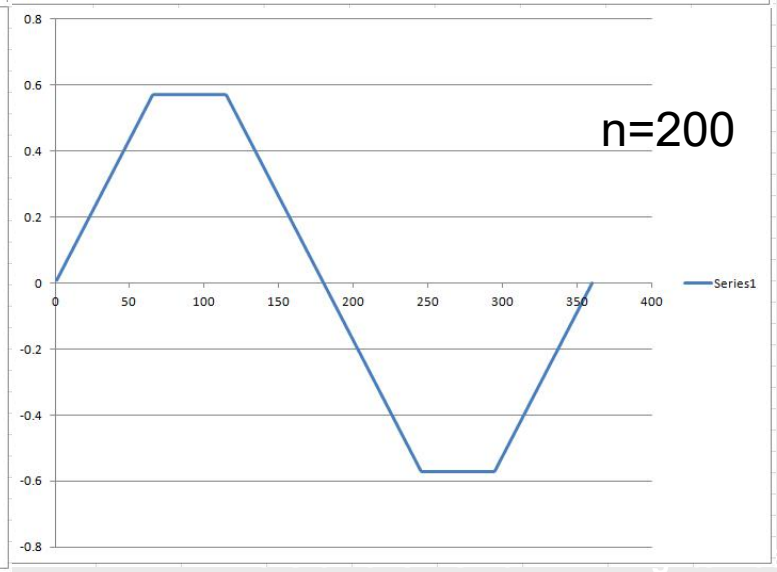
梯形波信号的富里叶级数

SIEMENS



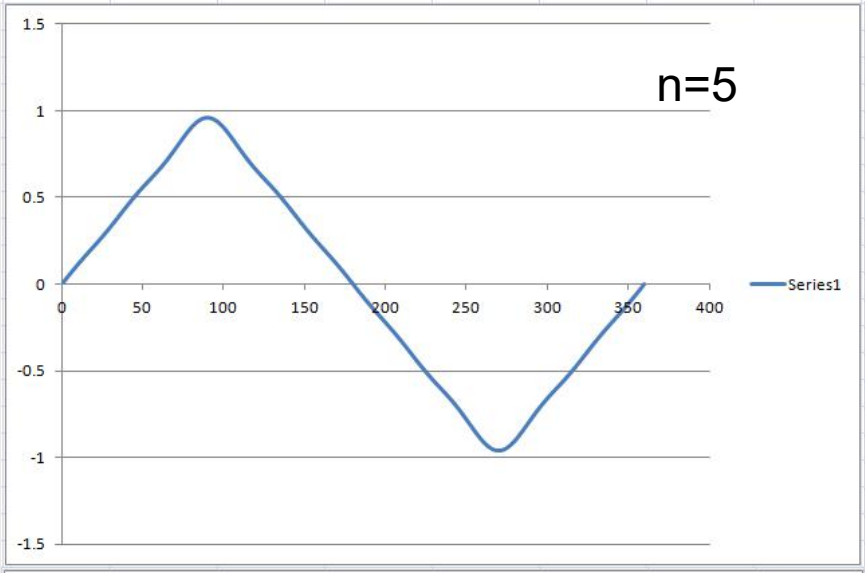


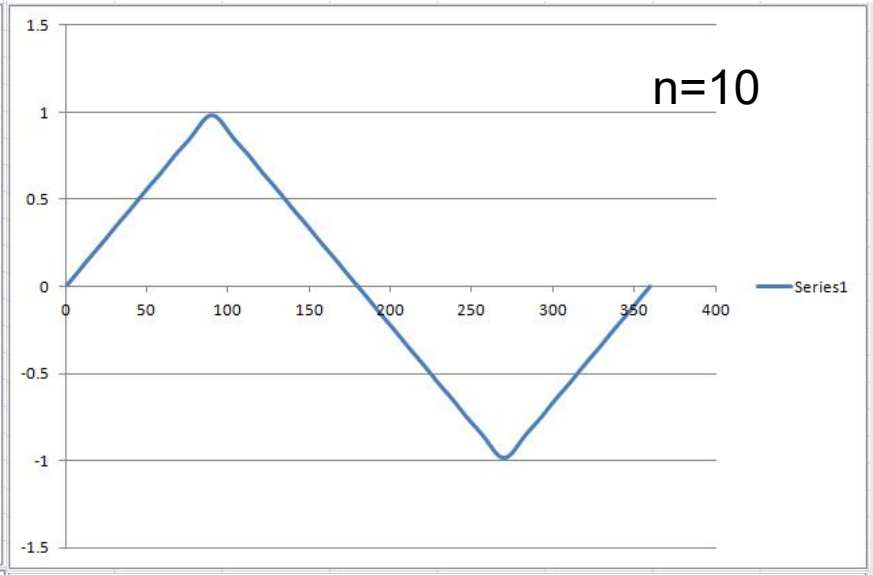


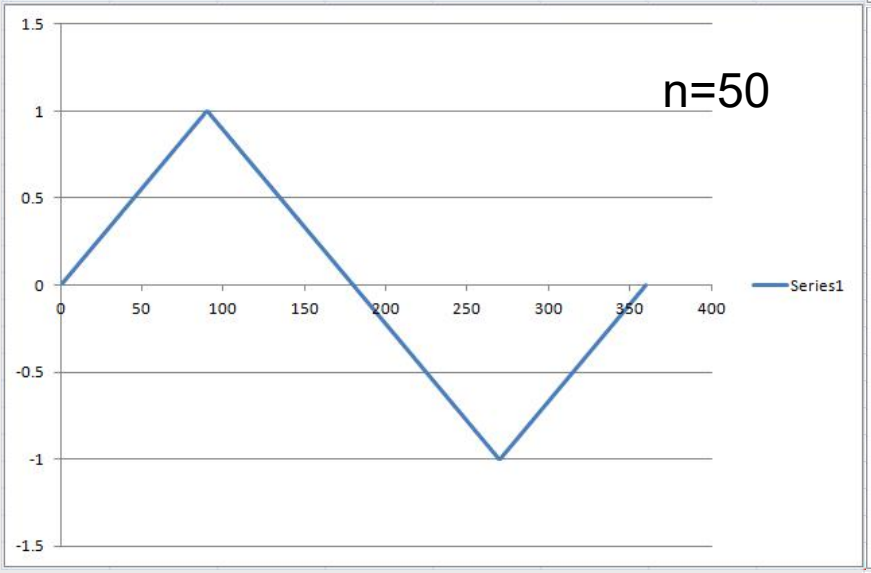


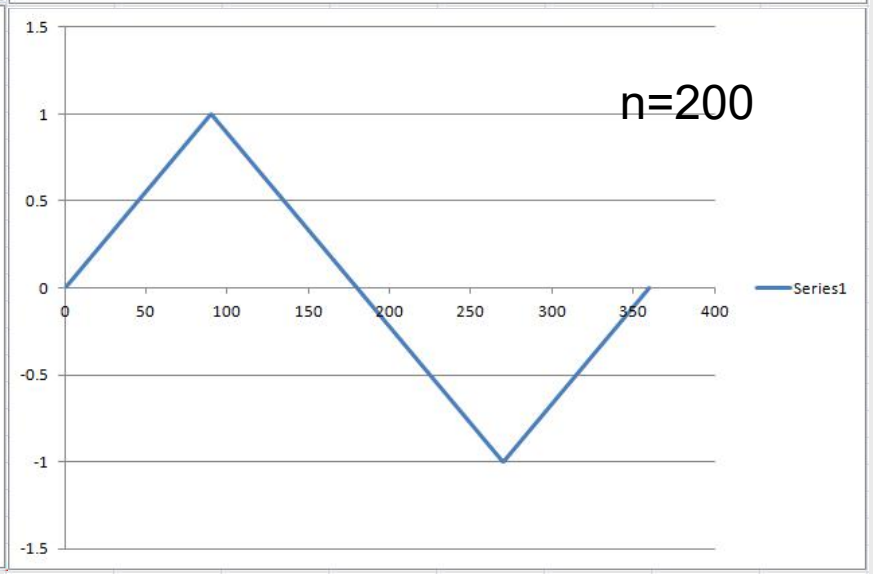
三角波信号的富里叶级数

SIEMENS



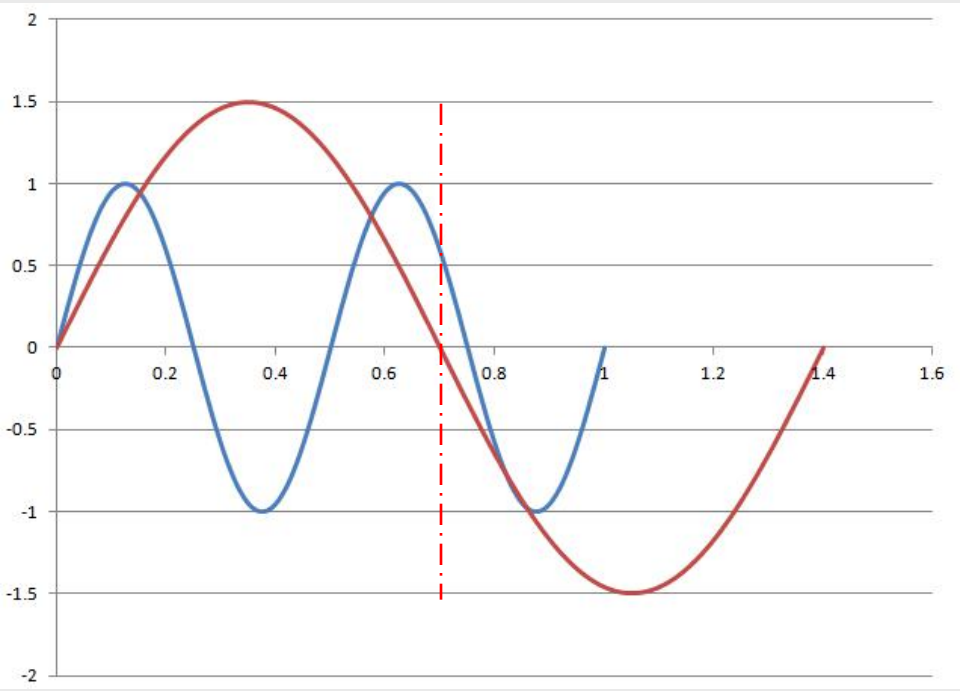


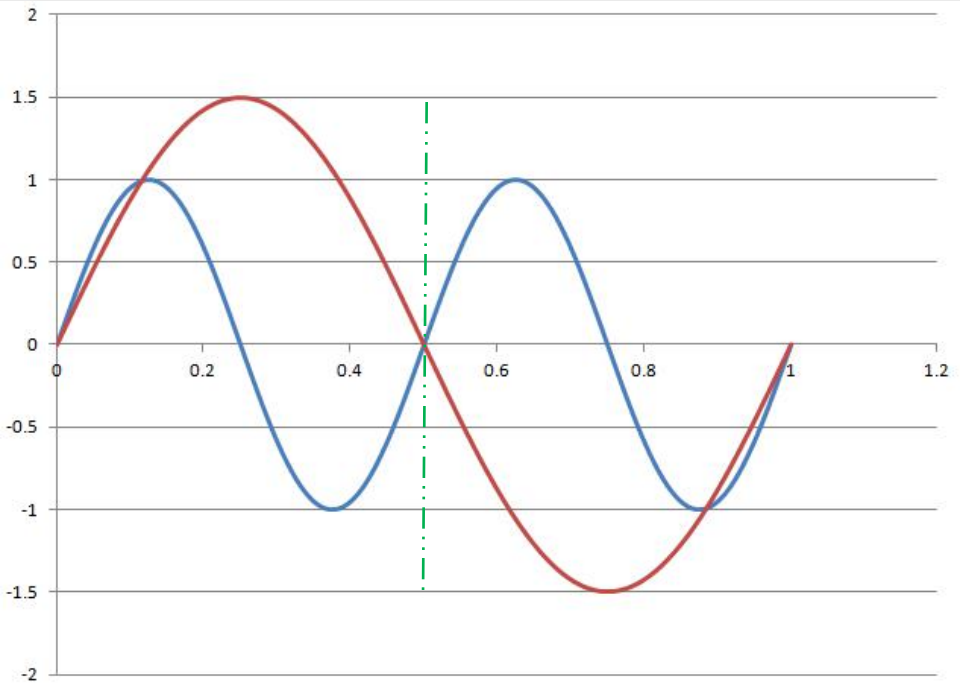




指令与固有频率

SIEMENS





$a = 1.5\ m/s^2$

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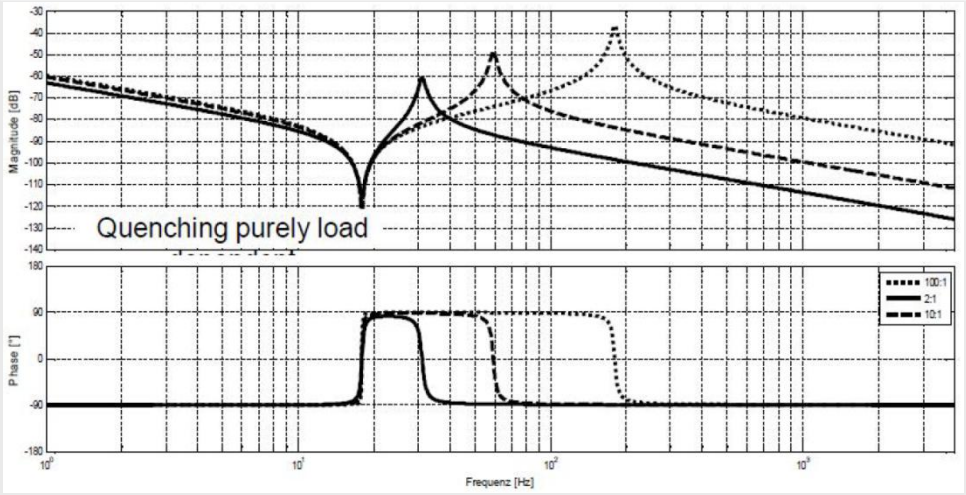
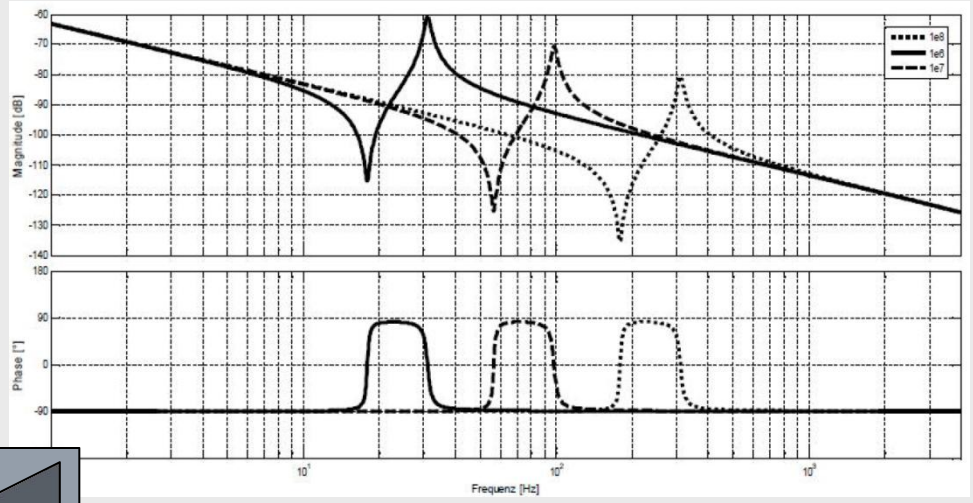
惯量与固有频率

SIEMENS



负载不变，减小电机惯量



惯量不变，改变刚性