Assignment: CD-tracking

1 Aim of this exercise

- The exercise aims at transferring some of the experience on the interaction between machine dynamics, control system design and the accuracy of high precision equipment.
- At the end of this exercise we expect that you will be capable to understand the effect that machine dynamics have on the controller design and the achieved accuracy in mechatronic systems. You will also understand that tuning/adjusting the “modal shapes” of vibration can help to improve system performance.
- In the conceptual design phase we use the following sequence:
  1 What are the system requirements?
  2 Which disturbing effect will occur?
  3 What conceptual specification results from this?
- As a carrier during this day we will look at the performance of a Compact-Disc lens actuator. The interaction between the required accuracy, the disturbing effects and concept design will be discussed.
- We will use a simulation environment (SimMechanics) designed to integrate the work from different disciplines in the conceptual design phase.

2 Introduction to Dynamics

2.1 Microscope

Let’s examine a simple example: With a camera and microscope we want to view details of a specimen. The smallest detail we want to image is 0.1 μm. The camera takes an image in about 1 second, and we must assure that during the exposure time, the variation of the relative position between the camera and the specimen doesn’t exceed our intended resolution. As can be seen in Figure 1, the specimen is fixed to a table, while the camera and microscope are put on a stand. If the stand were infinitely stiff, the camera and the specimen would always keep the same relative position. But this stiffness (indicated in Figure 1 by the spring connecting the stand to the camera) is limited, and it is our duty to ensure that it is high enough to cover our requirements.
A dominant disturbing effect is the vibration of the table. We might expect a suspension with natural frequency of about 5Hz. In typical environments amplitude of vibration at about 5 Hz of 10 μm can be expected. (Disturbing effect).

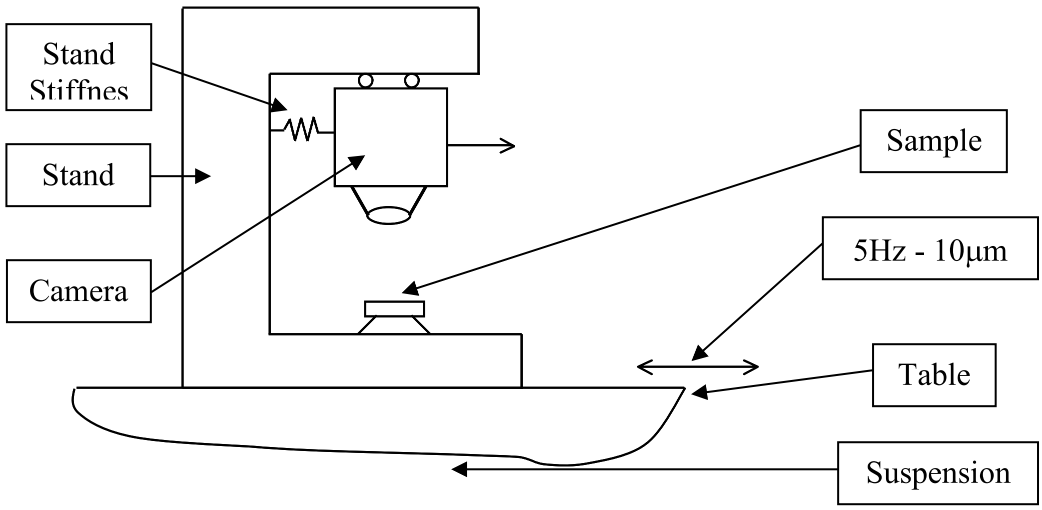


Figure 1 Microscope

Figure 2 shows a dynamic model of the system, where the table is moving at 5Hz - 10µm, and is transmitting this movement trough the spring to the microscope. The sensor on top is measuring the relative displacement, which we already noted must remain below 1µm.

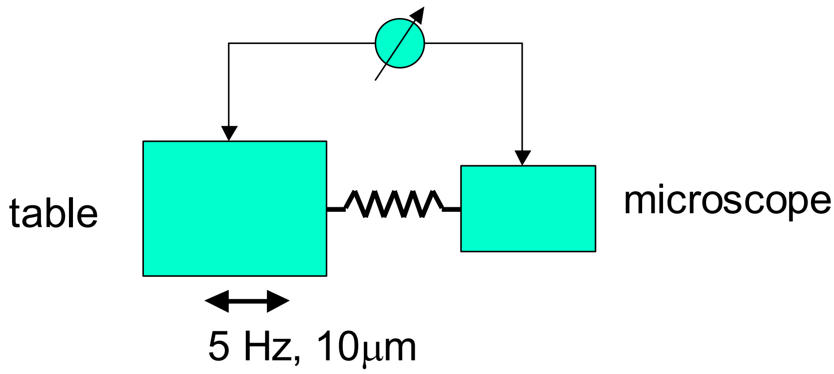


Figure 2 Dynamic model

If the microscope has a mass of 10 kg we can see that the peak accelerations and forces are:

$$acc_{peak} = (2\pi \cdot 5)^2 \cdot 10 \cdot 10^{-6} = 10 \cdot 10^{-3} m/s^2$$

$$F_{acc} = 10 \cdot 10 \cdot 10^{-3} = 0.1N$$

If the spring has a spring constant *c*, then the displacement of the camera relative to the specimen would be:

$$\Delta pos = \frac{F_{acc}}{c}$$

And since the requirement is that that displacement should remain smaller that 0.1 µm we get:

$$\Delta pos = \frac{F_{acc}}{c} < 1 \cdot 10^{-7} m$$

$$c > 1 \cdot 10^6 N/m$$

$$f_e = \frac{1}{2\pi}\sqrt{\frac{c}{m}} \cong 50Hz$$

In this case it turns out that a "conceptual specification" is that the stand/microscope combination must have a natural frequency of about 50 Hz, where low mass and high stiffness are usually preferable.

A simple design rule can be determined from this analysis for this particular kind of single mass systems. When the allowable error is very small relative to the disturbance amplitude,

$$acc_{peak} = (2\pi \cdot f_{dist})^2 \cdot dist$$
$$F_{acc} = m \cdot (2\pi \cdot f_{dist})^2 \cdot dist$$
$$c = \frac{F_{acc}}{error} = \frac{m \cdot (2\pi \cdot f_{dist})^2 \cdot dist}{error}$$
$$f_{eig} = \frac{1}{2\pi}\sqrt{\frac{\frac{m \cdot (2\pi \cdot f_{dist})^2 \cdot dist}{error}}{m}} = \sqrt{\frac{f_{dist}{}^2 \cdot dist}{error}}$$
$$\Rightarrow f_{eig}{}^2 = \frac{f_{dist}{}^2 \cdot dist}{error} \Rightarrow$$
$$\frac{dist}{error} = \left(\frac{f_{eig}}{f_{dist}}\right)^2 \qquad (1)$$

The ratio, error/dist, can be defined as the disturbance reduction factor.

2.2 CD PLAYER - SERVO STIFFNESS VERSUS MECHANICAL SPRING

In the CD-player case, the accuracy in the presence of disturbances is not achieved with a mechanical spring. In this case a control system is used. With a sensor the misalignment of the spot in the track is measured. Sending currents through the coil will lead to forces. A simple controller will create a force proportioned to the measured error.

In the regulator the movement of the disc should not lead to errors larger than 0.2 µm. The disc movements (caused by eccentricity of the hole in the disc) can be characterized as a 10 Hz movement (coming from the rotational speed of the music CD) with 200 µm amplitude and a vibration of the frame carrying the disc at 25 Hz with an amplitude of 200 µm. From a controller design standpoint the relation between error and disturbance is:

$$\frac{err}{dist} = \frac{1}{1 + \frac{Kp}{m \cdot s^2}} = \frac{1}{1 + H_O(s)} \qquad (2)$$

Here H_o is the open-loop transfer curve of the system and controller. At a frequency of 25Hz the ratio between error and disturbance must be better than 1:1000 in order to attenuate the 25Hz - 200 µm movement to the required 0.2 µm. Thus at this frequency the open-loop transfer, H_o, must be larger than 1000.

Assuming a simple model with a "-2-slope", this results in the following relation:

$$\frac{error}{dist} = \left(\frac{f_{dist}}{f_{BW}}\right)^2 \qquad (3)$$

And this expression is equivalent to expression (1) when f_{eig} is equivalent to f_{BW}. In the Dutch System design environment, based upon the work done at Philips and ASML, the term bandwidth is used in this sense. Here "Bandwidth" is defined as the unity-gain cross-over frequency.

2.3 STABILITY OF THE CONTROLLED SYSTEM

For those of you familiar to control design it will be clear that the feedback system we designed is not stable. In the "Bode-diagram" we can see that the "Phase-margin" at the 0-dB crossing is zero-degrees. To stabilize the system some damping can be added. In a controller this means the addition of a differential part. The combined system now uses a PD-controller.

3 Exercise

We will exercise these aspects in the design of a controller for the CD-player.
Construct the SimMechanics model following the description and the screenshots, and answer the subsequent questions.

Write a short report on your progress, referring to the assignment description by noting the section and question number, and collect all your weekly reports in one master report that is to be submitted before your oral exam.

The system consists of 2 masses, a small mass, m_1, equal to 1 gram representing the lens, and a larger mass, m_2, equal to 100 gram, representing the frame.

The spring-damper system that connects the frame to the fixed world and the perturbation signal has a 25Hz natural frequency, to represent the nature of the perturbations coming from shocks acting on the suspension.

The position of the lens, m_1, is measured relative to the disc in the frame, m_2, and with a force-actuator and a PD-controller its position can be controlled. The controller must assure that the position error remains smaller than 0.2 μm even when a shock-disturbance acts on the frame.

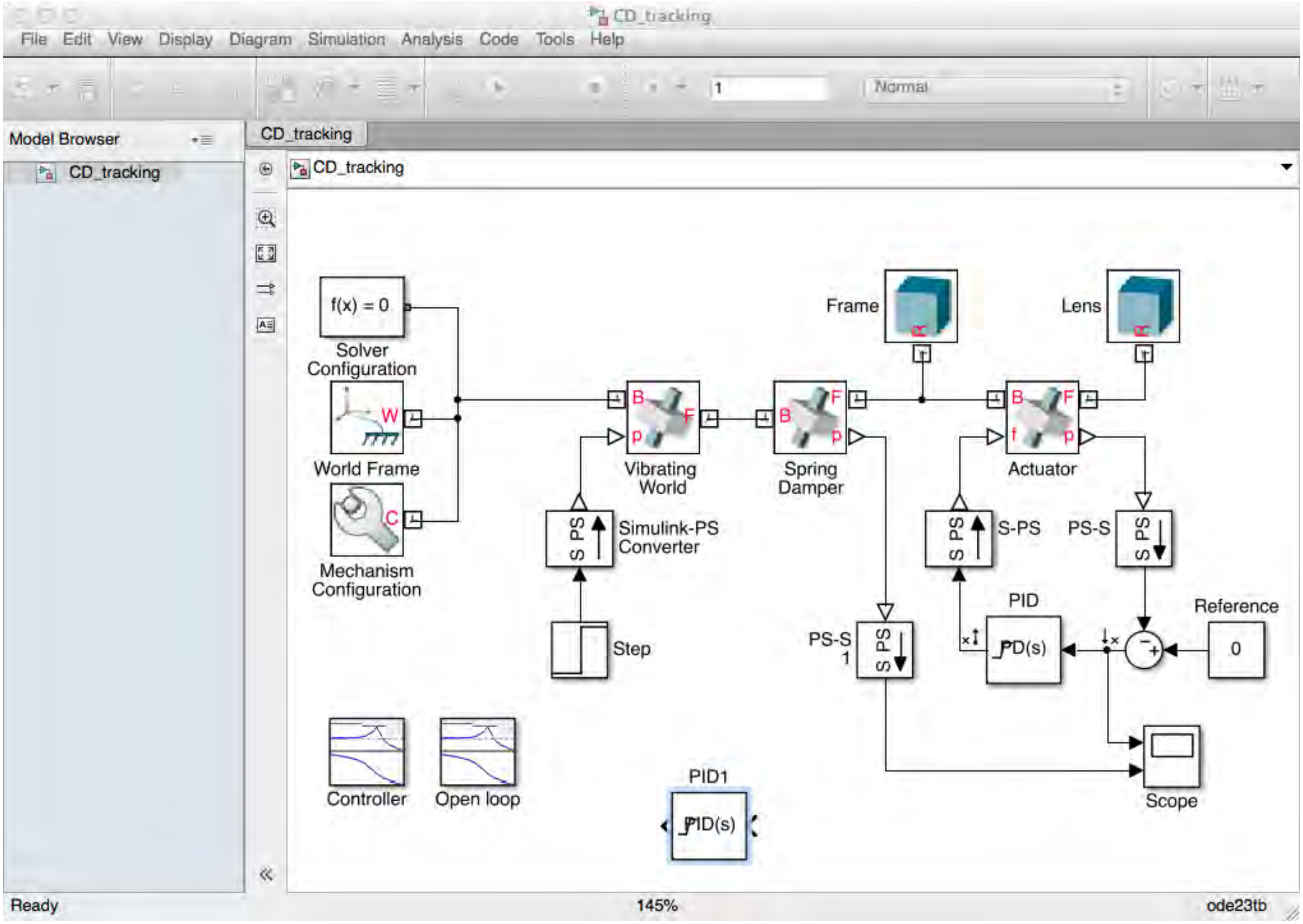
The frame is excited at t=0.1 sec. with a stepwise shift in position of 200 μm. As a result the frame will vibrate at about 25Hz and the lens (m_1) should follow the disc (m_2).

The system is presented on the next page.

Using the SimMechanics modeling package you will design the controller using the BODE-diagrams for the open-loop transfer curve. Parameters for the PD and PID controller-settings have to be determined.

1. Using equations (2) and (3), calculate the value of the proportional gain, K_p, to obtain the required open-loop gain at 25Hz.
2. Connect the controller to the system and set the proportional gain to 1. Set the controller to P-type. Observe the (open loop) Bode diagram from controller error to sensor output.
3. Verify the gain of the bode plot at 25Hz.
   You can also obtain the required K_p using this value. Please do so, and verify if the result is similar to the one obtained by your calculations in step 1. This is a useful empirical technique that you will need in other exercises.
4. Add the proportional gain, K_p, calculated in step 1 to obtain the required open-loop gain at 25Hz and observe the new bode plot.
5. Set the controller to PD-type and set the differentiating action to obtain sufficient phase-margin at the 0-dB crossing. The rule of thumb of using $f_d = \frac{f_{BW}}{3}$ and getting Td from there is usually a good

starting point, but your target is to locate the extra phase from the differentiation around the 0-dB crossing.



6 Due to the differentiating effect the 0-dB crossing has moved to higher frequencies. Reduce the gain K_p to make the frequency of 0-dB crossing back to the original value. Observe the Open Loop gain at 25 Hz. The rule of thumb of using $K_p^* = K_p/3$ is usually close.

7 To restore the required gain one can add “Integrating” action by using a PID controller. The rule of thumb of using $f_i = \frac{f_{BW}}{10}$ might be useful.

8 Observe the effects in BODE diagram.

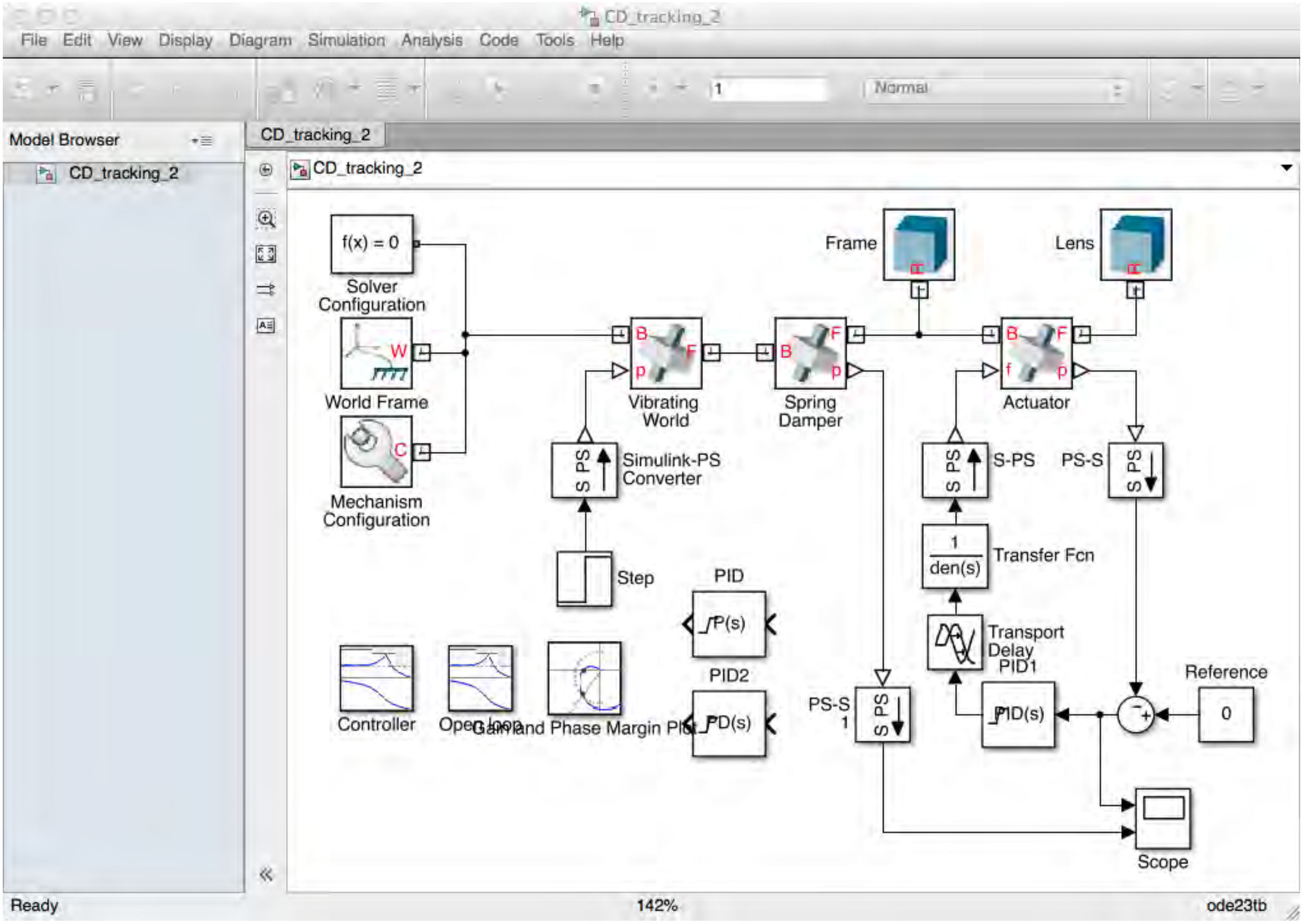
9 Check also the Nyquist plot. Zoom in the ([-1 1],[-1 1]) Right click on the graph and on Phase/Gain Margin, to see these values, and make sure your system is stable.

10 Run the time-simulator to see whether the error during the shock is effectively handled.

In this example all components are ideal. The mechanical system is just one free moving mass, the sensor and motor have ideal dynamics and the controller works in an infinite time. As a result one could apply a stable control system with infinitely high gains and thus Bandwidth.

In real systems this is clearly not the case. Limitations due to mechanical vibrations will be the main focus in this course. But we could also analyze the influence of limited motor dynamics and of delay in the controller on the maximum bandwidth that can be reached.

For this purpose we add a controller delay (2^{nd} order Pade approximation) and a limited motor bandwidth (low pass filter with transfer function $1/(1+\tau s)^2$) to our system.



Initially the values of the delay and bandwidth are set at 1μs and 50 kHz respectively.

13. Calculate the open-loop transfer for this system.
14. Set the low-pass filter frequency to 3 kHz and calculate the new open-loop. Compare the phase margin at the bandwidth. When a minimum margin of 35 degrees at 800 Hz is required how low can the bandwidth for the motor be set?
15. Reset the bandwidth to 50 kHz. Make the delay equal to 10μs and check the influence on the phase margin at 800 Hz. Create a controller with maximum bandwidth that has a phase margin larger than 35 degrees.