University of Utah
Electrical & Computer Engineering Department

ECE 3510 Lab 3

Second-Order System
(DC Motor Position Controller)

M. Bodson, A. Stolp, 1/30/06
rev 2/3/09, 2/1/17 Bhavana Mukunda, 1/29/18, 1/30/19

Note : Bring the lab-2 handout to use as a dSPACE tutorial. Bring your textbooks.

Objectives

- Build a position servo system using the dSPACE system.
- Observe second-order transient step responses for a critically damped and an underdamped system.
- Compare measurements to calculations.
- Observe the steady-state sinusoidal responses at many frequencies in order to create a frequency-response curve.
- Observe the transient response to a sinusoidal input.

Equipment and materials from stockroom:

- DC Permanent-magnet Motor (If you can, get the same-number motor you used last time)
- Dual Power Amp
- DSpace kit

dSPACE Control Desk Setup

Create a new folder in your 'X" drive or a thumb drive (let's call it "Kp_Control_DC_Motor"). This folder **MUST** be in some personal space of your own. Download the zip file named Kp_Control_DC_Motor from the lab website (currently: http://www.ece.utah.edu/~ece3510/ –> labs) and save in your new folder. Extract the files to this new folder.

- Start dSPACE ControlDesk (6.1).
- Create a new experiment, **File > New > Project + Experiment**
- Give the project a name, say ECE3510_lab3.
- Set the root directory as the folder you created earlier (X:\Kp_Control_DC_Motor in my case). **> next**
- Give the experiment a name, say ECE3510_lab3_exp. **> next**
- In the window, select the "DS1104 R&D Controller Board". **> next**
- **Import from file** Open the ECE3510_lab3.sdf **> Finish**
- Close the blank layout.
- Click on the **Layouting** tab and select "Import layout". Choose the ECE3510_lab3.lax.

Set up data recording

- On the left hand side of the big screen, click on the Measurement Configurations tab.
- Under Acquisition, expand Platform, right click on HostService, select "Measure Continuously (Disables Triggers)" and ensure that "Auto Repeat" is unchecked.
- Back to the Measurement Configurations tab, In "Recorders" section right click on "Recorder 1" and remove it. Right Click on "Recorders" then click on "Import Recorder". Choose "Recorder 1.xml" from the browser section > Open. Right click on Recorder 1 and

select Properties. Find the "Storage information". Under this section, check the "Automatic export" box. (You may edit the Automatic export: file name and data will be saved with the name you give and three digit count as suffix. We'll just leave it as "exp1".)

- In the Automatic export: folder line, use the browse button change the directory to your folder. (X:\Kp_Control_DC_Motor in my case)
- In the Automatic export: file type line, make sure to change the file type to .mat.
- Check the "Automatic save dialog" box.
- Under the Start Condition in the recorder properties, check the "Use start trigger" box.
- Click on the browse button to open the "Edit trigger rules" window. On the bottom left hand side, click on "Import". Find (I had to move up a couple of folders) the Trigger Rule 1.txt file > Open.
- Trigger delay, has been set to "-0.2" so the data will include data from 0.2 seconds before the trigger event.
- Under the Stop Condition, Type and TimeLimit should be set to TimeLimit and 2 seconds.
- Your data capture settings are now complete.

Experiment

Hook up the computer, dSPACE box, power amp, and motor as you did in the last lab. Refer to "Hardware Setup" in the handout. This time we will implement a position servo system similar to the crude servo you used in lab 1, just much better in quality.

The new layout for this lab is shown below. Look over the control screen (layout) of this new experiment and find the following: (You may have to resize the window)

1. The experiment ON and OFF buttons in the upper, left corner, labeled "simState".

2. The position display. It shows the angular position of the motor shaft in degrees. Go online and switch simState on and you can check the angular position readout manually. Turn the motor shaft ½ revolution and see how much the reading changes.
3. The velocity display. It shows the angular velocity of the motor shaft in degrees/second. Check for yourself by manually turning to motor shaft slowly and then again fast.
4. The RESET ENCODER button. You will have to click this before each run of the transient experiments to make sure the encoder begins at zero position for every execution.
5. The Input Signal Type section. Make sure that "Step Response" is selected.
6. A section titled "System Parameters" which only includes one parameter marked "Proportional Gain", k_p. Set this value to 2.09 and hit <Enter>. (If you forget to hit <Enter> it will go back to 0. All the data entry boxes are that way.) This "Proportional Gain" is what we simply called "Gain" on the crude servo. There it was controlled by a potentiometer and here by this number.
7. A section with three data entry boxes that control the input signal to the control loop. Think of it as the function generator that you hooked to the servo last week. Here the input signal is called the "reference" (Ref). When the Signal Type is set to "Step response" it will produce a step input to the servo. The step signal magnitude is set by "Ref. Magnitude (Degrees)". Set it to 0 (degrees). The step signal magnitude is relative to the zero encoder position– so you'll have to "Reset" the encoder between each run to zero the position sensor. The other two boxes are for the "Sinusoidal Response" only.
8. Two output graphs. The top one is the most important. It shows the reference and actual positions (in radians) vs time.

Make sure you are clear of the motor and then Turn on the power amp. Start triggered data capturing. Set "Ref. Magnitude (Degrees)" to 90 (degrees). When you hit <Enter>, the motor should turn 90° and stop. The data recorder should stop after 2 seconds and may ask you to confirm the file, don't save this time. The graphs should run for 2 seconds and the top graph should show the position change. Confirm the export of the data file if the experiment was executed in the right manner. **<u>Reduce the ref_magnitude to 0 and click on reset encoder until the theta_deg displays 0 (you may have to click this button more than once) before clicking on the OFF button to stop the experiment and then take the layout offline.</u>** You will have to follow this procedure every time you want to turn the experiment OFF. **<u>In general, make sure all the "Control loop inputs" are set to zero before hitting RESET ENCODER and turning the experiment OFF.</u>** Run the experiment a number of times with large degree numbers and without capturing the data to loosen up the motor and warm up the bearings.

Step Responses

Recall from the first lab how the gain affected the damping of the step response. In this lab you will use two gain (k_p) settings; 2.09 for critical damping and 10.5 for under damping, see the **appendix** for the calculations. (Yes, you can never actually set the gain to the exact number needed for critical damping, but it will be close enough for us.) If you have the same motor you used in lab 2 then you can use your own values of k and a to calculate the gain for critical damping and the gain to get a/b = ½ (the real part of the pole is ½ the imaginary part). If you calculate your own gains, then use those numbers in place of 2.09 and 10.5.

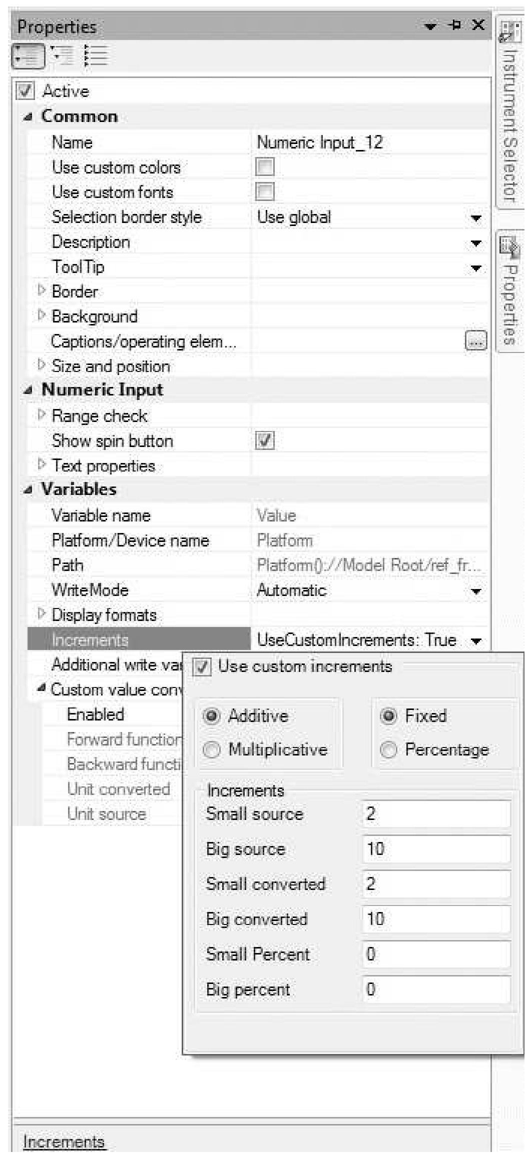
For the critically-damped case (k_p = 2.09), capture data of the step response for a 90 degree step. (Remember to check the step response input signal type, start the triggered data capturing, and ensure the theta_deg is at 0 before you start.) Check to see that a data file was created (>150kB). You may wish to check your data with a temporary plot in Matlab, using

Mat_Unpack. Later, you'll print finished plots, which will also include theoretical data.

Repeat for the under-damped case (k_p = 10.5). Make sure that the data graph shows ringing. Look in the appendix to see what the theoretical curves look like. Move your data into Matlab®. The rest of this section may be done after lab if you are short on time.

Next you will calculate and plot the theoretical step response of the system for k_p = 2.09. The Matlab® Control Toolbox function "step" may be used. You should check the help files for the functions "step()" and "tf()" to get the correct syntax. My appendix shows similar calculations and plots done in MathCAD and may help you. You may have to multiply your response by a factor because your step is 90 degrees, not a unit step. Now add your measured data on the same plot (you may find the "holdon" command useful here) and print it. Determine from the plot the values of the 10 -90% rise time for both curves (see curves in the appendix). Compare the curves, the rise times and steady-state errors.

Repeat this for the underdamped case (k_p = 10.5). Find the rise time, the 2% settling time, the percent overshoot and the frequency of oscillation of both curves. (To obtain the frequency of oscillation, you may estimate the half period as the time between the first peak (overshoot) and the second peak (undershoot)). Compare the curves and the values you found from the curves. Compare the frequency of oscillation to the imaginary part of the pole (b).



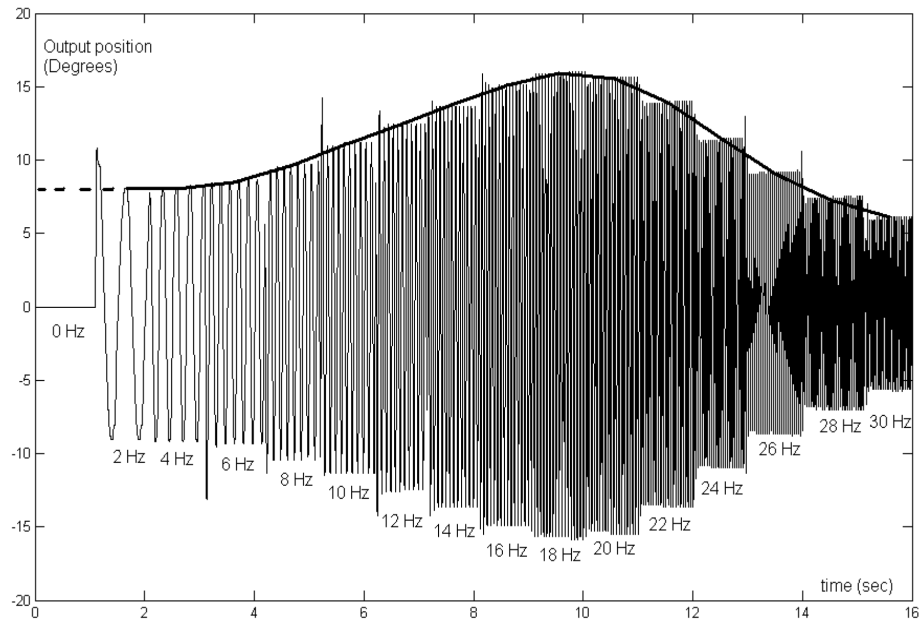
You should find that the measured overshoot and the frequency of oscillation are somewhat higher than calculated. That's because the calculations are based on a simplified version of the motor model which neglects the motor inductance, among other things. We'll consider the motor inductance in the next lab.

Sinusoidal Responses

For the remainder of this lab leave the gain (k_p) at 10.5 for under damping. The experiments in this section of the lab have a tendency to overheat the power amp. If you overheat the amp IC, that channel will shut down for quite a while. Occasionally feel the heat sink for the channel you are using to make sure the IC is not getting too hot. If one channel does shut down, move to the other channel and be more careful.

Change the Signal Type to "Sinusoidal Response" to get a sine wave reference input to the control loop. The amplitude is set by "Ref. Magnitude", set it to 10. The frequency is set by "Ref. Frequency (Hz)" and it should increment by 2 Hz each time you click on the up-arrow. (If it does not, right-click on it, select "Instrument properties" in the **Variables section > Increments** line > **UseCustomIncrements** dropdown list > check on **Use custom increments** box and change the Small source to 2 as shown at right). In the Recorder 1 properties, change the stop condition time limit to 16 seconds. This section of the experiment is also data intensive. Due to the sheer number of data points that are going to be processed, the layout may slow down so much so that it is entirely impossible to handle. At this point you will want to increase the downsampling from 1 to 10 (or more) in the HostService properties.

Now the next part is a bit tricky. What you want to do is run the motor at 0, 2, 4, 6, 8, 10, 12, 14, ... 30 Hz each for about 1 second. To do this, you first set the frequency to 0 Hz, then you click Run, then quickly move the mouse to the up-arrow button next to the frequency and hit it once every second (or as close as you can get). In the meantime you can watch an output plot like that shown on the next page appear on the screen. Be sure to stop the motor as soon as you're finished taking data or the power amp may overheat. To stop the motor, zero out the ref_freq and then the ref_magnitude, zero out the encoder and click on the OFF button. Then you may disengage the layout by going offline and turning off the amplifier.



Look at my figure to see if your data looks about right. Notice that the amplitude changes each time the frequency is changed. A plot of those amplitudes verses frequency is a frequency response curve. Mentally sketch a smooth line through the peaks at each frequency like my dark line on the plot. This gives you a rough idea of what the frequency response curve will look like. Look at my theoretical frequency response curve in the appendix for comparison. You may have to repeat this process more than once to get good data.

When you have data you are satisfied with, I want you to make a plot like mine. Plot in Matlab and add your frequencies and dark curve by hand. To get the frequencies, I just started from the left and counted the steps. Recall that the frequency changed in 2 Hz increments. Compare your plot to a theoretical frequency plot. You can compare to mine in the appendix, but I'd rather you make your own theoretical plot (The Matlab® function "freqs()" may be used for that purpose. With "freqs()", you will need to enter the frequencies in rad/s, but please label your plot in Hz.)

Compare the peak frequencies of the two plots and compare the magnitudes at the peaks. Most people find that the frequency and magnitude of peaking are both somewhat higher than theoretically expected.

Back in dSPACE, zoom in on your plot near the frequency of peaking, and look at both the input and output signals on the same graph. Estimate the phase lag of the frequency response. When I look at my theoretical phase plot, I see about 58° of phase lag at the frequency of peaking. How does your measurement compare?

Sinusoidal Transient

In this final experiment you'll look at the transient responses to cosine inputs that start abruptly. You may have already noticed these type of transients in the frequency response data when the frequency was changed from one value to another. My experimental data on the previous page shows significant transients at the 0 Hz to 2 Hz, 4 Hz to 6 Hz, and 8 Hz to 10 Hz transitions, among others.

Set the "Ref. Magnitude (Degrees)" to 50 (degrees), the "Ref. Frequency" to 50 Hz, and the "Ref. Phase" to 0. In the data capture section, change the length back to 0.5 seconds in the Recorder 1 stop condition and the downsampling to 20. You don't need to create data files but it is advised in order to spot the transients.

With the input signal type set to sinusoidal response, kp set to 10.5, hit "start triggered recording" and then ON. Once the data is captured, zero out the ref_freq and then ref_magnitude before resetting the encoder and hitting the OFF button. Observe that there is a transient at the beginning of the waveform and about how big that transient is. Remember in class that I said that a cosine wave makes a significant step at t = 0 whereas a sine wave does not, so you would expect a smaller transient if you started with a Refphase of +90 (degrees). Try that now. Be sure to hit Reset before you hit Run or it will start differently every time. Is the transient smaller now? Try again at several different phases to see if you can find the phase that produces the smallest transient.

Conclusion

Check - off and conclude as always.

ECE 3510 Second_Order lab, Position Control Appendix

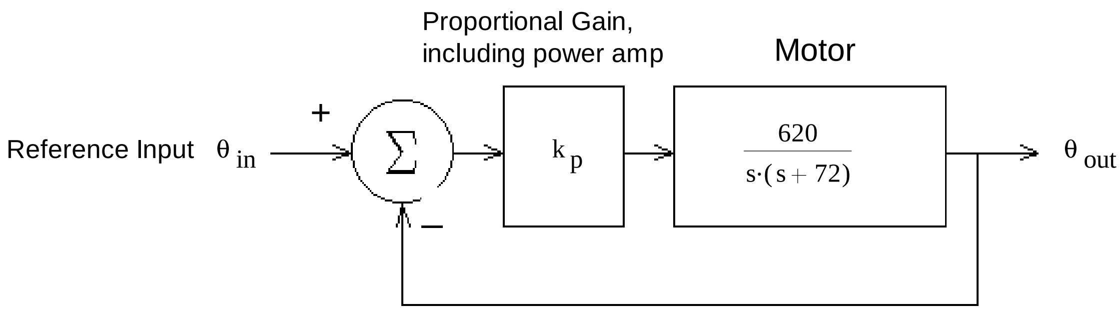
A.Stolp
1/29/06
rev1/31/19

Simplified motor transfer function (Without inductance, L_a): $\frac{\theta(s)}{V_a(s)} = \frac{k}{s\cdot(s+a)}$

From the first lab you should have found the constants k and a to be approximately: $k := 620$ $a := 72$

Now this motor is part of a control loop:

The system block diagram



Overall transfer function: $H(s) = \frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{k_p\cdot\left[\frac{620}{s\cdot(s+72)}\right]}{1+k_p\cdot\left[\frac{620}{s\cdot(s+72)}\right]\cdot 1} = \frac{k_p\cdot 620}{s\cdot(s+72)+k_p\cdot 620}$

$$= \frac{k_p\cdot 620}{s^2+72\cdot s+k_p\cdot 620}$$

For critical damping: $72^2 - 4\cdot(k_p\cdot 620) = 0$

$5184 = 2480\cdot k_p$ $\qquad k_p := \frac{5184}{2480} \qquad k_p = 2.09$

Input step: $90\cdot deg \qquad X(s) = \frac{90}{s}$

Step response: $Y(s) = X(s)\cdot H(s) = \frac{90}{s}\cdot\frac{k_p\cdot 620}{s\cdot(s+72)+k_p\cdot 620} = \frac{90}{s}\cdot\frac{2.09\cdot 620}{s^2+72\cdot s+2.09\cdot 620}$

$s^2 + 2\cdot a'\cdot s + \left(a'^2 + b^2\right) \qquad a' := \frac{a}{2} \qquad a = 72$

$b := 0$

$= \frac{90}{s}\cdot\frac{2.09\cdot 620}{(s+36)^2} = \frac{90\cdot 2.09\cdot 620}{s\cdot(s+36)^2} \qquad 90\cdot H(0) = \frac{90\cdot 2.09\cdot 620}{36^2} = 90$

$= \frac{90}{s} + \frac{B}{(s+36)} + \frac{C}{(s+36)^2}$

$90\cdot 2.09\cdot 620 = 90\cdot(s+36)^2 + B\cdot s\cdot(s+36) + C\cdot s$

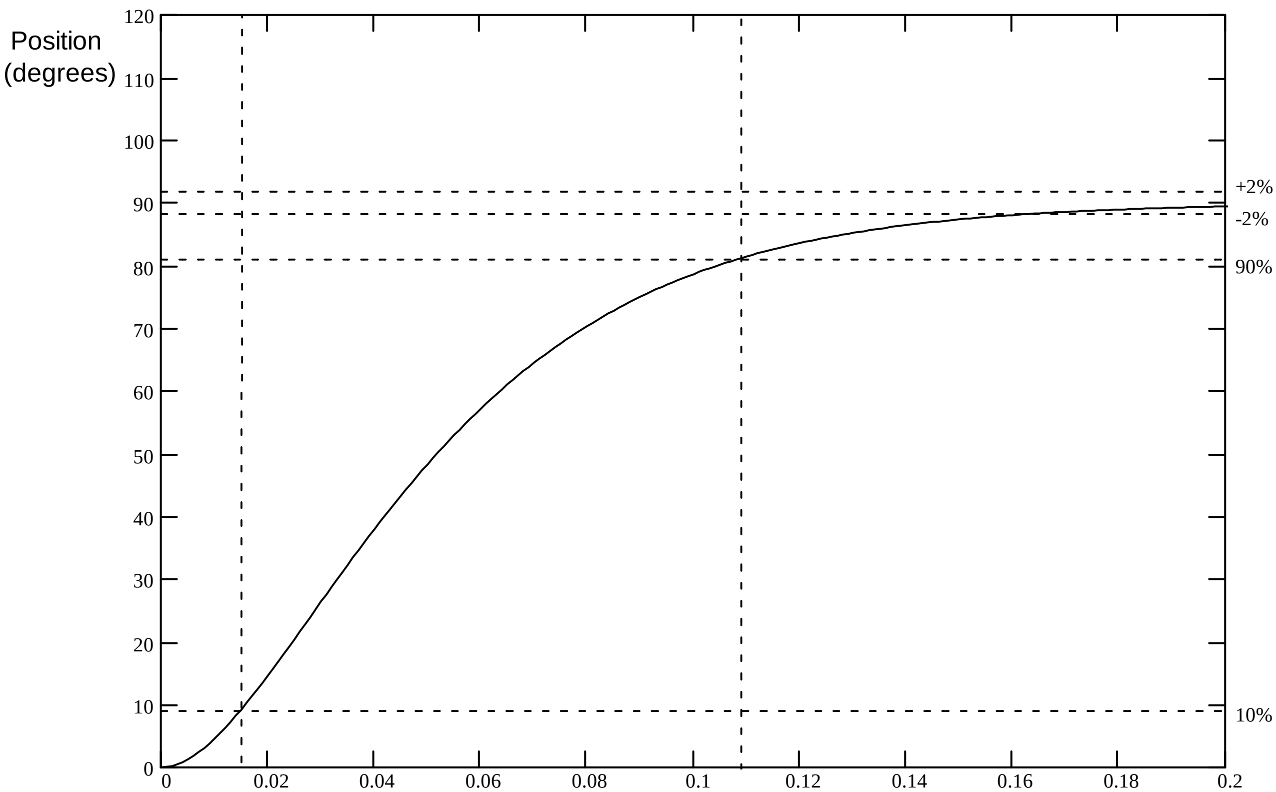
let $s := -36$

$90\cdot 2.09\cdot 620 = 0 + 0 + C\cdot(-36) \qquad C = \frac{90\cdot 2.09\cdot 620}{-36} = -3240$

$90\cdot 2.09\cdot 620 = 90\cdot s^2 + 9\cdot s + 90\cdot 2.09\cdot 620 + B\cdot s^2 + B\cdot 36\cdot s - 3240\cdot s$

$B := -90$

$y_{cd}(t) := 90 - 90\cdot e^{-36.\cdot t} - 3240\cdot t\cdot e^{-36.\cdot t}$



<--------- rise time 10% to 90% ---------> sec

$$Y(s) = X(s)\cdot H(s) = \frac{90}{s}\cdot\frac{k_p\cdot 620}{s^2 + 72\cdot s + k_p\cdot 620}$$

For under damping: $s^2 + 72\cdot s + k_p\cdot 620 = (s + a')^2 + b^2 = s^2 + 2\cdot a'\cdot s + a'^2 + b^2$

Choose imaginary part at twice the real part: $\frac{a'}{b} = \frac{1}{2}$ in eq. 3.37 in text $b := 72$

$$a'^2 + b^2 = 36^2 + 72^2 = 6480 = k_p\cdot 620$$

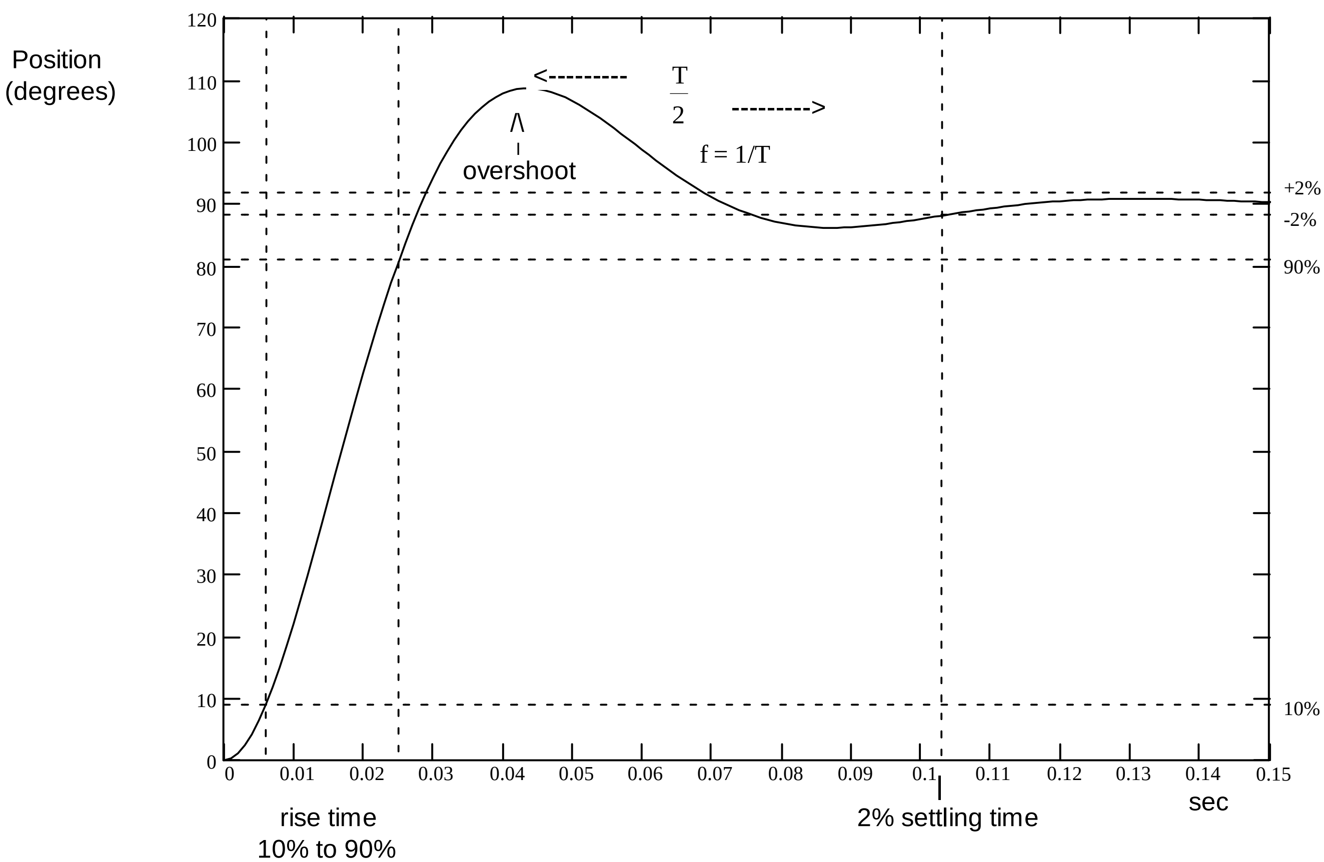
$$k_p := \frac{6480}{620} \qquad k_p = 10.452$$

Damping factor: $\zeta = \frac{a'}{\sqrt{a'^2 + b^2}} = 0.447$

Input step: $90\cdot deg = 1.571\,\bullet rad$ $\qquad X(s) = \frac{90}{s}$

Step response: $Y(s) = X(s)\cdot H(s) = \frac{90}{s}\cdot\frac{10.45\cdot 620}{(s + 36)^2 + 72^2}$ $\qquad x_m\cdot H(0) = \frac{90\cdot 10.45\cdot 620}{(0 + 36)^2 + 72^2} = 90$

$$y(t) := 90 - 90\cdot e^{-36\cdot t}\cdot\cos(72\cdot t) - 90\cdot\frac{36}{72}\cdot e^{-36\cdot t}\cdot\sin(72\cdot t)$$ From eq. 3.37



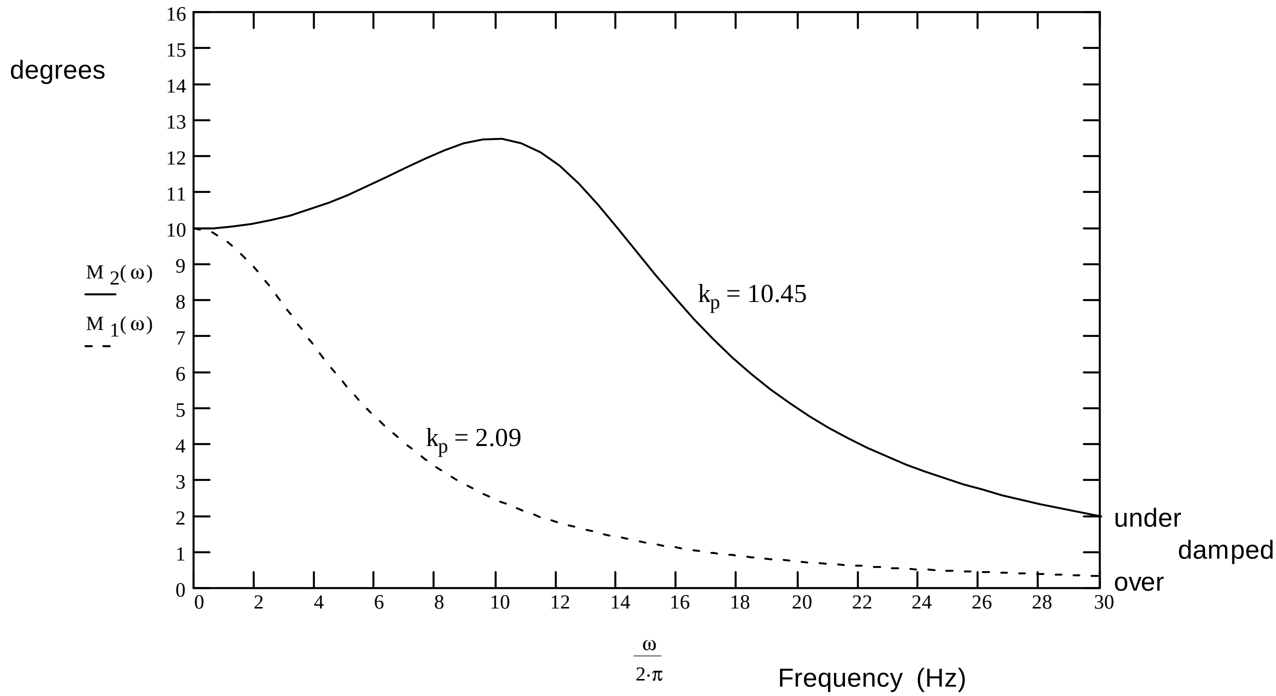
Frequency Response Curves

$k_p := 2.09$ $\quad M_1(\omega) := \left| \frac{10 \cdot k_p \cdot 620}{-\omega^2 + 72 \cdot j \cdot \omega + k_p \cdot 620} \right|$ $\quad \text{Phase}_1(\omega) := \arg\left(\frac{k_p \cdot 620}{-\omega^2 + 72 \cdot j \cdot \omega + k_p \cdot 620} \right)$

$k_p := 10.45$ $\quad M_2(\omega) := \left| \frac{10 \cdot k_p \cdot 620}{-\omega^2 + 72 \cdot j \cdot \omega + k_p \cdot 620} \right|$ $\quad \text{Phase}_2(\omega) := \arg\left(\frac{k_p \cdot 620}{-\omega^2 + 72 \cdot j \cdot \omega + k_p \cdot 620} \right)$

(Note that I used 10 rather than 90 degrees input magnitude)

Magnitude of the Transfer function



Phase of the Transfer function