

Laboratory Report

24-452: MECHANICAL SYSTEMS EXPERIMENTATION

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Department of Mechanical Engineering

Carnegie Mellon University

Harmonic Response of Second-Order Rectilinear Dynamic Systems

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Lab Section: B

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1. Executive Summary

This document presents the theory, methods, data analysis, and conclusions drawn from studying the harmonic response of second-order rectilinear dynamic systems. The associated theory and testing procedure for our experimental tests are described. The tests performed used different system parameters, including inertia, damping, and spring stiffness. Also, different forcing functions (swept sine and random excitations) were applied to our system. Through changing these system parameters we were able to conclude their effects on the system response. We were able to draw conclusions from the analysis of the data. We verified empirical relationships as and discovered relationships that exist in non-ideal systems. Using swept sine and random forcing functions to determine system parameters allowed us to conclude differences in the responses to these forcing functions (i.e. swept sine produces FRFs with less noise). Lastly we explore the use of Fourier series approximation to model a repeated forcing function.

2. Introduction

The purpose of this lab is to analyze different cases of harmonic response of second-order rectilinear dynamic systems. While harmonic response theoretically considers only the steady-state vibrations, the dynamic parameters extracted from analyzing harmonic response can be used to estimate the transient behavior.

Fundamentally, the harmonic response (the frequency response function (FRF)) allows the steady state response of dynamic systems to harmonic excitation to be determined without solving the system equations. When considered for a complicated system, such as a car, a washing machine, an airplane, frequency response function becomes an invaluable approach to estimate the system response. The main assumption used is that the dynamic response of the system to a sinusoidal excitation is itself sinusoidal, with the same frequency as the excitation, but with a phase shift. The magnitude of the FRF at a particular frequency indicates the ratio of the response amplitude to sinusoidal excitation-force amplitude. The phase of the FRF at a particular frequency indicates the phase shift between the sinusoidal force and associated the sinusoidal response.

In this lab, various methods for obtaining frequency response function of dynamic systems were used to determine frequency response characteristics of rectilinear systems.

3. Theory

Symbols:

Table 3.1.1: Explanation of Symbols used in Equations

k	Spring Rate
ω_n	Natural Frequency
m	Mass
ζ	Damping Ratio (Zeta)

c	Damping Constant
T	Period
x	Position
T ₀	Forcing Function Amplitude

The equation of motion for a second-order system with harmonic forcing function can be given (generically) as:

$$m\ddot{x} + c\dot{x} + kx = \sum_{i=1}^N T_{S0i} \sin(\omega_i t) + T_{C0i} \cos(\omega_i t) \quad \text{eq. 3.1}$$

where T_{S0} and T_{C0} are the coefficients of sine and cosine functions, respectively. Provided that the system behaves linearly (which means we can use the superposition principle), we can seek the response q_i of the system to each individual sine (or cosine) function, and then sum up the responses, i.e.,

$$x(t) = \sum_{i=1}^N x_i(t) \quad \text{eq. 3.2}$$

Therefore, we will concentrate on finding the steady-state response to

$$m\ddot{x} + c\dot{x} + kx = T_0 \sin(\omega t) = T(t) \quad \text{eq. 3.3}$$

The frequency response function (i.e., sinusoidal transfer function) of the system given in Eq. (3) can be written as

$$G(j\omega) = \frac{X(j\omega)}{T(j\omega)} = \frac{1}{(k - m\omega^2) + jc\omega} \quad \text{eq. 3.4}$$

$$= \frac{1/m}{(\omega_n^2 - \omega^2) + 2j\xi\omega\omega_n} \quad \text{eq. 3.5}$$

$$= \frac{1/k}{\frac{(1 - \omega^2)}{\omega_n^2} + \frac{2j\xi\omega}{\omega_n}} \quad \text{eq. 3.6}$$

This complex-valued frequency response function can further be written as a magnitude and phase as

$$|G(j\omega)| = \frac{\frac{T_0}{k}}{\sqrt{\left[\frac{(1-\omega^2)}{\omega_n^2}\right]^2 + \left[\frac{2j\xi\omega}{\omega_n}\right]^2}} \quad \text{eq. 3.7}$$

$$\angle G(j\omega) = -\tan^{-1} \frac{2\xi\omega/\omega_n}{1-\omega^2/\omega_n^2} \quad \text{eq. 3.8}$$

For a linear, second-order system, the response to a not only harmonic but also periodic functions may be obtained from the harmonic response analysis. The Fourier Series Expansion is used to convert a periodic function into a sum of harmonic functions. The response to each harmonic function can then be determined from the FRF, and summed to determine the response to the periodic function.

The Fourier Expansion Theorem indicates that any periodic function can be expressed as an infinite sum of harmonic functions. In general, however, only finite number of harmonic functions are sufficient for expressing most periodic functions. This is due to the fact that the Fourier series, provided that certain conditions are satisfied, converges. Given a periodic function $f(t)$, the (truncated, i.e., finite N -element) Fourier series expansion can be written as

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^N a_n \sin(\omega_n t) + b_n \cos(\omega_n t) \quad \text{eq. 3.9}$$

Where

$$a_0 = \frac{2}{T} \int_a^{a+T} f(t) dt \quad \text{eq. 3.10}$$

$$a_n = \frac{2}{T} \int_a^{a+T} f(t) \cos\left(\frac{2n\pi t}{T}\right) dt, n = 1 \dots \infty \quad \text{eq. 3.11}$$

$$b_n = \frac{2}{T} \int_a^{a+T} f(t) \sin\left(\frac{2n\pi t}{T}\right) dt, n = 1 \dots \infty \quad \text{eq. 3.12}$$

During these tests were used two different excitation methods, sine sweep and random excitation.

In the case of random excitation, a “random” signal is generated to excite the structure, and the response is measured. From the auto- and cross-correlation functions (which are forms of Fast-Fourier Transforms), the FRF is generated. The FRFs, however, only become accurate if a large number of averages (commonly 50 to 100) are taken, since only then the Random signals (on average) deliver constant energy to all frequencies. To assess the increased accuracy of the

response, coherence function is calculated. The closer the coherence to unity (1), the better the response characteristics (reduced overall noise). Random excitations are particularly favorable in rejecting random (or white) noise from the system. However, the random excitations do not perform well for systems with nonlinearities.

For both linear and nonlinear structures, sweep-sine and step-sine test can provide complete and high-quality information about the system dynamics. The disadvantage of these techniques, in general, as opposed to hammer impact and pseudo-random tests is that they are considerably more time consuming to apply (step-sine being the slowest one). In sweep-sine tests, the frequency of excitation continuously changes from zero to the maximum value. By providing the total time for testing, and the range of frequencies, the A value is determined. As such, this method is (essentially) a way of providing sinusoidal excitations at every frequency. Again, the excitation force and response are post-processed (commonly using Fast-Fourier Transforms (FFTs)), and an FRF is generated. Figure 2 shows a sweep-sine excitation force in both time and frequency domains.

Step-sine testing is very similar; however, the tests continue at small frequency steps $\Delta\omega$, and at each step, a sine signal is used as an excitation. Amplitude ratios and phase shifts between the response and excitation are calculated at each frequency step. Therefore, the FRFs are generated point-by-point (as opposed to all other methods, where the entire FRF is generated at the end of one single tests). While very slow, step-sine testing is the most accurate method, especially when nonlinear structures are considered.

4. Experimental Setup

The experiment used the ECP 210 Rectilinear dynamic system, which can be seen in Figure 4.1.

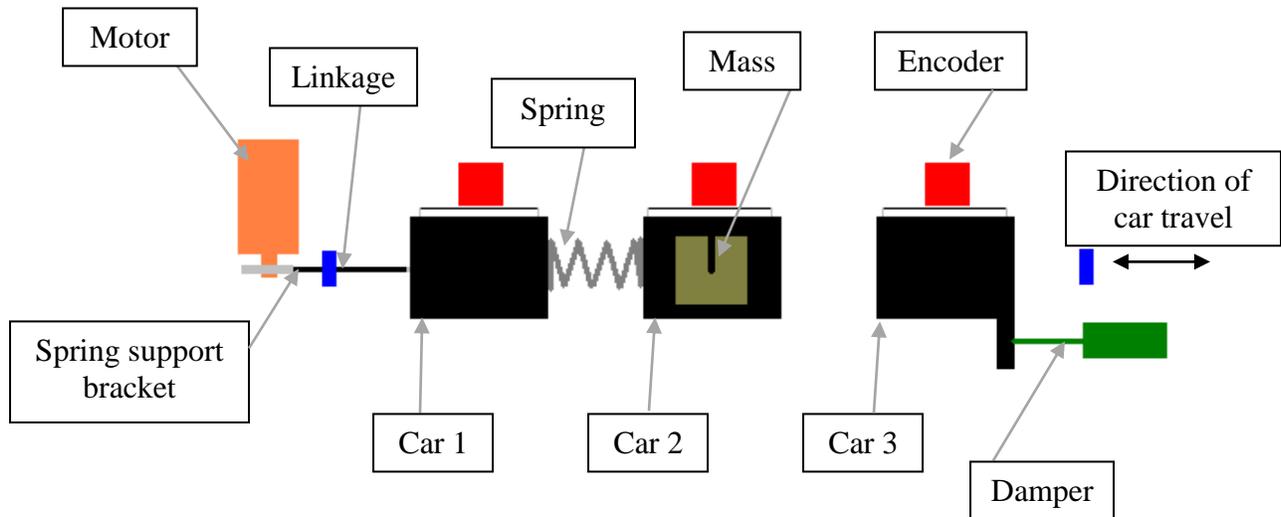


Figure 4.1: Drawing of Experimental Setup

The system consists of three low-friction cars that have one degree of freedom (direction of travel indicated in Figure 1). Each of the cars is attached to an encoder that measures the linear displacement. Each car also has a screw and nut that can be used to secure additional masses that increase the mass of the car. There are three large masses and one smaller mass. There are 3 springs, one with high stiffness, one with medium stiffness, and one with low stiffness, which can be attached with bolts between two cars or between a car and a spring support bracket. The cars can also be locked in place to prevent their movement. A motor is connected with a linkage to Car 1 by way of a rack and pinion gear. This motor can be used to provide a forcing function to the system. Car 3 has a bracket which can be attached to air cylinder to provide damping to the system. The encoders and motors interface with a computer, which runs software necessary to control the motor and read and store data output from the encoders.

5. Procedure

The purpose of Experiment 1 was to obtain the harmonic response (in the form of FRFs) of a single degree of freedom system with sine-sweep excitation force. The first car only was used with no masses and with the strongest spring attached between Car 1 and the spring support bracket. The software was used to set prescribed stiffness and damping coefficients. Subsequently, a sine-sweep signal was configured with the given amplitude (four such tests at four amplitude levels) from 1 Hz to 10 Hz frequency range within 40 seconds. For each amplitude level, five tests were conducted and the results averaged to obtain FRFs. Data was saved for post processing.

The purpose of Experiment 2 was to obtain the harmonic response, in the form of FRFs, of a single degree of freedom system with random excitation force. The same physical setup from Experiment 1 was used. Prescribed stiffness and damping was set through the software, and a random signal with given amplitude (for two tests using different amplitudes) was configured from 1 to 10 Hz, with 10 tests being averaged. The software would then provide the FRFs and associated coherence plots.

In Experiment 3, effect of changes in spring constant, damping coefficient, and mass on the FRF characteristics were evaluated. The same physical setup used in the sweep-sine tests (Experiment 1) was used. In first 7 tests, only the mass of the car was considered. For the last two tests, mass blocks were added to evaluate the effect of added mass. In addition to the spring and inherent damping coefficient, springs rate and damping coefficients were prescribed through the software for many tests. Each test was conducted using a swept sine force with a 1.2 N amplitude from 1 Hz to 10 Hz frequency range for 40 seconds. Each test was averaged over 2 sets of tests. Data was saved for post-processing.

The purpose of Experiment 4 was to excite the system using single frequency sinusoidal functions in order to compare the magnitude and phase of the system's steady state responses to ones predicted by FRFs obtained in previous experiments. Experiment 4 used the same physical spring and the first car's mass, like in other experiments. All tests were performed using a sinusoidal excitation force with a 1.2 N amplitude for a 40 second duration. A software stiffness of 200 Nm/rad and a software damping of 2 Nms/rad were used. The data was saved for post-processing.

The purpose of Experiment 5 was to investigate the use of the Fourier series expansion for representing a periodic function, as well as the response of a second order system to the periodic function using harmonic response principles. To perform the tests in Experiment 5, the previous setup was used (Car 1 with no masses and stiffest spring attached). For the first five tests that are listed on Table 5.1, Equation (9) was utilized, adding one additional term each time. A software stiffness of 200 Nm/rad and a software damping of 2 Nms/rad were used. The data was saved for post-processing.

Table 5.1: Terms added in Fourier series expansion

Test	Added term
2	$6.4846 \cdot \sin(3.1416 \cdot t)$
3	$-0.7205 \cdot \sin(3.1416 \cdot 3 \cdot t)$
4	$0.2594 \cdot \sin(3.1416 \cdot 5 \cdot t)$
5	$-0.1323 \cdot \sin(3.1416 \cdot 7 \cdot t)$
6	$0.0801 \cdot \sin(3.1416 \cdot 9 \cdot t)$

6. Results, Discussion & Observations

Question 1: Comparison of Test 3 and 4

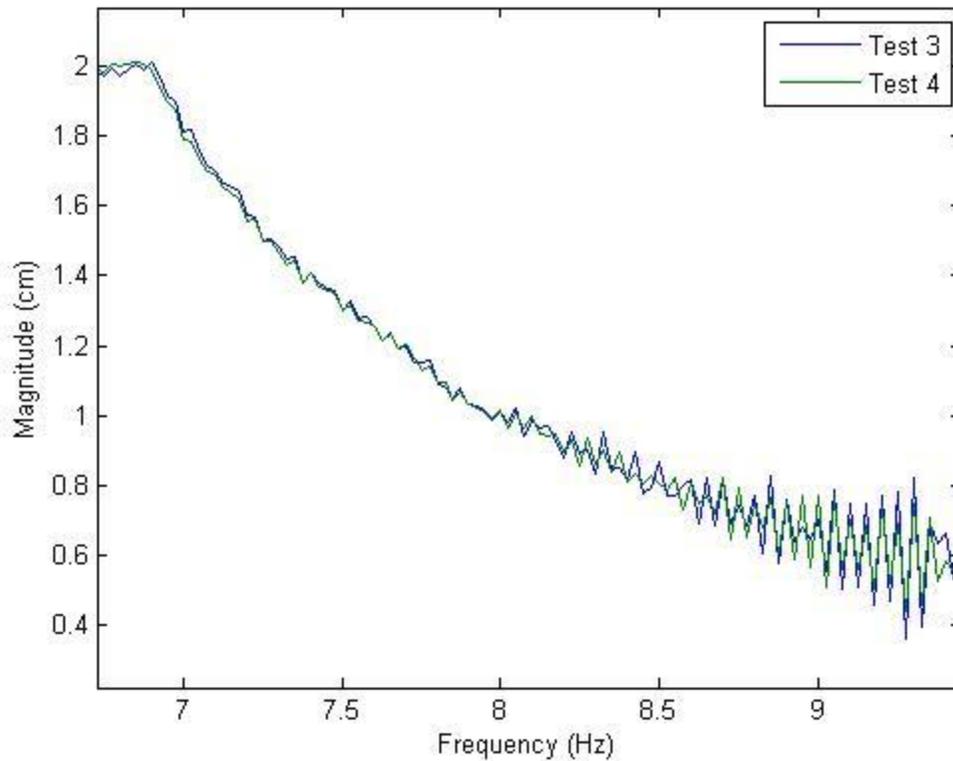


Figure 6.1.1: FRFs from tests 3 and 4

Shown in Figure 6.1.1 is a zoomed in view of the FRFs from tests 3 and 4. This shows that increasing the number of averages above 2 did not significantly decrease the amount of noise, as the signals generally overlap one another. There are little to no differences between the two FRFs, which leads us to believe that increasing the averages above 2 does not significantly decrease the amount of noise in the system. To this end, 2 averages are sufficient to remove most noise from the system, and we should not consider noise a factor in any test which has 2 averages or more, unless there is evidence to the contrary.

Question 2: Determining the bandwidth of excitation for stepped sine forcing function

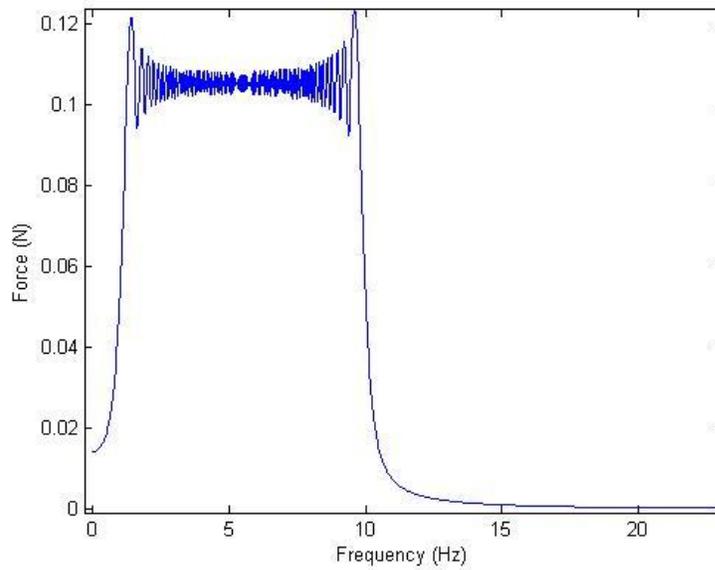


Figure 6.2.1: Flat region, and drop off past the flat region for stepped sine test

The bandwidth which represents -3db below the “flat region” is 1.2 Hz to 9.89 Hz.

Question 3: Comparing tests 1-3 and 5

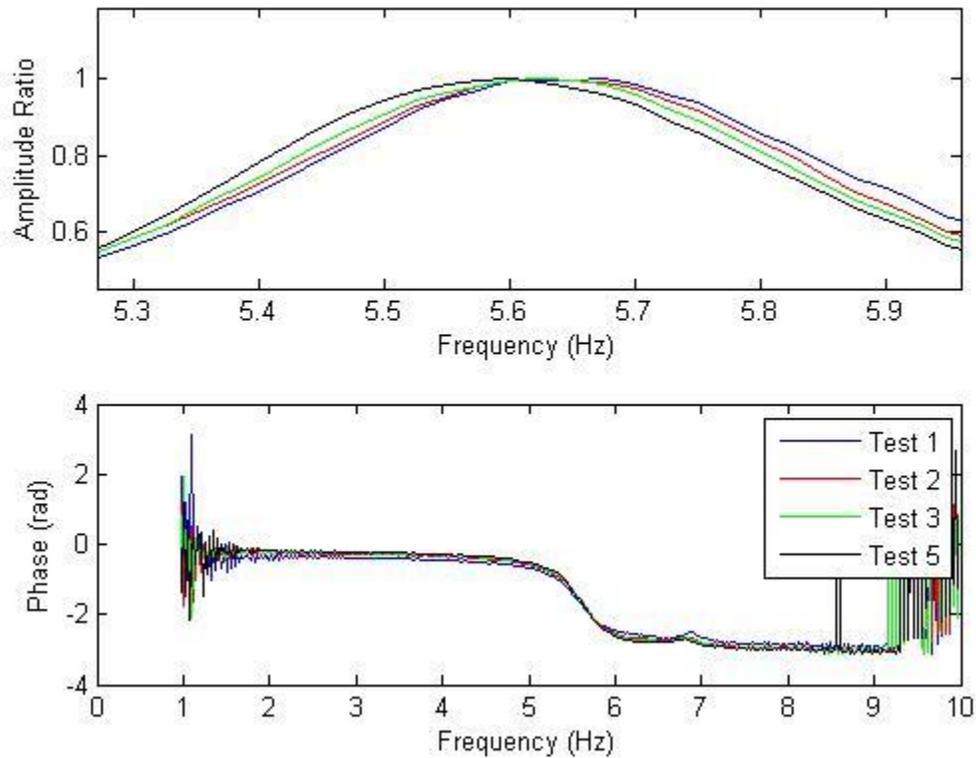


Figure 6.3.1: Amplitude ratio and phase diagrams for test s 1-3 & 5

As the amplitude of the forcing function increases, the natural frequency decreases, and the phase shift also decreases. The graph presents a zoomed in view of the amplitude ratio to highlight this shift, as it is less noticeable in the rectilinear case than the torsional. This may be due the difference in inertia. The amount of noise in these plots does not change with increase in amplitude. The linear range of these plots is from 2 Hz to 8 Hz. Any values above or below those limits has too much noise to be considered coherent.

Question 4:

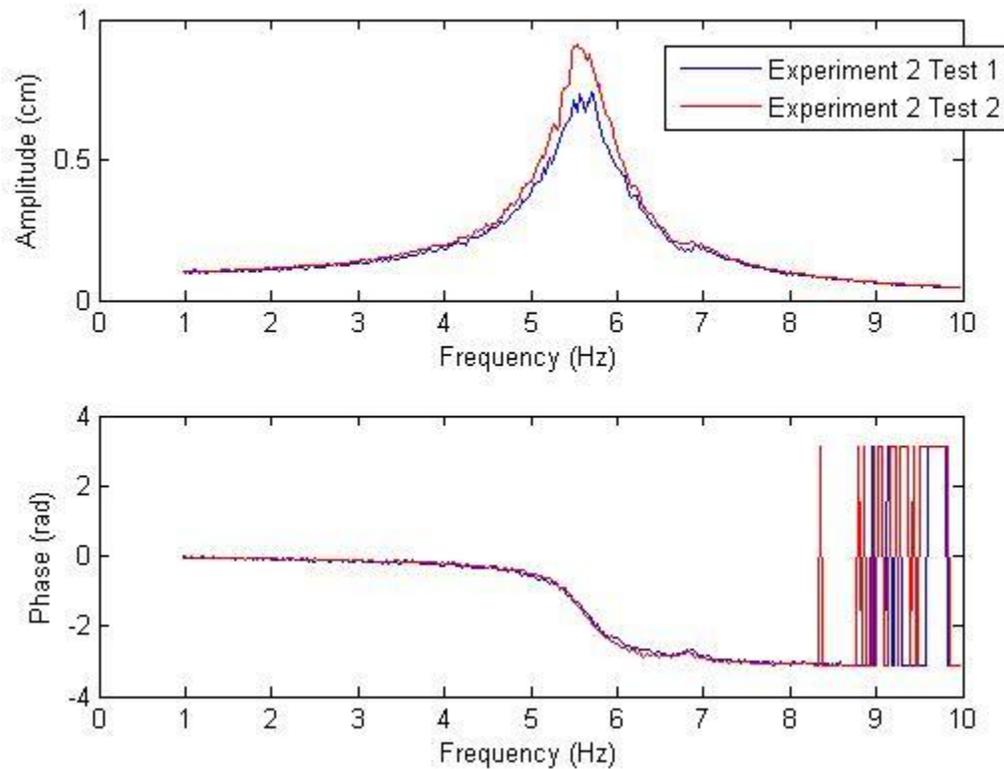


Figure 6.4.1: Amplitude and Phase diagrams for Exp 2 Test 1 and Test 2

In general these two tests appear to have the same phase and natural frequency. However, test 2 has less noise in the peak of the natural frequency than test 1. Also, the noise in the phase graph starts earlier for the higher amplitude test. Other than these two factors, the graphs appear to be very similar.

Question 5: Comparing Experiment 2 Test 1 and Experiment 1 Test 2

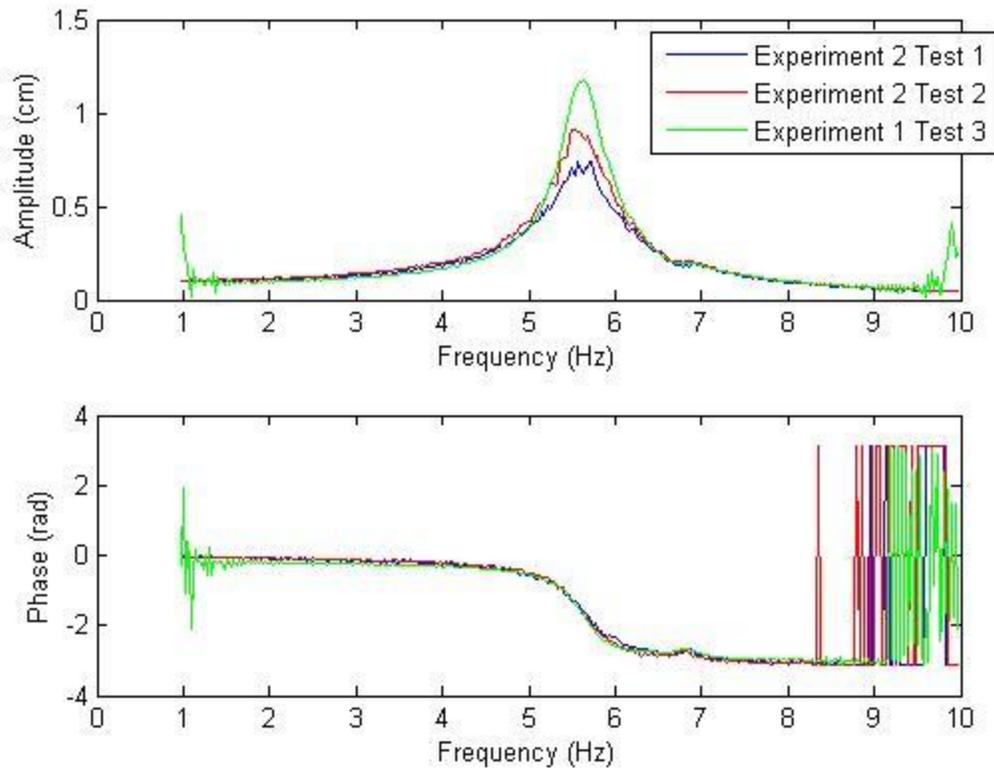


Figure 6.5.1: Amplitude and Phase diagrams for Exp 2 and Exp 1 Test 3

The results from experiment 1 test 3 are cleaner than the results from experiment 2. This is because we used a stepped sine function excitation, so the forcing function increased linearly in frequency. In experiment 2 we used a random forcing function, which may have missed various frequencies, causing errors in the data. Experiment 2 results would become smoother if we tested the random forcing function for longer, allowing for more data points and a more accurate result. However, the stepped sine tests have more noise in the beginning and end of the test. Our hypothesis for why this happens is that the randomly generated signal produces a normal distribution of forced frequencies over the applied frequency range. This means that there is more forcing in the middle of the frequency range, and less at the end points. There may be insufficient data at the end regions of the forcing function, so that the noise which would normally be there is not displayed. This hypothesis cannot be tested without knowing how the randomly generated forcing function is actually generated.

Question 6: Determining the bandwidth of excitation for random forcing function

The excitation bandwidth for the random forcing function is similar to that of the stepped sine function (1.2 Hz to 9.89 Hz). However, the stepped sine has a much more clearly defined “flat” region, making the determination of the bandwidth clearer. This may be caused by the normal distribution hypothesis as stated above, which supports that assumption of a normal distribution of frequencies in the randomly generated forcing function. Below is a “flat region” which can be compared to Figure 6.2.1

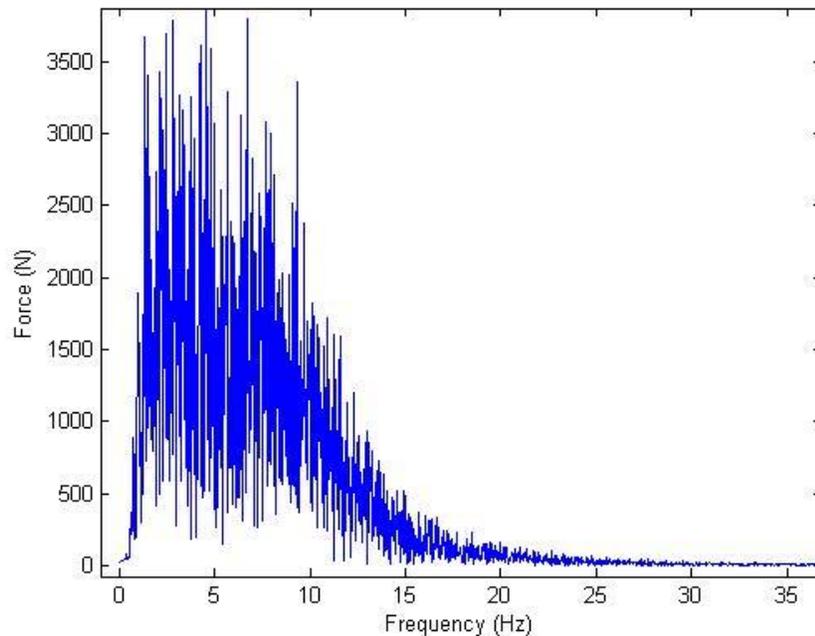


Figure 6.6.1: Flat region, and drop off past the flat region for random excitation test

Question 7: Determination of system parameters using FRF fitting

Table 6.7.1: Dynamically determined system parameters

Test	Calculated m (kg)	Calculated c (Nms)	Calculated K (Nm)
1	0.7181	1.3663	883.4
2	0.7406	2.5471	914.8
3	0.8956	10.2699	1109.1
4	0.9644	18.8907	1237.6
5	0.8738	42.9406	1230.4
6	0.8539	2.8058	941.4
7	0.8684	3.1324	848.6
8	1.9211	3.0940	844.8
9	2.6099	3.0013	810.1

The calculated parameters match fairly well with the observed parameters (off by roughly 15%) for low damping coefficients. This is because for higher damping coefficients the amplitudes do not have a well defined peak to choose a range to fit the FRF to. When the damping ratio is too high, the values do not match at all. From this we can conclude that fitting an FRF is an accurate measurement method for systems with low damping, but inaccurate for systems with relatively high damping.

Question 8: Plotting of FRF Amplitudes from Experiment 2, Tests 1-5

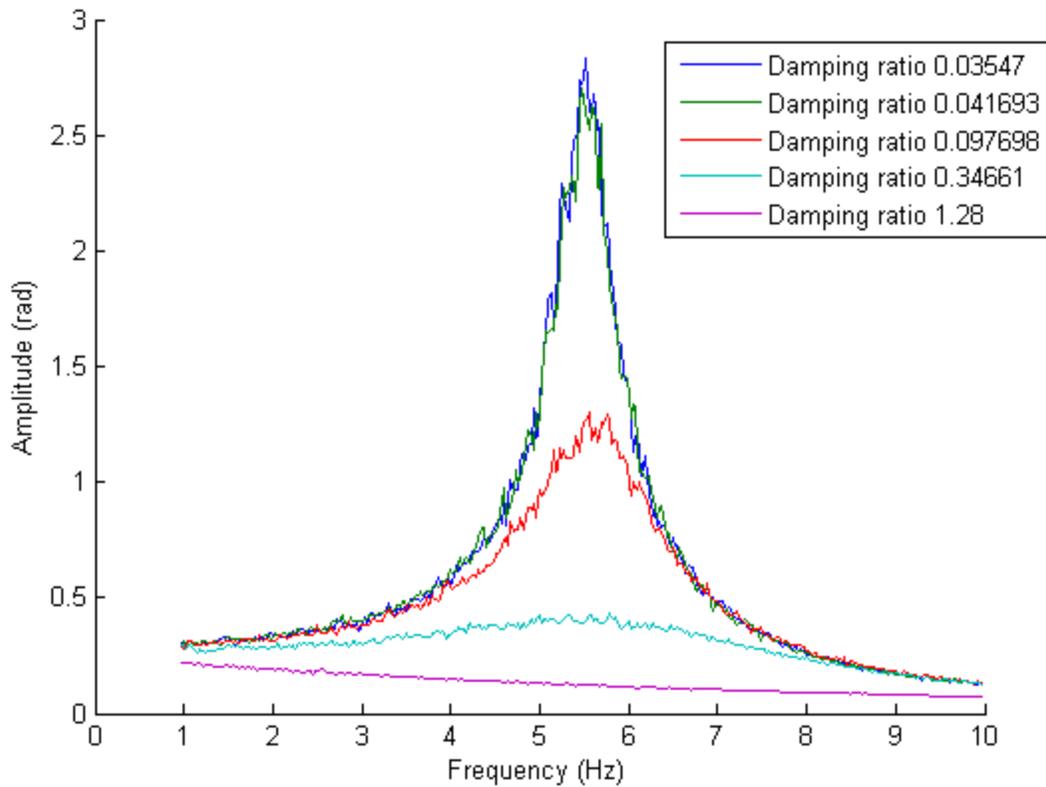


Figure 6.8.1: FRF amplitude response for changing damping ratio

As seen in Figure 6.7.1, as the damping ratio increases, the amplitude of the frequency response decreases. It appears that small changes in damping, like the change between the first to damping ratios (approximately 0.006) also result in small changes in amplitude. Also, when the system is overdamped, the shape of the amplitude response curve changes from convex to concave. Aside from the lack of smoothness, the overall shape of the curves is very similar to what is expected from when plotting theoretical FRF amplitude plots.

Question 9: Effects of Different Dynamic Parameters on System

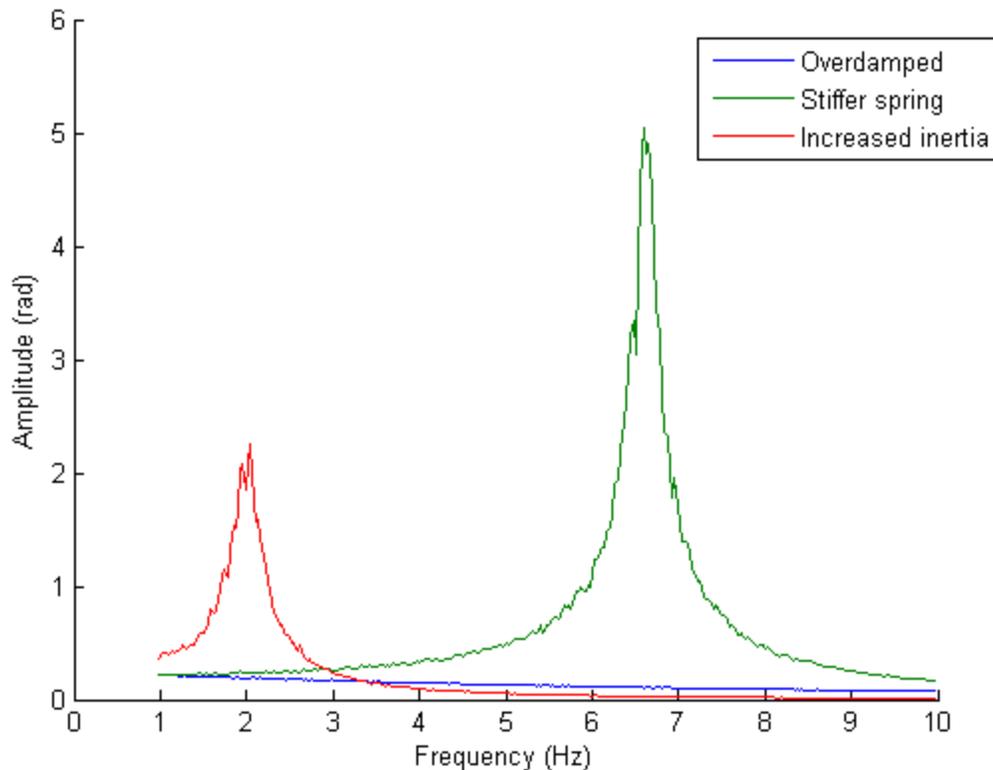


Figure 6.9.1: FRF amplitude response for different system parameters

As seen in Figure 6.8.1, different system parameters have different effects on the amplitude response. For the overdamped case, there is no frequency response. This is expected from theory, since the damping is very high and the vibrational energy is absorbed. For the case of where a simulated spring constant was used, the natural frequency increased as well as the amplitude of the response. From theory, the increase in frequency is expected since $W \propto \sqrt{K}$, and K increases in this case. The amplitude increase is also expected since the mass stays the same but the spring force is increased, so the amplitude goes up. For the case of increasing inertia, the natural frequency decreased as well as the amplitude response. The decrease in frequency is expected since $W \propto 1/J$. The amplitude decrease is also expected since increasing the inertia of the system increases the load on the bearings, which increases the system damping.

Question 10: Amplitude and Phase Shift for Experiment 3

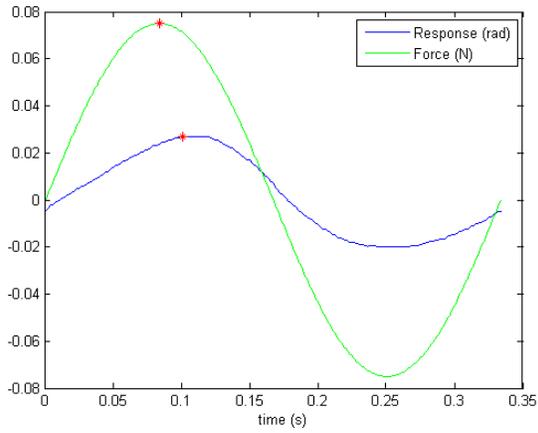


Figure 6.10.1: Experiment 3 Test 1, steady state response, phase and amplitude shift

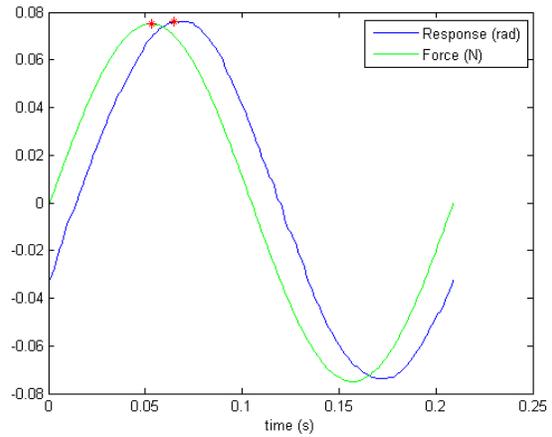


Figure 6.10.1: Experiment 3 Test 2, steady state response, phase and amplitude shift

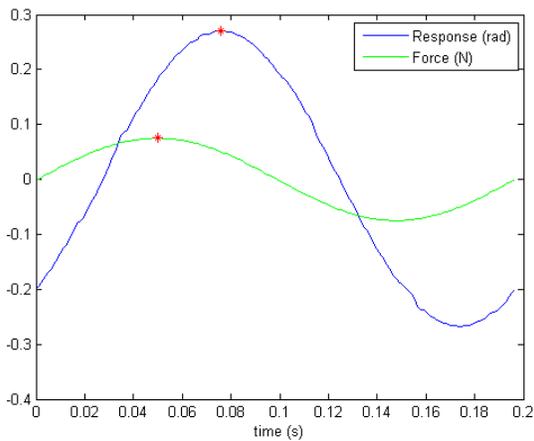


Figure 6.10.3: Experiment 3 Test 3, steady state response, phase and amplitude shift

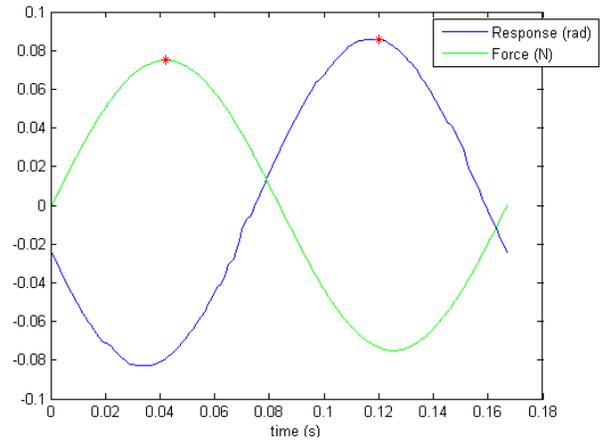


Figure 6.10.4: Experiment 3 Test 4, steady state response, phase and amplitude shift

Table 6.10.1: Amplitude and phase ratios for Tests 1-4

Test #	Amp. Ratio	Phase Ratio
1	0.0234	-0.3204
2	0.0749	-0.3619
3	0.2683	-0.8332
4	0.0843	-2.9405

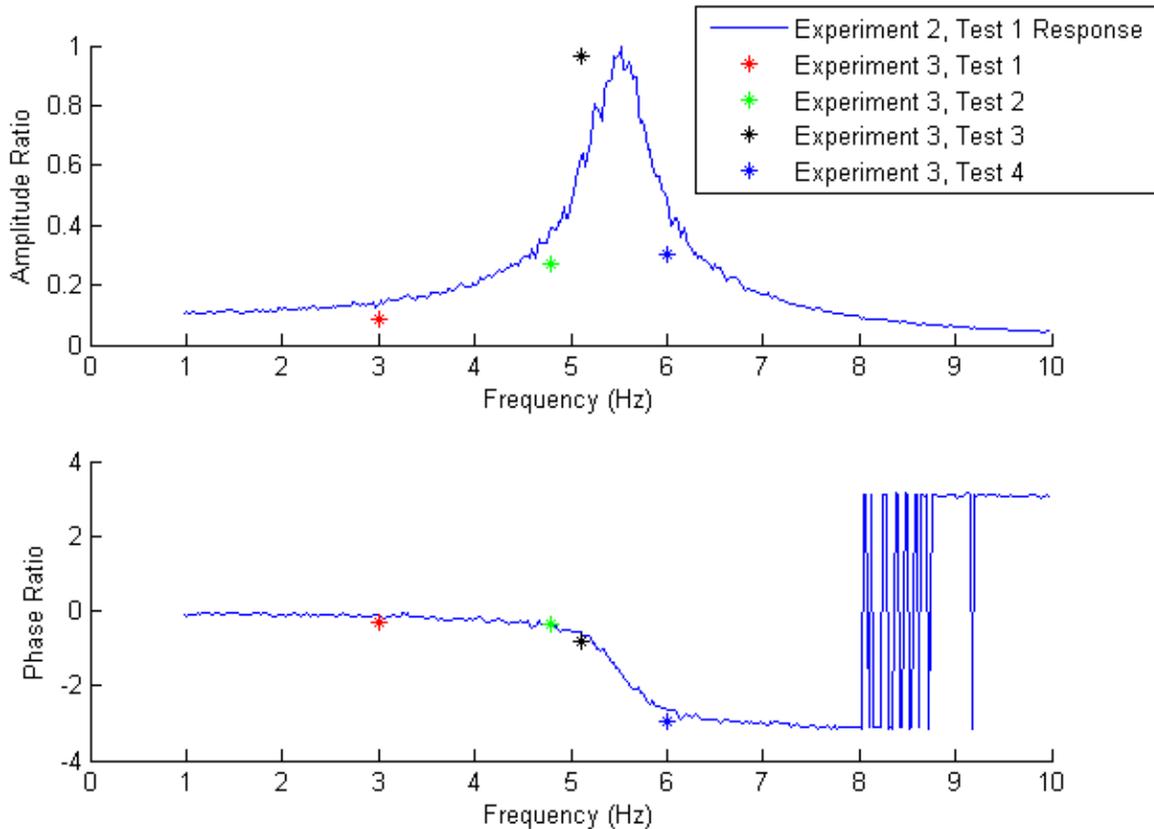


Figure 6.10.4: FRF of Experiment 2, Test 1, with points of amplitude and phase ratios from Table 6.10.1 plotted

The amplitude ratio agreement between the Experiment 2 curve and the Experiment 3 points is not good. The points from Tests 1, 2, and 4 seem all seem to lie the same distance under the curve. This error may be due a mistake in the scaling factor used to adjust the points or the curve (associated code used on this problem can be found in the Appendix, Question 9). The point from Test 3 actually lies above the curve, and is off by a larger factor. This error may be due to not taking any averages during Experiment 3; each test was only run once, compared to Experiment 2, which took 10 averages. There may have been an anomaly when recording data, like someone bumping the table. If averages were taken, there might be less error. There is very good agreement between the phase from both experiments, since the phase requires no scaling to the curve.

Question 11: Step Sine Simulation

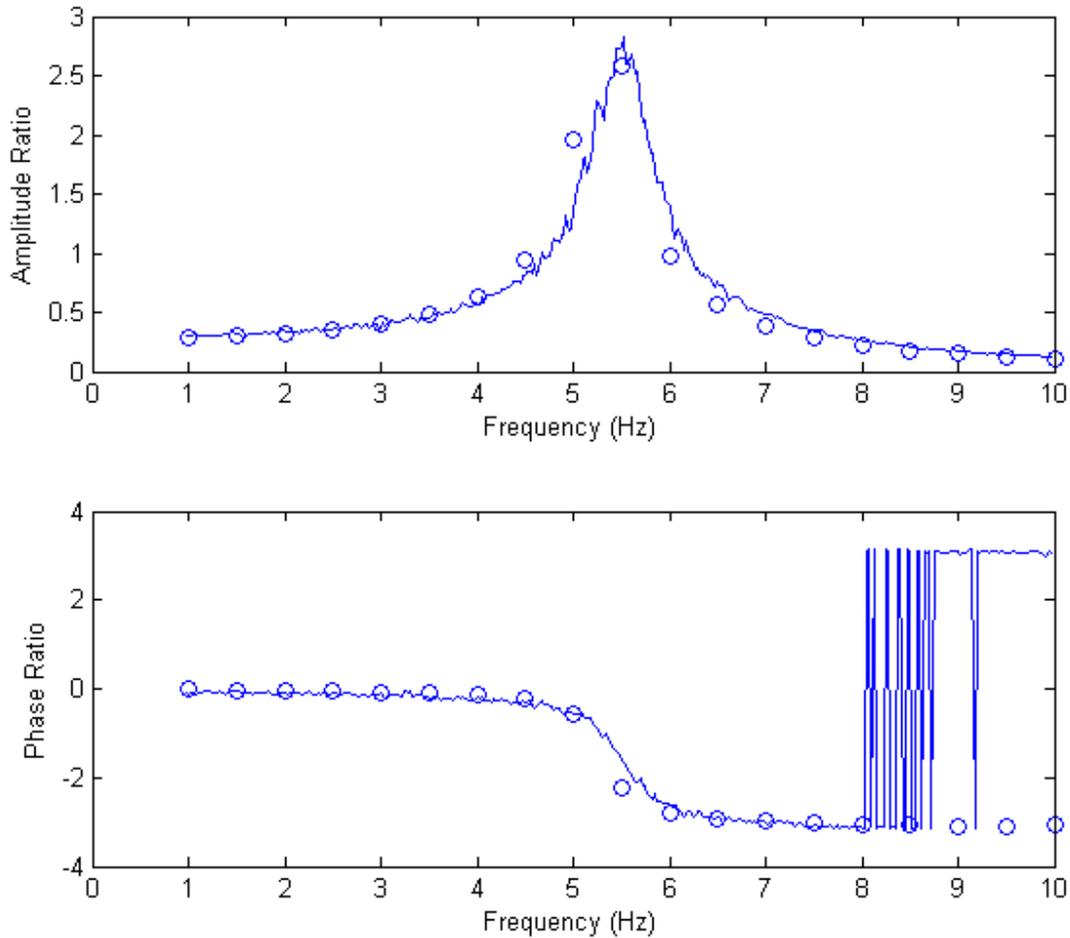


Figure 6.11.1: Experimental curve from Experiment 2, Test 1, vs analytical step response

The agreement between the experimental curves and analytical points in Figure 6.10.1 is very good. For the amplitude, the agreement is best between 1 to 4 Hz and 7 to 10 Hz. For the phase, the agreement is best between 1 to 5 Hz and 6 to 8 Hz. The agreement does not match further due to lots of noise in the phase graph, which was common to results from all experiments. Since the overall agreement in on both curves is good, we can conclude that our step sine model is a good representation of the experimental system.

Question 12: Fourier series to represent a triangle wave forcing function

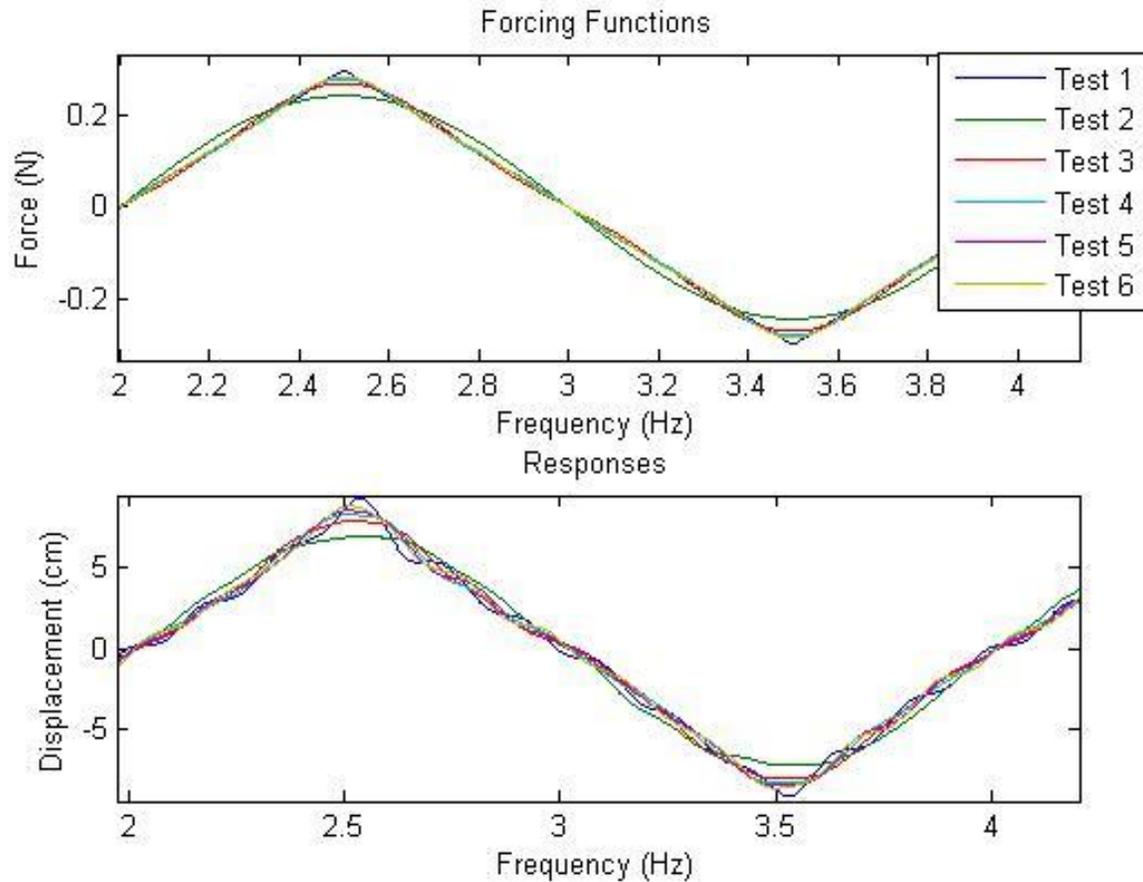


Figure 6.12.1: Forcing functions and responses for experiment 4, first cycle

Figure 6.11.1 shows a zoomed in view of the forcing functions and responses to a triangle wave and the Fourier series approximation of a triangle wave where the number of terms increases. The view is zoomed in to the first period to highlight the differences between the actual triangle wave and the Fourier approximation. Both the forcing functions and the responses get closer and closer to the actual triangle wave as the order of the Fourier series approximation increases.

Question 13: FRF comparison for Fourier series approximation

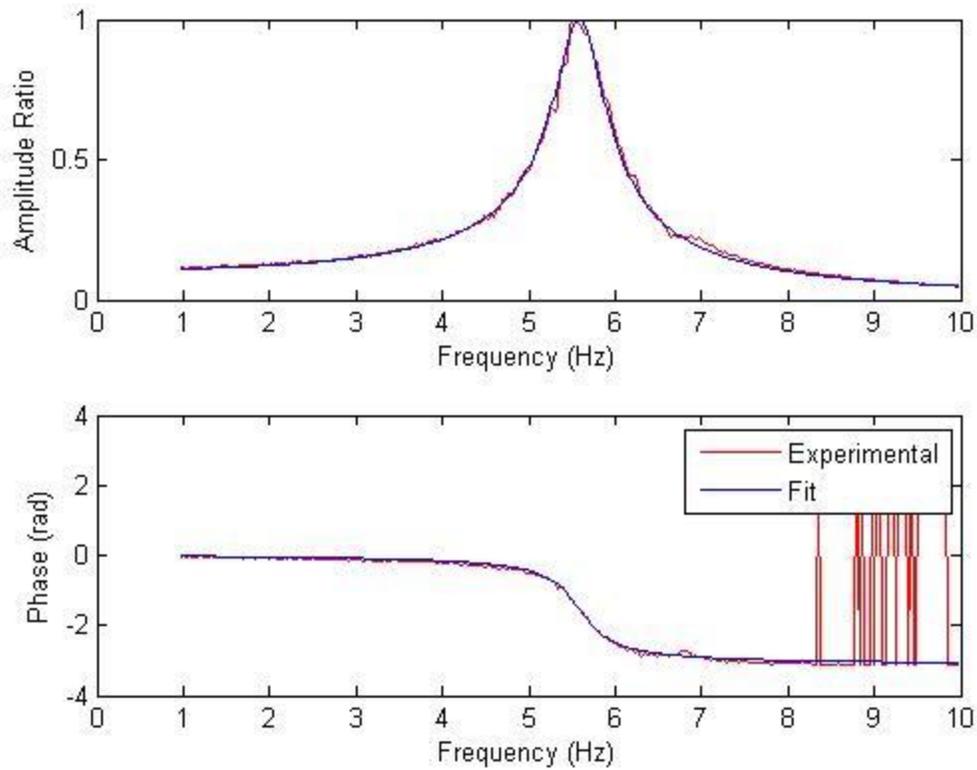


Figure 6.13.1: Experimental FRF for Experiment 2 Test 1

Reading off the amplitude ratio and phase at each of the frequencies for the different terms in the Fourier series expansion produces table 6.12.1

Table 6.13.1: Amplitude ratio and phase

Test	F (Hz)	Amplitude Ratio	Phase (radians)
2 (1 st term)	0.5	0.10	0.00
3 (3 rd term)	1.5	0.12	-0.03
4 (5 th term)	2.5	0.13	-0.06
5 (7 th term)	3.5	0.15	-0.11
6 (9 th term)	4.5	0.29	-0.23

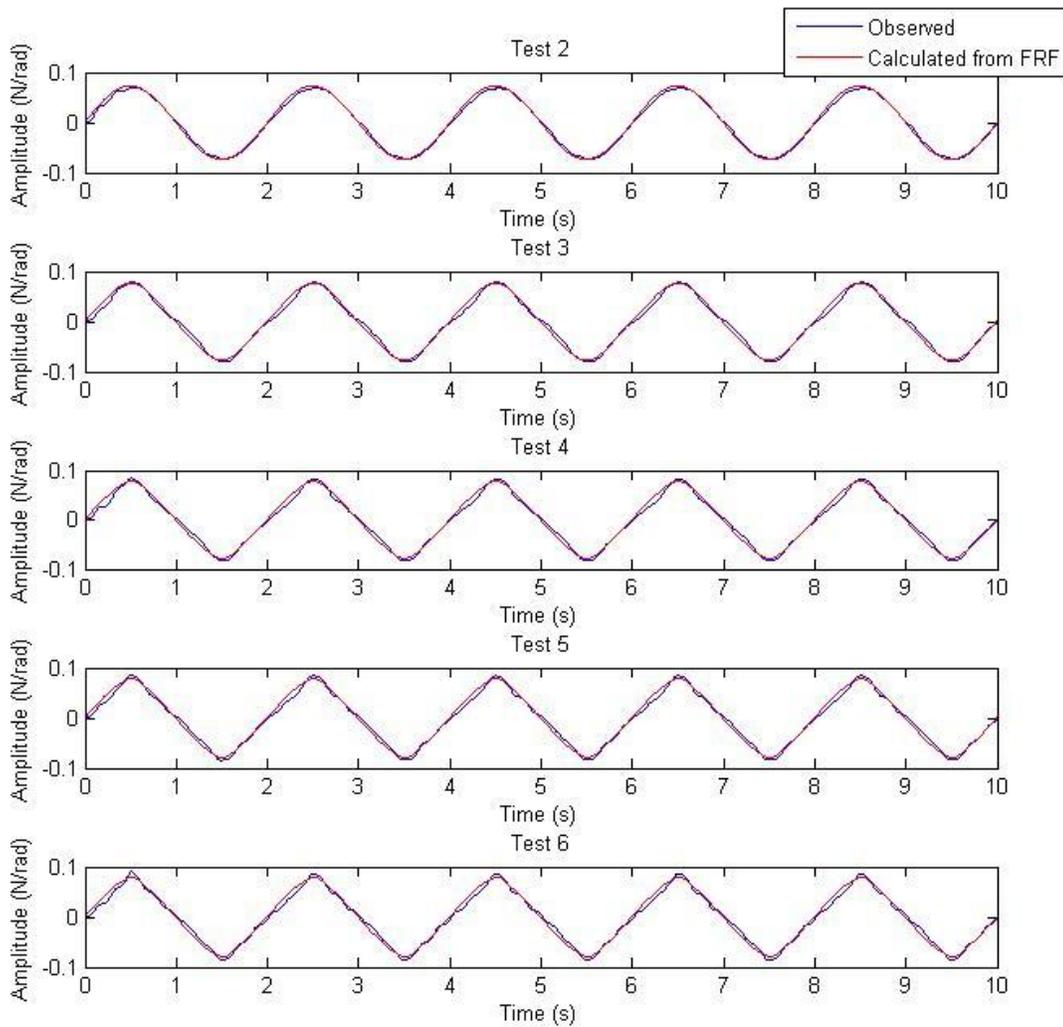


Figure 6.13.2: Observed results compared to results calculated from FRF values

The observed and calculated values do match, because we found the missing amplitude ratios for the first 2 frequencies. We were instructed to use values of 1 for the amplitude ratio and 0 for the phase for the first two frequencies of the Fourier series. However, linearly approximating the graph, the values should have been in the range of 0.1 to 0.3 for the amplitude ratio. By adjusting these two values iteratively, we found the actual phase amplitude such that the observed response closely matched the calculated response. This method allowed us to find the missing amplitude ratios for the first and second frequencies in the Fourier series.

7. Conclusion

After completing this lab and lab report, we were able to draw several important conclusions. We verified the following from the empirical data relationships. First, when the spring constant is

increased, the natural frequency of the system will increase, and the amplitude of the frequency response will increase as well. Also, increasing the system's mass will lower the natural frequency of the system and increase the amplitude of the response. Another relationship verified is that when the amplitude of the forcing function is increased, the natural frequency and phase of the system will decrease.

Conclusions were also reached from study of the system's damping. It was determined that overdamping results in no excitation of the system's natural frequency. As a result, there is no peak in the FRF data, and normal curve fitting techniques which expect that peak are unsuitable. However, these curve fitting techniques are accurate for low damping where a peak is present.

Our system has a clearly defined bandwidth for which results are expected to be linear. Outside of the bandwidth, our testing produced inconclusive results. This bandwidth was very well defined for a swept sine forcing function, but less so for a random input. This difference is a result of the inconsistencies in the frequencies which are tested by a random excitation with a low number of averages. However, for swept sine, using more than 2 averages did not noticeably decrease the amount of noise present in the data. From this we concluded that using only 2 averages for all swept sine testing was sufficient to reduce noise to an acceptable level.

The different tests we used were swept sine, and random excitation, as well as a simulation of stepped sine. All of these testing methods can accurately give system parameters, though is best suited for different testing restrictions. Also, using a Fourier series approximation can accurately model a repeating forcing function. The accuracy of this approximation increases as the order of the Fourier series increases.

8. References

Ogata, Katsuhiko. System Dynamics: Fourth Edition. Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

9. Appendices

Matlab code used:

fitfrf.m

```
function [m c k]=fitfrf(freq,amp,pha)
% b=textread('3.1_k200_c2_1.2N.txt','','headerlines',23);
plot(amp,'r')
xx=ginput(2);
h=amp(ceil(xx(1,1)):floor(xx(2,1)))/1000.*exp(i*pha(ceil(xx(1,1)):floor(xx(2,1))));
[num,den]=invfreqs(h,freq(ceil(xx(1,1)):floor(xx(2,1)))*2*pi,0,2);
hh=freqs(num,den,freq*2*pi);
mag=abs(hh);
ang=angle(hh);
subplot(2,1,1)
plot(freq,amp,'r')
```

```

hold on
plot(freq,mag)
xlabel('Frequency (Hz)')
ylabel('Amplitude Ratio')
subplot(2,1,2)
plot(freq,pha,'r')
hold on
plot(freq,ang)
xlabel('Frequency (Hz)')
ylabel('Phase (rad)')
hold off
denn=den/num;
m=denn(1);
c=denn(2);
k=denn(3);

```

readfreq.m

```

function [freq,val]=readfreq(filename,pm)
a=textread(filename,',' , 'headerlines',23);
if strcmp(pm,'m')
    val=a(40:400,2);
end
if strcmp(pm,'p')
    val=a(40:400,4);
end
freq=a(40:400,1);

```

sweepfft.m

```

clear all
close all

[tt,force,disp]=readenc('timesweep.txt','d',1);

fft_force=fft(force);
freq_axis=[0:1/tt(end):(length(tt)-1)*1/tt(end)];

figure;
plot(tt,force)

figure;
plot(freq_axis,abs(fft_force))

```

%Question 1

```

[freq1,val1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','m');
[freq2,val2] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t4.txt','m');
plot(freq1,val1)

```

```

hold all
plot(freq2,val2)
legend('Test 3','Test 4')
xlabel('Frequency (Hz)')
ylabel('Magnitude (cm)')

```

%Question 2

```

[tt,force,disp]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','d',1);
fft_force=fft(force);
freq_axis=[0:1/tt(end):(length(tt)-1)*1/tt(end)];
figure;
plot(tt,force)
figure;
plot(freq_axis,abs(fft_force)/1000)
xlabel('Frequency (Hz)'),ylabel('Force (N)')

```

%Question 3

```

[freq1,mag1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t1.txt','m');
[freq1,phase1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t1.txt','p');
[freq2,mag2] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t2.txt','m');
[freq2,phase2] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t2.txt','p');
[freq3,mag3] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','m');
[freq3,phase3] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','p');
[freq5,mag5] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t5.txt','m');
[freq5,phase5] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex1t5.txt','p');
figure();
max1 = max(mag1(20:250,:));
max2 = max(mag2(20:250,:));
max3 = max(mag3(20:250,:));
max5 = max(mag5(20:250,:));
subplot(2,1,1), title('Magnitude')
plot(freq1,mag1/max1,'b',freq2,mag2/max2,'r',freq3,mag3/max3,'g',freq5,mag5/m
ax5,'black')
xlabel('Frequency (Hz)'), ylabel('Amplitude Ratio')
subplot(2,1,2), title('Phase')
plot(freq1,phase1,'b',freq2,phase2,'r',freq3,phase3,'g',freq5,phase5,'black')
xlabel('Frequency (Hz)'), ylabel('Phase (rad)')
legend('Test 1','Test 2','Test 3','Test 5')

```

%Question 4

```

[freq1,mag1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex2t1.txt','m');
[freq1,phase1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex2t1.txt','p');

```

```

[req2,mag2] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','m');
[req2,phase2] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','p');
figure()
subplot(2,1,1)
plot(freq1,mag1/10,'b',freq2,mag2/10,'r')
xlabel('Frequency (Hz)'), ylabel('Amplitude (cm)')
subplot(2,1,2)
plot(freq1,phase1,'b',freq2,phase2,'r')
xlabel('Frequency (Hz)'), ylabel('Phase (rad)')
legend('Experiment 2 Test 1','Experiment 2 Test 2')

```

%Question 5

```

[req1,mag1] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t1.txt','m');
[req1,phase1] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t1.txt','p');
[req2,mag2] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','m');
[req2,phase2] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','p');
[req3,mag3] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','m');
[req3,phase3] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex1t3.txt','p');
figure()
subplot(2,1,1)
plot(freq1,mag1/10,'b',freq2,mag2/10,'r',freq3,mag3/10,'g')
xlabel('Frequency (Hz)'), ylabel('Amplitude (cm)')
subplot(2,1,2)
plot(freq1,phase1,'b',freq2,phase2,'r',freq3,phase3,'g')
xlabel('Frequency (Hz)'), ylabel('Phase (rad)')
legend('Experiment 2 Test 1','Experiment 2 Test 2','Experiment 1 Test 3')

```

%Question 6

```

[tt,force,disp]=readenc('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\exp2test2.txt','d',1);
fft_force=fft(force);
freq_axis=[0:1/tt(end):(length(tt)-1)*1/tt(end)];
figure;
plot(tt,force)
figure;
plot(freq_axis,abs(fft_force))
xlabel('Frequency (Hz)'),ylabel('Force (N)')

```

%Question 7

```

[req1,mag1] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex3t1.txt','m');
[req1,phase1] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex3t1.txt','p');
[m1,c1,k1] = fitfrf(freq1,mag1,phase1);
[req2,mag2] = readfreq('C:\Documents and Settings\roclub\Desktop\Lab 3
Rectilinear\B6\ex3t2.txt','m');

```

```

[freq2,phase2] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t2.txt', 'p');
[m2,c2,k2] = fitfrf(freq2,mag2,phase2);
[freq3,mag3] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t3.txt', 'm');
[freq3,phase3] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t3.txt', 'p');
[m3,c3,k3] = fitfrf(freq3,mag3,phase3);
[freq4,mag4] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t4.txt', 'm');
[freq4,phase4] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t4.txt', 'p');
[m4,c4,k4] = fitfrf(freq4,mag4,phase4);
[freq5,mag5] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t5.txt', 'm');
[freq5,phase5] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t5.txt', 'p');
[m5,c5,k5] = fitfrf(freq5,mag5,phase5);
[freq6,mag6] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t6.txt', 'm');
[freq6,phase6] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t6.txt', 'p');
[m6,c6,k6] = fitfrf(freq6,mag6,phase6);
[freq7,mag7] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t7.txt', 'm');
[freq7,phase7] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t7.txt', 'p');
[m7,c7,k7] = fitfrf(freq7,mag7,phase7);
[freq8,mag8] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t8.txt', 'm');
[freq8,phase8] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t8.txt', 'p');
[m8,c8,k8] = fitfrf(freq8,mag8,phase8);
[freq9,mag9] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t9.txt', 'm');
[freq9,phase9] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex3t9.txt', 'p');
[m9,c9,k9] = fitfrf(freq9,mag9,phase9);
m = [m1,m2,m3,m4,m5,m6,m7,m8,m9] '
c = [c1,c2,c3,c4,c5,c6,c7,c8,c9] '
k = [k1,k2,k3,k4,k5,k6,k7,k8,k9] '

% %Question 7
[F1,a1]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t1.txt', 'm');
[F2,a2]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t2.txt', 'm');
[F3,a3]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t3.txt', 'm');
[F4,a4]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t4.txt', 'm');
[F5,a5]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t5.txt', 'm');

J = 0.0024;%System parameters determined from Lab 1 torsional
K = 2.69;%System parameters determined from Lab 1 torsional

```

```
c = 0.0057;%System parameters determined from Lab 1 torsional
```

```
c1 = 0;  
c2 = 0.001;  
c3 = 0.01;  
c4 = 0.05;  
c5 = 0.2;
```

```
z1 = (c + c1)/(2*sqrt(K*J));  
z2 = (c + c2)/(2*sqrt(K*J));  
z3 = (c + c3)/(2*sqrt(K*J));  
z4 = (c + c4)/(2*sqrt(K*J));  
z5 = (c + c5)/(2*sqrt(K*J));
```

```
figure(1);  
hold all  
plot(F1, a1, 'DisplayName', ['Damping ratio ' num2str(z1)]);  
plot(F2, a2, 'DisplayName', ['Damping ratio ' num2str(z2)]);  
plot(F3, a3, 'DisplayName', ['Damping ratio ' num2str(z3)]);  
plot(F4, a4, 'DisplayName', ['Damping ratio ' num2str(z4)]);  
plot(F5, a5, 'DisplayName', ['Damping ratio ' num2str(z5)]);  
legend show  
xlabel('Frequency (Hz)');  
ylabel('Amplitude (rad)');  
hold off
```

```
%Question 8
```

```
[F5,a5]=readfreq('C:\Documents and  
Settings\roboclub\Desktop\Lab5\B6\ex2t5.txt','m');  
[F6,a6]=readfreq('C:\Documents and  
Settings\roboclub\Desktop\Lab5\B6\ex2t6.txt','m');  
[F7,a7]=readfreq('C:\Documents and  
Settings\roboclub\Desktop\Lab5\B6\ex2t7.txt','m');
```

```
k6 = 1.5;  
Jmasses = 0.0187; %determined in torsional lab 1  
cmasses = 0.0013;
```

```
z6 = (c + c2)/(2*sqrt((K+k6)*J));  
z7 = (cmasses + c2)/(2*sqrt(K*Jmasses));
```

```
figure(2);  
hold all  
plot(F5, a5, 'DisplayName', 'Overdamped');  
plot(F6, a6, 'DisplayName', 'Stiffer spring');  
plot(F7, a7, 'DisplayName', 'Increased inertia');  
legend show  
xlabel('Frequency (Hz)');  
ylabel('Amplitude (rad)');  
hold off
```

```
%Question 9
```

```
[t,f,val]=readenc('C:\Documents and  
Settings\roboclub\Desktop\Lab5\B6\ex3t1.txt','d',1);
```

```

w=3;
T=1/w;
sr=1000;
a=length(val);
val2=val(floor(a-4*T*sr):floor(a-3*T*sr));%
f2=f(floor(a-4*T*sr):floor(a-3*T*sr));
t2=0:1/sr:(length(f2)-1)*0.001;
figure(3);
plot(t2,val2)
hold on
plot(t2,f2,'g')
amp1=(max(val2)-min(val2))/2
indp1=find(val2==max(val2));
plot(t2(indp1(1)),val2(indp1(1)),'r*')
indp2=find(f2==max(f2));
plot(t2(indp2(1)),f2(indp2(1)),'r*')
xlabel('time (s)')
legend('Response (rad)','Force (N)')
hold off
pha1=(t2(indp2(1))-t2(indp1(1)))*2*pi/T

[t,f,val]=readenc('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex3t2.txt','d',1);
w=4.8;
T=1/w;
sr=1000;
a=length(val);
val2=val(floor(a-4*T*sr):floor(a-3*T*sr));%
f2=f(floor(a-4*T*sr):floor(a-3*T*sr));
t2=0:1/sr:(length(f2)-1)*0.001;
figure(4);
plot(t2,val2)
hold on
plot(t2,f2,'g')
amp2=(max(val2)-min(val2))/2
indp1=find(val2==max(val2));
plot(t2(indp1(1)),val2(indp1(1)),'r*')
indp2=find(f2==max(f2));
plot(t2(indp2(1)),f2(indp2(1)),'r*')
xlabel('time (s)')
legend('Response (rad)','Force (N)')
hold off
pha2=(t2(indp2(1))-t2(indp1(1)))*2*pi/T

[t,f,val]=readenc('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex3t3.txt','d',1);
w=5.1;
T=1/w;
sr=1000;
a=length(val);
val2=val(floor(a-4*T*sr):floor(a-3*T*sr));%
f2=f(floor(a-4*T*sr):floor(a-3*T*sr));
t2=0:1/sr:(length(f2)-1)*0.001;
figure(5);
plot(t2,val2)
hold on

```

```

plot(t2,f2,'g')
amp3=(max(val2)-min(val2))/2
indp1=find(val2==max(val2));
plot(t2(indp1(1)),val2(indp1(1)),'r*')
indp2=find(f2==max(f2));
plot(t2(indp2(1)),f2(indp2(1)),'r*')
xlabel('time (s)')
legend('Response (rad)','Force (N)')
hold off
pha3=(t2(indp2(1))-t2(indp1(1)))*2*pi/T

[t,f,val]=readenc('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex3t4.txt','d',1);
w=6;
T=1/w;
sr=1000;
a=length(val);
val2=val(floor(a-4*T*sr):floor(a-3*T*sr));%
f2=f(floor(a-4*T*sr):floor(a-3*T*sr));
t2=0:1/sr:(length(f2)-1)*0.001;
figure(6);
plot(t2,val2)
hold on
plot(t2,f2,'g')
amp4=(max(val2)-min(val2))/2
indp1=find(val2==max(val2));
plot(t2(indp1(1)),val2(indp1(1)),'r*')
indp2=find(f2==max(f2));
plot(t2(indp2(1)),f2(indp2(1)),'r*')
xlabel('time (s)')
legend('Response (rad)','Force (N)')
hold off
pha4=(t2(indp2(1))-t2(indp1(1)))*2*pi/T

[F,a]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t1.txt','m');
[F,p]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t1.txt','p');

figure(7)
hold on
subplot(2,1,1)
hold on
plot(F, a/max(a));
plot(3,amp1/(0.75/2.69), 'r*')
plot(4.8, amp2/(0.75/2.69), 'g*')
plot(5.1, amp3/(0.75/2.69), 'k*')
plot(6, amp4/(0.75/2.69), 'b*')
xlabel('Frequency (Hz)');
ylabel('Amplitude Ratio');

hold off
subplot(2,1,2)
hold on
plot(F, p)
plot(3,pha1, 'r*')

```

```

plot(4.8, pha2, 'g*')
plot(5.1, pha3, 'k*')
plot(6, pha4, 'b*')
legend('Experiment 2, Test 1 Response','Experiment 3, Test 1', 'Experiment 3,
Test 2','Experiment 3, Test 3','Experiment 3, Test 4')
xlabel('Frequency (Hz)');
ylabel('Phase Ratio');

hold off
hold off

%Question 10
clear all
close all
m = 0.0024;%System parameters determined from Lab 1 torsional
k = 2.69;%System parameters determined from Lab 1 torsional
c = 0.0057 + 0.001;%System parameters determined from Lab 1 torsional
x0=0; %zero initial conditions
v0=0;
Tsim=40; %simulation time
F=0.75;%Forcing amplitude
fres=1:0.5:10;%create the vector that contains the frequencies on which the
system is going to be excited(1-10Hz with a resolution of 0.5 Hz)
for i=1:length(fres);
    freq=fres(i);%pick the frequency to be run for this iteration from the
pre-created frequency vector
    sim ('simstep'); %call the simulation

    T = 1/freq;
    sr = 1000;
    a=length(x);
    val2=x(floor(a-4*T*sr):floor(a-3*T*sr));%
    f2=f(floor(a-4*T*sr):floor(a-3*T*sr));
    t2=0:1/sr:(length(f2)-1)*0.001;
    amp=(max(val2)-min(val2))/2
    indp1=find(val2==max(val2));
    indp2=find(f2==max(f2));
    pha=(t2(indp2(1))-t2(indp1(1)))*2*pi/T

    subplot(2,1,1)
    plot(freq,amp,'o')%on the top, plot the determined amplitude at the
prescribed frequency (normalize the amplitude by dividing it by the static
displacement
    hold on
    subplot(2,1,2)
    plot(freq,pha,'o')%on the bottom, plot the determined phase at the
prescribed frequency
    hold on
    drawnow %this shows the plotted point immediately after it is plotted so
you can see your FRF is dynamically created
end
[Freq,a]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t1.txt','m');
[Freq,p]=readfreq('C:\Documents and
Settings\roboclub\Desktop\Lab5\B6\ex2t1.txt','p');
subplot(2,1,1)

```

```

plot(Freq,a)
subplot(2,1,2)
plot(Freq, p)

```

%Question 12

```

t = (0:0.001:10);
f1 = -.3.*sawtooth((t-.5)*pi,.5);
f2 = 0.2432.*sin(pi.*t);
f3 = f2 + -0.027.*sin(3.*pi.*t);
f4 = f3 + 0.0097.*sin(5.*pi.*t);
f5 = f4 + -0.005.*sin(7.*pi.*t);
f6 = f5 + 0.003.*sin(9.*pi.*t);
figure()
subplot(2,1,1)
plot(t,f1)
xlabel('Frequency (Hz)'),ylabel('Force (N)');
title('Forcing Functions')
hold all
plot(t,f2);plot(t,f3);plot(t,f4);plot(t,f5);plot(t,f6)
[tt,force1,disp1]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t1.txt','d',1);
[tt,force2,disp2]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t2.txt','d',1);
[tt,force3,disp3]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t3.txt','d',1);
[tt,force4,disp4]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t4.txt','d',1);
[tt,force5,disp5]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t5.txt','d',1);
[tt,force6,disp6]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t6.txt','d',1);
hold off
subplot(2,1,2)
plot(tt,disp1)
xlabel('Frequency (Hz)'),ylabel('Displacement (cm)');
title('Responses')
hold all
plot(tt,disp2);plot(tt,disp3);plot(tt,disp4);plot(tt,disp5);plot(tt,disp6);
hold off
legend('Test 1','Test 2','Test 3','Test 4','Test 5','Test 6')

```

%Question 13

%Part A

```

[freq1,mag1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','m');
[freq1,phase1] = readfreq('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex2t2.txt','p');
[m1,c1,k1] = fitfrf(freq1,mag1,phase1);
legend('Experimental','Fit')
subplot(2,1,1)
hold on
plot(.5,0:.01:1)

```

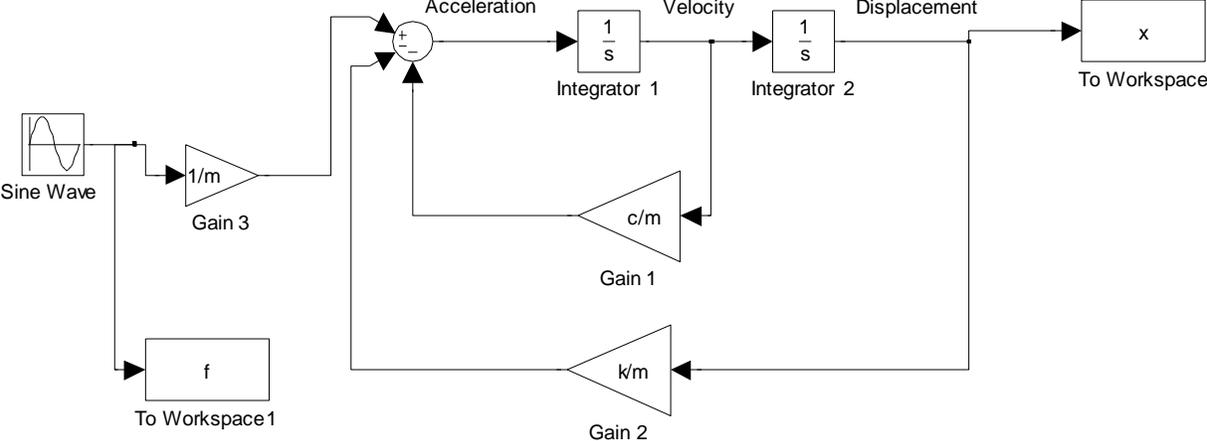
```

plot(1.5,0:.01:1)
plot(5*.5,0:.01:1)
plot(7*.5,0:.01:1)
plot(9*.5,0:.01:1)
subplot(2,1,2)
hold on
plot(.5,-4:.01:4)
plot(1.5,-4:.01:4)
plot(5*.5,-4:.01:4)
plot(7*.5,-4:.01:4)
plot(9*.5,-4:.01:4)

%Part B
W0 = .5*2*pi; %from the graph
[tt2,force2,disp2]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t2.txt','d',1);
[tt3,force3,disp3]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t3.txt','d',1);
[tt4,force4,disp4]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t4.txt','d',1);
[tt5,force5,disp5]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t5.txt','d',1);
[tt6,force6,disp6]=readenc('C:\Documents and Settings\roboclub\Desktop\Lab 3
Rectilinear\B6\ex5t6.txt','d',1);
figure()
hold on
subplot(5,1,1)
plot(tt2,disp2/100), hold on
plot(tt2,.2432*.3*sin(W0.*tt2+0),'r')
xlabel('Time (s)'),ylabel('Amplitude (N/rad)')
title('Test 2')
subplot(5,1,2)
plot(tt3,disp3/100), hold on
plot(tt2,-0.027*.15*sin(3*W0.*tt2-(0.03*2*pi))+.2432*.3*sin(W0.*tt2+0),'r')
xlabel('Time (s)'),ylabel('Amplitude (N/rad)')
title('Test 3')
subplot(5,1,3)
plot(tt4,disp4/100), hold on
plot(tt4,.13*0.0097*sin(5*W0.*tt4-(2*pi*.06))+-0.027*.15*sin(3*W0.*tt2-
(0.03*2*pi))+.2432*.3*sin(W0.*tt2+0),'r')
xlabel('Time (s)'),ylabel('Amplitude (N/rad)')
title('Test 4')
subplot(5,1,4)
plot(tt5,disp5/100), hold on
plot(tt4,-0.005*.15*sin(7*W0.*tt4-(2*pi*.11))+.13*0.0097*sin(5*W0.*tt4-
(2*pi*.06))+-0.027*.15*sin(3*W0.*tt2-
(0.03*2*pi))+.2432*.3*sin(W0.*tt2+0),'r')
xlabel('Time (s)'),ylabel('Amplitude (N/rad)')
title('Test 5')
subplot(5,1,5)
plot(tt6,disp6/100), hold on
plot(tt4,.29*0.003*sin(9*W0.*tt4-(2*pi*.23))+-0.005*.15*sin(7*W0.*tt4-
(2*pi*.11))+.13*0.0097*sin(5*W0.*tt4-(2*pi*.06))+-0.027*.15*sin(3*W0.*tt2-
(0.03*2*pi))+.2432*.3*sin(W0.*tt2+0),'r')
xlabel('Time (s)'),ylabel('Amplitude (N/rad)')
title('Test 6')
legend('Observed','Calculated from FRF')

```

Simulink Model:



10. Suggestions/Feedback for Improvement of the Lab

-decrease number of questions, because we spent much longer on the analysis on this report than the previous ones

Each of the undersigned lab team members hereby declares that:

1. he/she has participated in the entire lab session,
2. he/she has read and approved the entire content of this report,
3. each and all of the undersigned team members have participated in composing this report, and
4. this report is the original work of the undersigned team members.

	Team Member* Name	Team Member Signature
1.	<u>Brad Hall</u> (MAIN AUTHOR)	_____
2.	<u>Rich Pantaleo</u> (EDITOR #1)	_____

* EACH MEMBER OF THE TEAM IS REQUIRED TO PARTICIPATE FULLY IN ALL ASPECTS OF THIS REPORT.

Graded by	Date	Grade