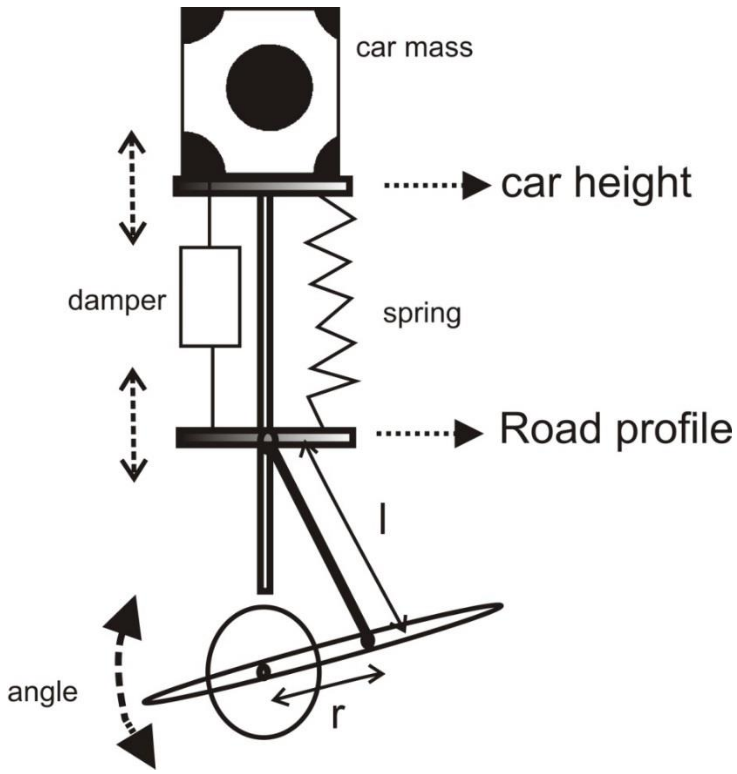
Time Domain Analysis of a Mass, Spring, Damper System

Ben Taylor



Learning Outcomes

Produce	Describe how a simple non-linear system can be linearized for small changes about an operating point.
Practical	Calculate simple performance characteristics based on a step response plot.
Practical	Calculate the Mean Absolute Error of a system response, compared to that of a desired reference.

Time Domain Analysis of a Mass, Spring, Damper System: Pre-experiment Activity

A pre-experimental activity must be completed before starting this experiment. Failure to complete these tasks may result in being refused entry into the laboratory.

1 Aims and Objectives

The aim of this exercise is to measure the performance characteristics of an oscillatory system, in this case a mass spring damper system, and observe the effects of changing the physical system parameters.

During the pre-laboratory exercises, you will calculate the system performance characteristics for a simulated system. You will then derive the transfer function of different mass spring damper systems, and observe how the rotary crank system can be linearized for small rotational angles. Finally, you will discuss across which range of angles this linear approximation remains valid.

During the laboratory session, you will observe the effects that changing the three parameters of: spring stiffness, damping coefficient, and system mass, has on the step response characteristics of the system. Finally, you will observe the reaction of the system to road profile, and calculate the Mean Absolute Error of the mass position, compared to the road profile input.

2 Feedback and Marking

Before the start of pre-laboratory activities and laboratory sessions, you should review any feedback you have been provided from previous pre-laboratory/laboratory activities, and reflect on how this feedback could help improve your performance during these activities.

At the start of the laboratory session, your pre-laboratory will be marked, and you will be provided some verbal feedback on your work. The teaching staff will write your mark into the back of your pre-laboratory session, but it is your responsibility to record any verbal feedback provided, either in the space provided at the back of the worksheet or in another space where you can use it to reflect on your laboratory activities.

During the course of the laboratory session your laboratory work will be periodically checked by a number of different teaching staff, and verbal feedback will be provided on your performance in the laboratory session. Again, it is your responsibility to record the verbal feedback provided, in a similar manner to the pre-laboratory feedback.

Verbal feedback will be provided as part of the informal discussions you have with the laboratory teaching staff during the marking of your work. It is your responsibility to recognise when feedback is being provided and record any useful comments made during this discussion

After the laboratory session, you should review the feedback provided, reflect on this, and other feedback, to improve your performance for future activities.

3 Background

The experimental Mass Spring Damper system that you will be using during this laboratory exercise is designed to emulate the behaviour of a car suspension system. The suspension and car are represented by two linked plates, which can move independently up and down a slide rail, as illustrated in Figure 1. The lower plate represents the profile of the road and the upper plate represents the car body. The two plates are linked by a spring and a damper and the upper plate carries a mass to represent the weight of the car.

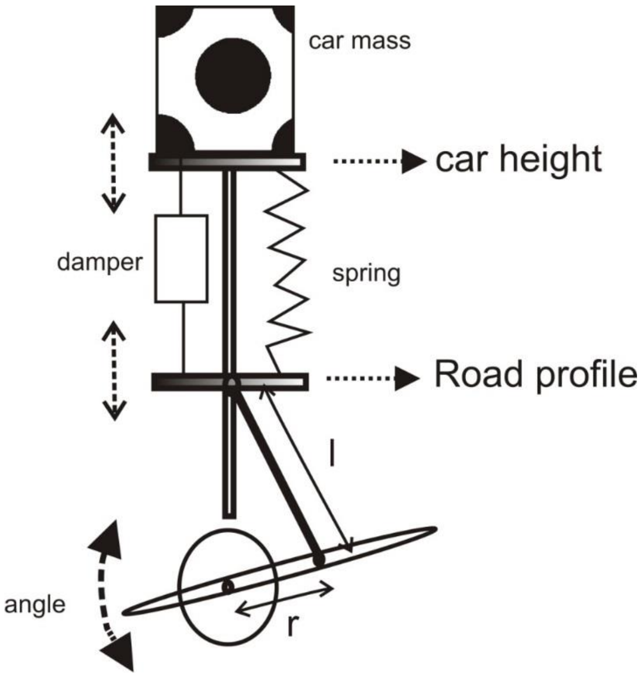


Figure 1. Illustration of the Mass Spring Damper system.

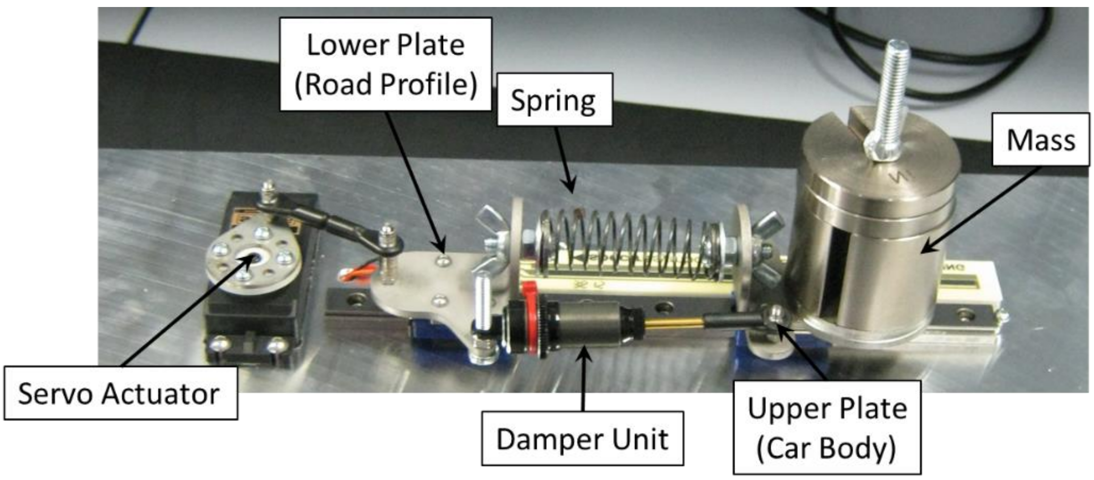


Figure 2. Picture of the Mass Spring Damper assembly used in the laboratory experiments

The lower plate or road profile is delivered via two arms, one of length ‘r’ and one of length ‘l’. The arm of length ‘r’ is rotated directly by a high gain servo through an angle as marked in the figure (typically no more variation than about plus or minus 30-40 degrees). As this arm rotates, it drives the link of length 'l' which moves the lower plate directly. The position of the mass is measured by a magnetically coupled potentiometer. Figure 2 shows a photograph of the experimental Mass Spring Damper assembly, with the main components identified.

It should be noted that the experimental system operates in the horizontal plane, as shown in Figure 2, and not vertically, as implied from Figure 1. This is to simplify the system analysis, by removing the system disturbance effects of gravity acting on the system Mass. The free body diagram for the experimental system is shown in Figure 6.

3.1 Typical system response parameters

When designing and analysing a control system, system response characteristics are used to describe the desired and observed system behaviour. The response characteristic, shown in Figure 3, shows the output response of a system to a step input, (step occurs at t=0, and has a magnitude of 1), and illustrates a number of the standard performance metrics often provided for control system design.

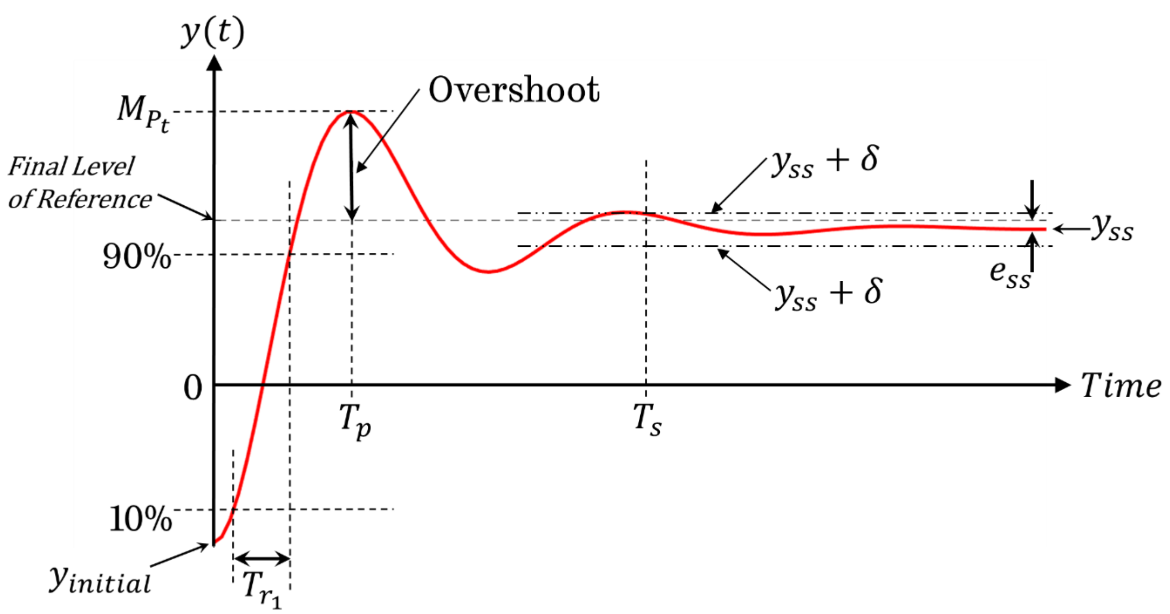


Figure 3. Normalised step response of characteristic, illustrating a of performance specification parameters

Where: $y_{initial}$ is the initial output signal value before the step input, y_{ss} is the steady state output value of the system, M_{P_t} is the maximum peak value of the overshoot, and e_{ss} is the steady-state error between y_{ss} and the final level of the reference signal, as illustrated in Figure 3.

Three of the standard performance metrics often specified for oscillatory systems are:

- **Percentage overshoot, P.O.:** the percentage of the steady-state output level, from the initial level, that the output of the system overshoots by, in response to a step input, before steeling back to its steady state level. For the response shown in Figure 3, this would be:

$$P.O. = \frac{M_{P_t} - y_{ss}}{y_{ss} - y_{initial}} \times 100\%$$ ***Equation 1***

- **Settling time, T_s:** is defined as the time for the system to settle within 2% of its steady-state value, after the initial step, i.e. $y_{ss} \pm 2\% \times (y_{ss} - y_{initial})$
- **Rise Time, T_{r_1}:** is defined at the time for the system step response to rise between 10% and 90% of the steady-state output value, from the initial value, as illustrated in Figure 3 . (In the case of Figure 3, the initial value is zero – this will not be the case for the experimental system).

4 Pre-Laboratory Exercises

Pre-Lab Q1: For this step response characteristic of a suspension system, shown in Figure 4, calculate the three performance parameters: Percentage Overshoot, Settling Time and Rise time, as discussed in section 3.1.

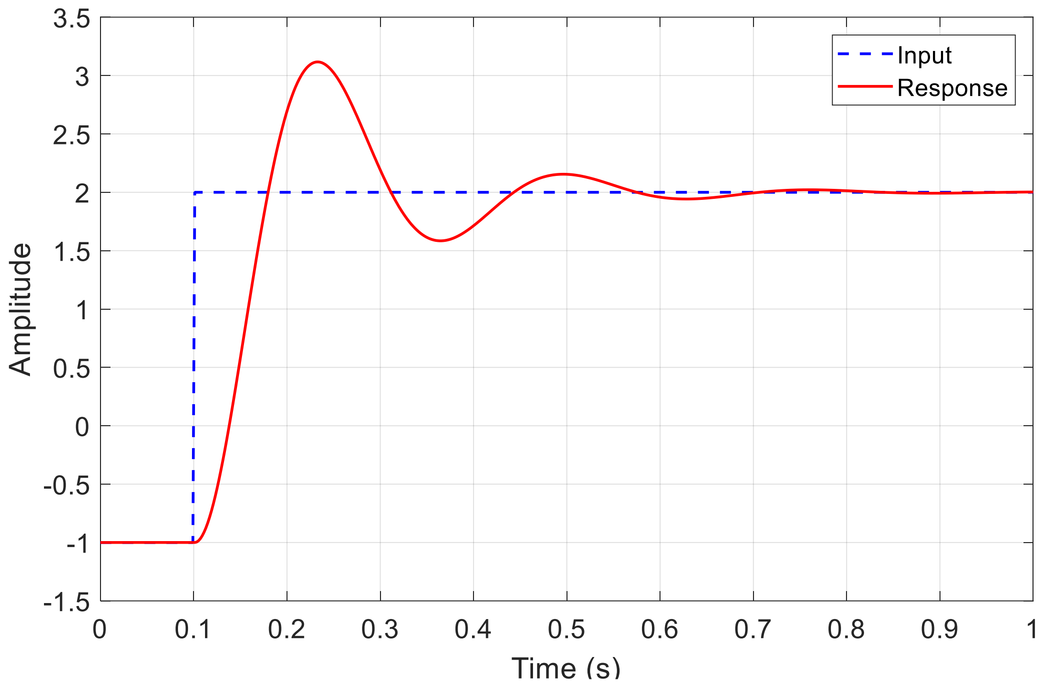


Figure 4. System step response for a suspension system

Parameter:	Value:
Percentage Overshoot (%)	
Settling Time (s)	
Rise Time (s)	
Use the area provided for your answer and any necessary calculations:	

Use extra paper if needed

Figure 5 illustrates a mass, spring, damper system, where: F_{IN} is the input force to the system operating in the X-direction, F_M is the inertial force of the mass, F_D is the resistance force of the damper, and F_S is the elastic force of the spring.

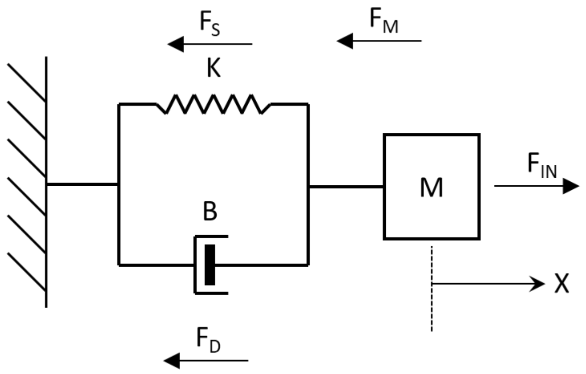


Figure 5. A free body diagram of a simple mass, spring, damper, illustrating force vectors acting on the system.

Where: X is the displacement of the Mass, M, K is the spring coefficient, and B is the damping coefficient of the damper.

The Force balance equation for the system, shown in Figure 5 is:

$$F_{IN} = F_S + F_D + F_M$$

Pre-Lab Q2. Complete the table below and, in the space provided, derive the transfer function of the system, showing your working.

Force Component	**Differential Equation**		**Laplace Transform**
F_S		⇔	
F_D		⇔	
F_M		⇔	

Use the area provided for your answer and any necessary calculations:
Use extra paper if needed

The free body diagram, shown in Figure 6, describes the in-lab experimental mass, spring, damper system, shown in Figure 2.

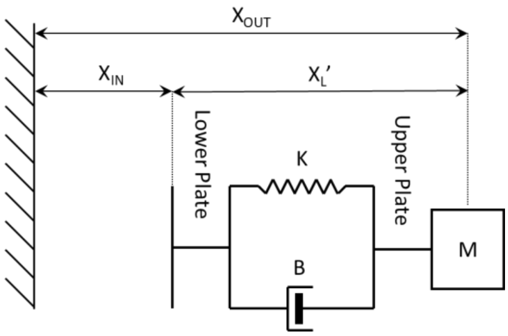


Figure 6. Free body diagram of the experimental mass, sprint, damper system.

Where: X_{IN} is the Lower plate position, X_{OUT} is the upper plate position, and X_L' is the separation distance between the lower and upper plates, such that:

$$X_{OUT} = X_{IN} + X_L' \qquad\qquad X_L' = X_{L_0} + \Delta X_L$$

Where: X_{L_0} is the natural separation distance between the lower and upper plate when the spring force is zero, i.e. $F_S = 0$, and ΔX_L is the change spring length when a force is applied to the lower or upper plate. The three force components of the system now become:

$$F_S = X_L' K$$

$$F_D = \frac{dX_L'}{dt} B$$

$$F_M = \frac{dX_{OUT}}{dt^2} M$$

If a displacement is applied to the lower plate, then the force balance equation becomes:

$$F_S + F_D + F_M = 0$$

Pre-Lab Q3. In the space provided below, derive the system transfer function for the mass, sprint, damper system, illustrated in Figure 6, for an input displacement X_{IN} and an output displacement X_{OUT}. (**Hint:** *To simplify the solution, assume natural separation distance* $X_{L_0} = 0$*.)*

Use the area provided for your answer and any necessary calculations: Use extra paper if needed

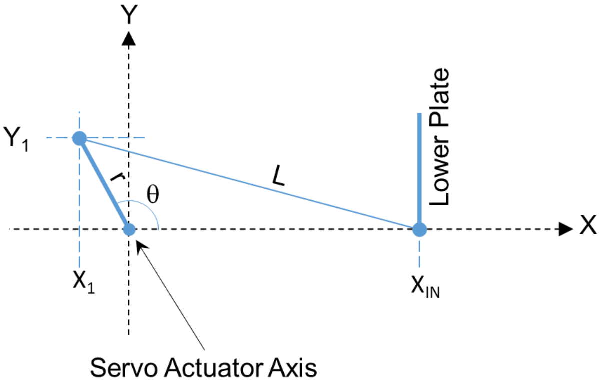


Figure 7. Diagram of the crank linkages, between the servo and the lower plate

Figure 7 illustrates the crank arm and crank linkage between the servo actuator and the lower plate of the mass, spring, damper system. The crank arm should be considered to be of length r, the crank linkage of length L, similar to that shown in Figure 1. The axis of the servo actuator is located at the origin of the X-Y plane, $(0, 0)$. The angle between the horizontal reference plane and the crank arm is θ, and the lower plate is free to move in the horizontal, X-plane.

Pre-Lab Q4. Using the space provided below, derive an equation for the displacement of the lower plate (the road profile), X_{IN}, with respect to the angle of rotation of the servo, θ.

Note: Just copying the solution from the next question is not acceptable; marks will only be awarded for a derived solution.

(**Hint:** you can start by solving the position (X_1, Y_1), then you can use Pythagoras's theorem to help solve the lower plate position, X_{IN})

Use the area provided for your answer and any necessary calculations:
Use extra paper if needed

Example of Taylor Series Linearisation to Simplify Modelling and Analysis: A solution for the relationship between the lower plate position, X_{IN}, and angle of rotation of the servo, θ, as described in Figure 7, is shown below:

$$X_{IN} = \sqrt{L^2 - (r\sin\theta)^2} + r\cos\theta$$

Note: This next section is covered in ACS133 lecture material further towards the end of the teaching semester, but has been included as an example of system linearisation, to simplify system modelling and analysis. You are not expected to perform the linearisation as part of this activity, but it has been included for example of how it can be used, future reference.

A Taylor series approximation can be used to approximate a linear relationship between the rotational angle of the servo and the displacement of the lower plate. This approximation is only valid for small deviations of the servo angle around the operating point, $\bar{\theta} = {}^{\pi}/_{2}\, rads$:

$$f(\theta)\Big|_{\bar{\theta}} \approx f(\bar{\theta}) + \frac{df(\theta)}{d\theta}\bigg|_{\bar{\theta}} (\theta - \bar{\theta})$$

Note: you must work in radians for this type of calculation, because the numerical solution does no work correctly in degrees.

A complete solution for this for this derivation is provided in the Blackboard folder for this activity. The final solution for this linearisation, around the operating point, $\bar{\theta} = {}^{\pi}/_{2}\, rads$ becomes:

$$f(\theta)\Big|_{\bar{\theta}} \approx \sqrt{L^2 - r^2} - r\left(\theta - {}^{\pi}/_{2}\right)$$

Therefore:

$$X_{IN} \approx \sqrt{L^2 - r^2} - r\left(\theta - {}^{\pi}/_{2}\right)$$

For small deviations of θ round the operating point, $\bar{\theta} = {}^{\pi}/_{2}\, rads$

Pre-Lab Q5. If the crank arm length is r=20mm, and the crank linkage length is L=49mm, then use MATLAB to plot the following two traces, on the same axes:

- The linearized solution for X_{in} against servo angle, θ, provided in the example, above.
- The non-linear solution, (provided in the example, above).

You should plot your graph for a servo angle range of $\theta = 0 \rightarrow \pi$

(**Remember**, your graph should have a title, x-axis label, y-axis label and a plot legend, and your graph should be plotted in radians.)

You should bring a copy of your MATLAB Script and graph to lab session.

Pre-lab Q6. In the space provided, briefly discuss how the graph plotted in ***Pre-lab Q5*** demonstrates that the output response can be approximated as a linear relationship. Using your 'Engineering Judgement' and your graph, from ***Pre-lab Q5***, discuss over which range this approximation can be justified.

(**Note:** As part of your argument for this question, you may annotate your graph from ***Pre-lab Q5***, but must also provide some written argument.)

Use the area provided for your answer and any necessary calculations: Use extra paper if needed

<table>
<tr><th colspan="4">This space is provided to record the marks you have been allocated for the pre-lab exercises.</th></tr>
<tr><td colspan="2">Pre-Lab Q1.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Pre-Lab Q2.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Pre-Lab Q3.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Pre-Lab Q4.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Pre-Lab Q5.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Pre-Lab Q6.</td><td>2 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td colspan="2">Total Pre-Lab Mark:</td><td>12 Marks</td><td>Enter Mark Here:</td></tr>
<tr><td>The Pass Mark for the Pre-Lab Assessment:</td><td>7 Marks</td><td>Assessment Outcome:</td><td>Pass / Fail</td></tr>
</table>

Note: *The Pass Mark for the Pre-Laboratory has been set at approximately 60% at the time of printing - this may be subject to change. If the pass mark has changed from 60%, then this will be indicated in the Blackboard folder for the experiment.*

Date:

Time Domain Analysis of a Mass, Spring, Damper System: Experimental Record

This section is to be completed during the experiment. It must be marked by a lab academic, teaching technician or lab demonstrator before leaving the laboratory.

1 Aims and Objectives

The aim of this exercise is to measure the performance characteristics of an oscillatory system, in this case a Mass Spring Damper system, and observe the effects of changing the physical system parameters.

During the laboratory session, you will observe the effects that changing the three parameters of: Spring stiffness, damping coefficient, and system mass, has on the step response characteristics of the system. Finally, you will observe the reaction of the system to road profile, and calculate the Mean Absolute Error of the mass position, compared to the road profile input.

2 Names of collaborators for the experiment

Use this space to record the member of the group you are conducting the experiment with.

Name of Lab partner(s)	Lab Desk Number

3 Equipment

During this laboratory exercise, you will be working with the Mass Spring Damper, described in the introduction to the pre-laboratory section. Before starting the exercises, you will need to download the LabVIEW project for the experiment and connect the unit to the ELVIS system.

3.1 Downloading the LabVIEW Software for use in this Laboratory Session

Before starting this laboratory session, you will need to download the LabVIEW project, and expand it into your University network file storage, (U-drive). To achieve this, you will need to follow the following steps:

1. If you don’t already have a directory called ‘LabVIEW Labs’ folder in your U-Drive root, please create one.
2. From the Blackboard site for this laboratory session, download the LabVIEW code for this laboratory session, and **expand** the .ZIP file into your ‘LabVIEW Labs’ folder. (You must expand the .ZIP file into you project folder, because the LabVIEW Vis will not operate

correctly from within a compressed .ZIP file.)

3. Launch LabVIEW, by navigating into the ‘Time Domain MSD Lab’ folder, that was created when you expanded the .ZIP file, and double clicking on the ‘Main - Time Domain MSD.vi’.

This should start LabVIEW and automatically load the VI that you will be using later in the laboratory session.

3.2 Starting and Stopping the LabVIEW Program

To run the program press the button located towards the top left of the front panel. If the button is showing, this means that the program is already running. Please use the big red STOP button, STOP , on the front panel to stop the execution of the program, **NOT** the abort button, , located beside the run code arrow, . A screen shot of the LabVIEW software is provided in Figure 8

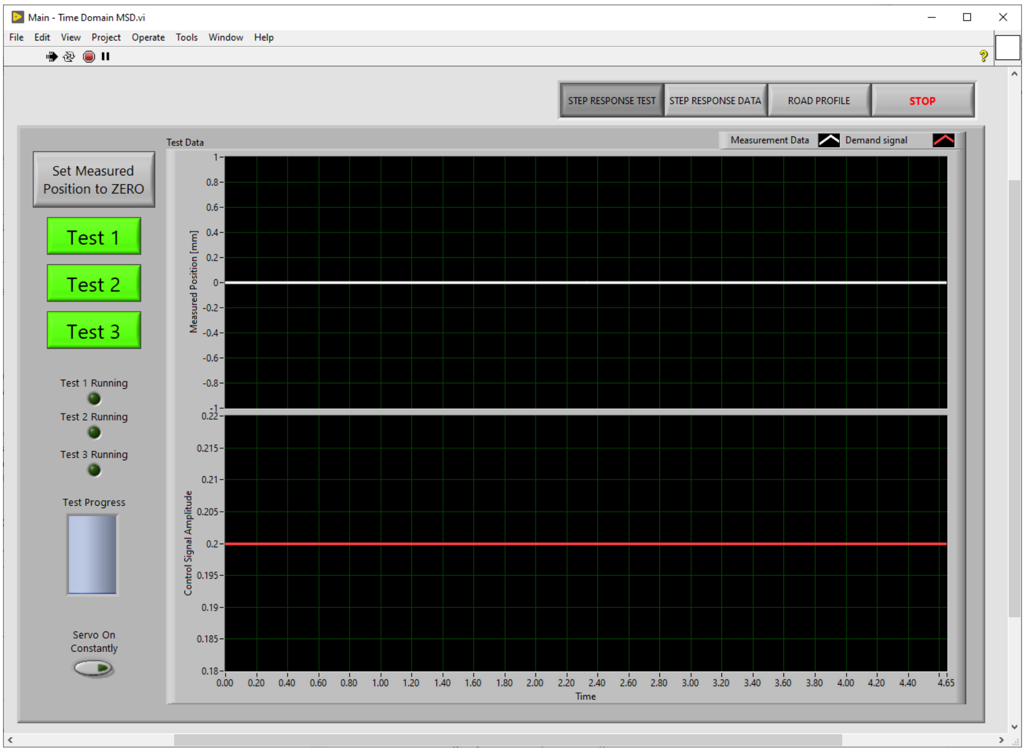


Figure 8. Screen shot of the LabVIEW software

3.3 Connections to the Interface board

The Mass Spring Damper, MSD, system is controlled using a National Instruments ELVIS II+ multifunctional data acquisition platform, with the Diamond’s custom made Control Equipment Interface Board.

To connect the MSD system to the Control Equipment Interface Board, you will need to use the two cables illustrated in Figure 9. The Beige Cable can be found in the Control Equipment Cables box that can be found in the middle “Equipment” cupboard, under the desk

(a)

(b)

Figure 9. (a)The Beige 5-pin DIN Cable, (b) The Red 5-pin DIN Cable

The connections to the equipment should be made as follows:

1. **Beige 5-pin DIN Cable**, shown in Figure 9a: Connect one end of this cable to the **Encoder 2** channel on the Control Equipment Interface Board, shown in Figure 10,, and the other end into the silver DIN socket, Marked **E2** on the end of the Mass Spring Damper unit, shown in Figure 11.
2. **Red 5-pin DIN Cable**, shown in Figure 9b: Connect one end of this cable to the **Encoder 1** channel on the Control Equipment Interface Board, shown in Figure 10, and the other end into the Red DIN socket, Marked **E1** on the end of the Mass Spring Damper unit, shown in Figure 11.

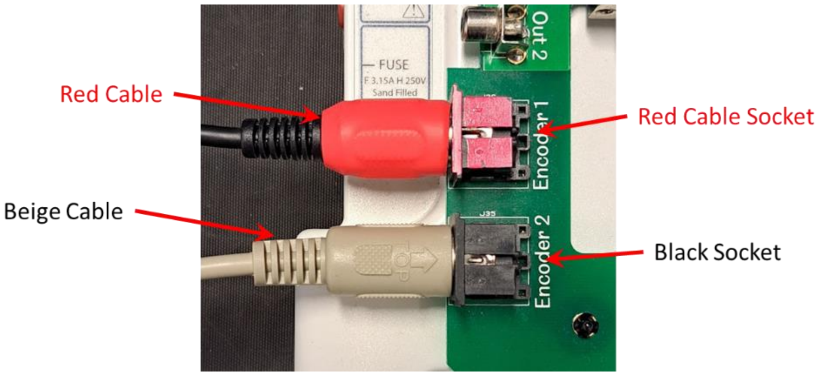
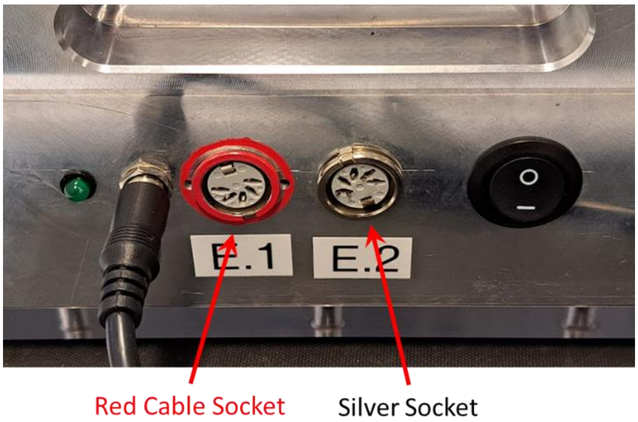
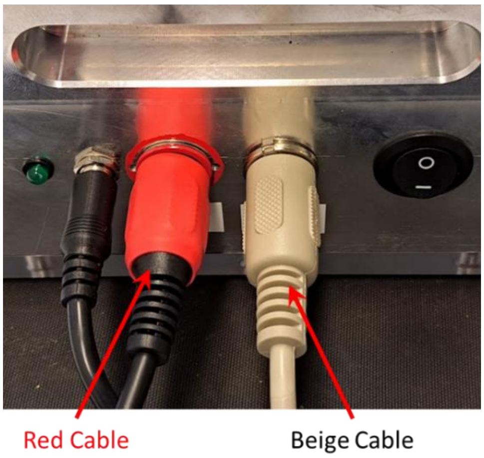


Figure 10. Connections into the Control Equipment Interface Board



(a)



(b)

Figure 11. Connections into the Mass Spring Damper Unit

Before connecting the cables, please ensure that the MSD unit is switched off, i.e. the power switch is in the ‘0’ position, and the green LED, on the end of the unit, is not illuminated.

Ensure also that the ELVIS unit is switched-on, using the switch at the back of the unit, **AND** the Control Equipment Interface Board is switched-on, using the switch in the top of the unit.

3.4 The Springs

There are four different springs that can be used with the mass spring damper, each with a different spring constant, as illustrated in Table 1.

Spring End Colour	Spring Number (Written on Tag)	Tag Colour	Spring Constant (lbs/in)	Spring Constant (N/m)
Green	1	Brown	1.6	280
Red	2	Red	2	350
Orange	3	Orange	3	525

Table 1. Different springs available for this experiment, describing identifying markers and spring constants

The springs are attached to front face of each platform, by pushing the threaded ends of the spring through the hole, and fastening it in place with a smaller wing nut.

3.5 The Additional Dampers

The friction present between the upper platform bearing and the guide rail provides the system with certain amount of damping.

There are two additional damping elements that can be added to the system. The first element is a light damper, and provides a small amount of additional damping to the system; this is marked with a yellow cable tie. The damping element marked with the red cable tie, will provide considerably stronger damping to the system.

When attaching the dampers to the system, please ensure that they are fully slotted onto the correct studs.

3.6 The Masses

Additional Masses can be added to the upper platform of the Mass, Spring, Damper system, as described in Table 2.

Text Marker on the Mass	Mass (Kg)	Number of units available
1N	Approx. 0.100	5
5N	Approx. 0.500	1

Table 2. Table describing the available masses for the experiment

When attaching the masses to the upper platform stud, please ensure that you have fastened then down using the larger wing nut provided, and that there is a washer between the wing nut and the masses.

4 Laboratory Exercises

During the laboratory exercises you will observe the changes in the step response characteristics of the system due to changes in the mass, spring and damping parameters of the system. Finally, in the last experiment you will operate the mass spring damper unit with a servo position profile, to simulate a road profile, and calculate the Mean Absolute Error of the upper cart position with respect to the initial, at rest, cart position.

4.1 Experiment 1 – Effects Of Changing The Spring Constant On The Response Of The System

During this experiment, you will investigate the effects that changing the stiffness of the spring has on the response of the system.

1. Ensure the power switch on the side of the Mass Spring Damper is switched to '0'
2. Start the LabVIEW program, and click the Step Response Test button, located at the top of the LabVIEW VI
3. Attach the Number 1 Spring between the two carts, and load the upper cart with approximately 500g of mass. Do not attach a damping unit.
4. Switch-on the Mass Spring Damper unit by switching the power switch to '1', and ensure the power LED on the side of the unit is illuminated,
5. Select Test 1, and the unit should operate for 20 seconds. A cycle of data will be recorded on the Step Response Results tab for this test
6. Switch off the Mass Spring Damper unit and replace points 3-5 for spring Number 2 and Number 3, recording data with using the Test 2 and Test 3 buttons, respectively
7. Click the Step Response Data Button, and use the axis provided in Figure 12 to sketch the 3 graphs displayed on the screen of the Step Response Results tab. (Ensure you label each of the three sketches)
8. In Table 3, write down the Percentage Overshoot, Settling Time and Rise time for the three tests, and then answer Lab Q1.

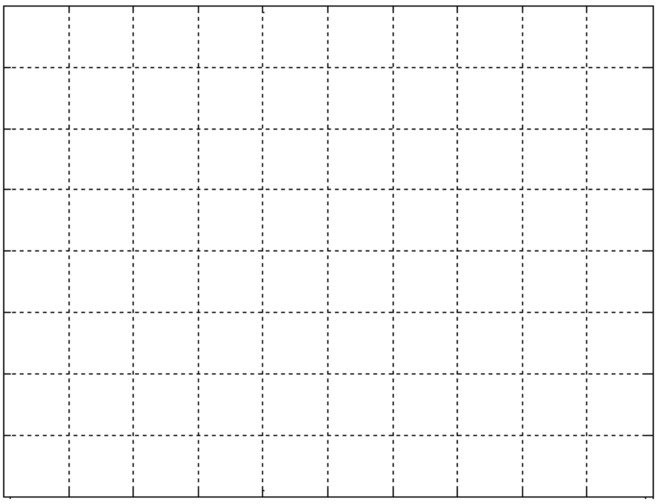


Figure 12. Graph Axis for recording the results from Experiment 1.

Use the area provided for any calculations: Use Extra Paper if needed			
Parameter:	**Test 1:**	**Test 2:**	**Test 3:**
Percentage Overshoot (%)			
Settling Time (s)			
Rise Time (s)			

Table 3. Table of results for Experiment 1

Lab Q1: From your results in Table 3 and Figure 12, comment on the effects that increasing the spring stiffness has on the performance of the system. (The higher the sprint constant, stiffer the spring)

Use Extra Paper if needed

At this point, you should show your work to one of the laboratory teaching staff for assessment of this exercise

4.2 Experiment 2 – Effects Of Changing The Damping On The Response Of The System

During this experiment, you will change the level of damping in the system and investigate the affects that this has on the system output.

1. Ensure the switch on the side of the Mass Spring Damper unit is switched to '0'
2. Attach the Number 1 Spring between the two carts, and load the upper cart with approximately 1000g of mass. Do not attach a damping unit.
3. Click the Step Response Data button and press the 'Clear Graphs' button, to reset the graph axes for this exercise.
4. Switch-on the Mass Spring Damper unit by switching the power switch to '1', and ensure the power LED on the side of the unit is illuminated,
5. Click the Step Response Test button to return to the Step Response Test, and press the Test 1 button, and the unit should operate for 20 seconds.
6. Switch off the Mass Spring Damper unit and add the lighter damper, with the yellow marker.
7. Switch-on the Mass Spring Damper unit, and run Test 2 for the lighter damper.
8. Switch off the Mass Spring Damper unit and add the stronger damper, with the red marker.
9. Switch-on the Mass Spring Damper unit, and run Test 3 for the stronger damper.
9. Click the Step Response Data Button, and use the axis provided in Figure 13 to sketch the 3 graphs displayed on the screen of the Step Response Results tab. (Ensure you label each of the three sketches)
10. In Table 4, write down the Percentage Overshoot, Settling Time and Rise time for the three tests, and then answer Lab Q2.

Note: *it may not be possible to calculate the Percentage Overshoot for all three tests*

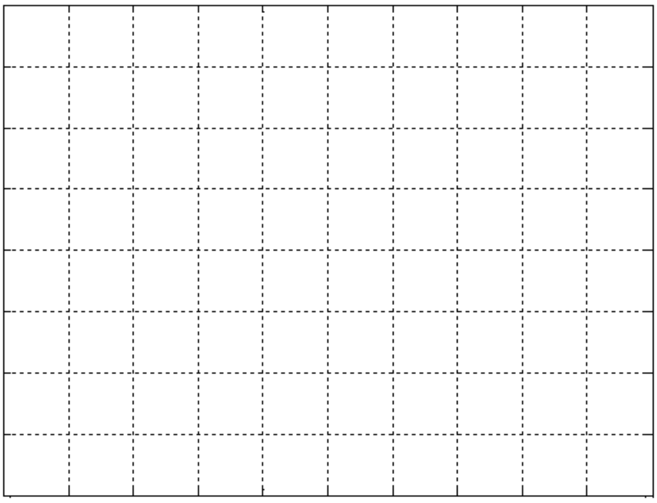


Figure 13. Graph Axis for recording the results from Experiment 2.

Use the area provided for any calculations:

Use Extra Paper if needed

Parameter:	**Test 1:**	**Test 2:**	**Test 3:**
Percentage Overshoot (%)			
Settling Time (s)			
Rise Time (s)			

Table 4. Table of results for Experiment 2

Lab Q2: From your results in Table 4 and Figure 13, comment on the effects of adding increasing levels of system damping affect the system response.

Use Extra Paper if needed

At this point, you should show your work to one of the laboratory teaching staff for assessment of this exercise

4.3 Experiment 3 – Effects Of Changing The Mass On The Response Of The System

During this experiment, you will investigate how changing the size of the mass on the upper platform affects the performance of the system.

1. Ensure the switch on the side of the Mass Spring Damper unit is switched to '0'
2. Attach the Number 1 Spring between the two carts, and load the upper plate with approximately 200g of mass. Do not attach a damping unit, and switch-on the Mass Spring Damper unit.
3. Click the Step Response Data button and press the 'Clear Graphs' button, to reset the graph axes for this exercise.
4. Switch-on the Mass Spring Damper unit by switching the power switch to '1', and ensure the power LED on the side of the unit is illuminated,
5. Click the Step Response Test button to return to the Step Response Test, and press the Test 1 button, and the unit should operate for 20 seconds.
6. Switch-off the system and load upper plate with a total of approximately 600g of mass.
7. Switch-on the Mass Spring Damper unit and run Test 2 with this mass
8. Switch-off the system and load upper plate with a total of approximately 1000g of mass.
9. Switch-on the Mass Spring Damper unit and run Test 3 for this mass
10. Click the Step Response Data Button, and use the axis provided in Figure 14 to sketch the 3 graphs displayed on the screen of the Step Response Results tab. (Ensure you label each of the three sketches)
11. In Table 5, write down the Percentage Overshoot, Settling Time and Rise time for the

three tests, and then answer Lab Q2.

(Note: it may not be possible to calculate the Percentage Overshoot for all three tests)

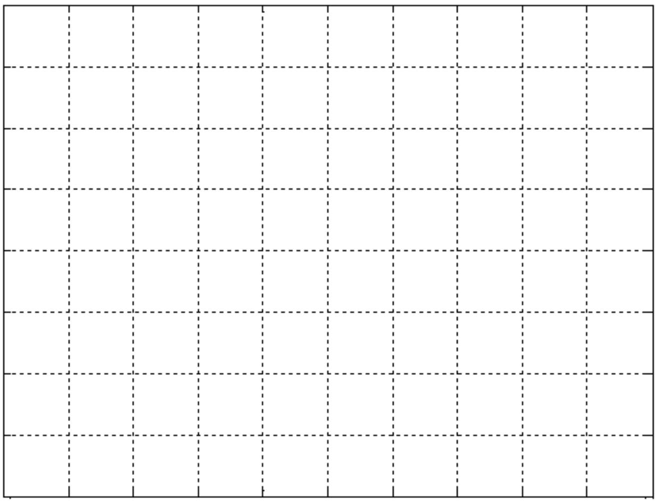


Figure 14. Graph Axis for recording the results from Experiment 3.

Use the area provided for any calculations:

Use Extra Paper if needed

Parameter:	Test 1:	Test 2:	Test 3:
Percentage Overshoot (%)			
Settling Time (s)			
Rise Time (s)			

Table 5. Table of results for Experiment 3

Lab Q3: From your results in Table 5 and Figure 14, comment on how changes in the mass of the upper plate affects the system response.

Use Extra Paper if needed

At this point, you should show your work to one of the laboratory teaching staff for assessment of this exercise

4.4 Experiment 4 – Response of the System to a Simulated Road Profile

During this experiment, the Mass Spring Damper unit will be stimulated with a realistic road profile that a suspension system (on a car, for example) may be subjected to. The 'road profile' that will be investigated is shown in Figure 15. In this experiment you will calculate the mean absolute error (MAE), using the equation provided below. This equation considers the difference between the 'actual' real-time position of the upper plate (i.e. the car) and the 'reference' input to the suspension system (i.e. the road profile).

1. Ensure the switch on the side of the Mass Spring Damper unit is switched to '0'
2. Attach the Number 1 Spring between the two plates, attach a total of approximately 600g of mass to the upper plate, and attach the lighter damper, with the yellow marker.
3. Click the Road Profile Button on the LabVIEW VI
4. Start the test, by pressing the Start Test button, and allow it to run to the end of the profile.
5. Use Table 6 to record the actual measured position (in mm) of the upper plate, at a sample interval of 0.25 seconds.
6. At the same time intervals, you should also record the 'reference position', that is: the road profile position at the same time step.
7. Using this data, calculate the Mean Absolute Error for the test, using the following formula:

$$MAE = \frac{\sum|Actual - Reference|}{N}$$

Note: *When calculating the MEA value, you may find it more convenient to use Excel or MATLAB to perform the data analysis, than attempting to perform the calculation on paper. Use the "Export this data to CSV" button to export the data to a .csv file, which you can then load into Excel, MATLAB, etc…*

Time (s)	Actual Measured Position (mm)	Reference Position (mm)	Time (s)	Actual Measured Position (mm)	Reference Position (mm)
0			5.25		
0.25			5.5		
0.5			5.75		
0.75			6		
1			6.25		
1.25			6.5		
1.5			6.75		
1.75			7		
2			7.25		
2.25			7.5		
2.5			7.75		
2.75			8		
3			8.25		
3.25			8.5		
3.5			8.75		
3.75			9		
4			9.25		
4.25			9.5		
4.5			9.75		
4.75			10		
5					

Table 6.Results table for Experiment 4.

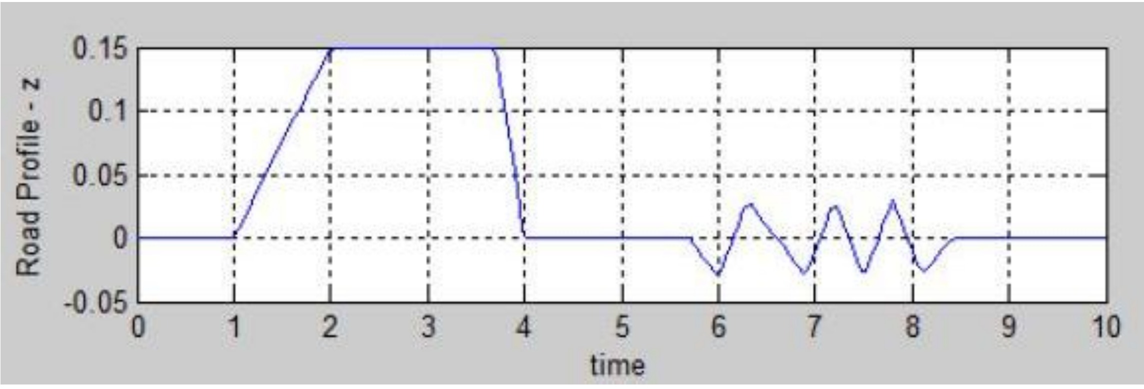


Figure 15. Road profile for Experiment 4.

What is the resulting MEA Value?

At this point, you should show your work to one of the laboratory teaching staff for assessment of this exercise

This space is provided to record the marks for your pre-lab exercises. Please record any verbal feedback you receive for these activities in the space provided, at the back of the worksheet.		
Section:	**Marking Criteria:**	**Please Circle the Mark Awarded**
Experiment 1.	Graphs sketched, table completed and questions answered with sufficient detail	Pass / Fail
Experiment 2.	Graphs sketched, table completed and questions answered with sufficient detail	Pass / Fail
Experiment 3.	Graphs sketched, table completed and questions answered with sufficient detail	Pass / Fail
Experiment 4.	table completed and value provided	Pass / Fail
Pre-Lab Assessment:	Copied from Pre-Lab marking table	Pass / Fail
Resulting Overall Assessment	Pass in all sections to achieve an overall pass mark	Pass / Fail

Ensure ALL marks have been recorded by the laboratory staff, before leaving the laboratory session. Marks will not be rewarded after you have left the lab session

Once finished, please switch-off the amplifier, The MSD system and the ELVIS unit. Please also, carefully unplug all the wires from the ELVIS board and the MSD system, and return them neatly back into the Control Cables box.

When your system is disconnected, your work area is tidy and all your marks have been recorded, you may leave the laboratory.

Post-experimental activity

There is no mandatory post laboratory activity for this laboratory, but we would be grateful if you could complete the feedback form in the Blackboard folder for this experiment. The results of the feedback you provide will be used to improve labs for future sessions.