

Laser Vibrometry Lab

Objective

Laser vibrometry provides a method for quantitatively characterizing surface vibrations in a mechanical system. In this lab, a Polytec PDV 100 Laser Doppler Vibrometer (LDV) will be used to measure the displacement, velocity, and acceleration of mechanical vibrations in a speaker cone when harmonically excited at various frequencies. Empirical measurements will then be used to determine the damping ratio of the speaker cone and give insight to the mechanical limits of the system.



Theory

Mechanical systems undergoing repeated loading and unloading or frequent motion will also experience some significant vibration. The magnitude of these vibrations can impact the integrity and lifetime of the mechanical system making the amount of vibration an important parameter to consider in the design of the system. This idea can be illustrated with a simple bench experiencing a load. Each time the bench is loaded and unloaded by an individual sitting on the bench then standing again, some vibration occurs. This vibration is most likely not noticed because the bench is designed to withstand the load of a person. However, if a person stands on top of the bench and jumps up and down repeatedly, the vibration is easily seen. If the jumping continues long enough under a high enough load, the bench could break.. Similar types of failures can occur in more complicated systems. A bridge, for example, would experience similar types of vibrations when an object is traveling across, or the car itself would experience some types of vibrations in the axle or sheet metal when traveling at high speeds. Measuring these vibrations helps to ensure that the design will not fail under real-world conditions.

These vibrations are characterized by the natural frequency, which is dependent on mass on and the spring constant, and the damping ratio. The natural frequency is the frequency at which the material is oscillating at indefinitely once set in motion, granted that there is no damping. However, if damping is put into the system, the oscillations

will eventually die out, and the materials will experience less vibration over time. Therefore, by considering the natural frequency of materials, the system can be designed to increase damping, which will decrease strain on the materials and thus decrease the likelihood of failure.

The Laser Doppler Vibrometer allows for the measurement of vibrations by projecting a laser at the surface of interest. When the surface vibrates, the velocity of the vibration is calculated by the software using the relationship illustrated by the Doppler Effect. From the velocity, other data can be obtained such as the displacement and acceleration.

In this lab, displacement, velocity, and acceleration of the vibrations of a speaker cone will be measured in response to a harmonic input. In this system, the speaker cone has a mass that gives it an inertial force contribution, an elastic stiffness that contributes to the spring force, and some damping forces. When all these forces are present, the system can be described as second order system by the following equation:

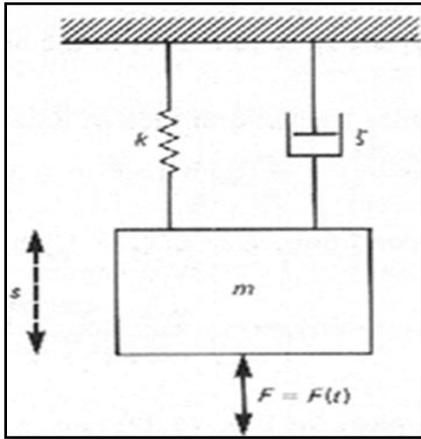


Figure 1: Generalized dynamic system.

$$m \frac{d^2s}{dt^2} + c \frac{ds}{dt} + ks = F(t) \tag{1}$$

Where s is the displacement, m is the mass, c is the damping coefficient, and k is the spring constant. $F(t)$ the input force that excites the system, can be harmonic or a step input.

The damping coefficient is related to the damping ratio by the equation:

$$\xi = \frac{c}{2\sqrt{km}} \tag{2}$$

For a second order system with a step input, the underdamped ($\xi < 1$) solution to equation (1) is:

$$\frac{s}{s_s} = 1 - e^{-\xi\omega_n t} \sqrt{\frac{1}{1 - \xi^2}} \cos(\omega_{nd}t - \beta),$$

$$\beta = \tan^{-1}\left[\frac{\xi}{\sqrt{1 - \xi^2}}\right],$$
(3)

Where ω_{nd} is the natural frequency.

The overdamped ($\zeta > 1$) solution to the equation would be:

$$\frac{P}{P_s} = \frac{-\xi - \sqrt{\xi^2 - 1}}{2\sqrt{\xi^2 - 1}} e^{(-\xi - \sqrt{\xi^2 - 1})\omega_n t} + \frac{\xi - \sqrt{\xi^2 - 1}}{2\sqrt{\xi^2 - 1}} e^{(-\xi + \sqrt{\xi^2 - 1})\omega_n t} + 1.$$
(4)

The image below shows an example of overdamped, underdamped, and critically damped responses of a second order system to a step input.

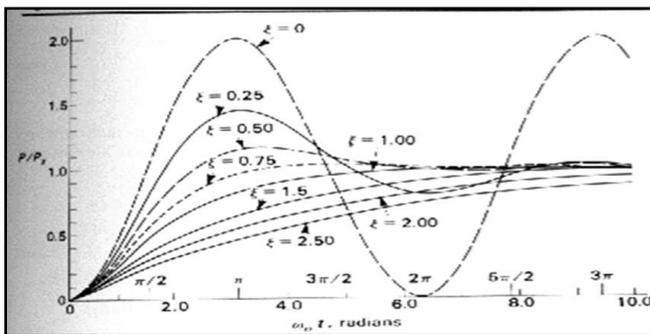


Figure 2: Second Order System Response to a step input

For a harmonically excited system:

$$F(t) = F_0 \sin(\Omega t) \quad (4)$$

And thus, the solution to equation (1) becomes

$$\frac{s_d}{s_s} = \frac{P_d}{P_s} = \frac{1}{\sqrt{[1 - (\Omega/\omega_n)^2]^2 + [2\xi\Omega/\omega_n]^2}}$$
(5)

This solution gives the normalized amplitude where s_d is the amplitude of the periodic steady state displacement and

Ω = the frequency of excitation (rad/s),

$$\phi = \tan^{-1} \left[\frac{2\xi\Omega/\omega_n}{1 - (\Omega/\omega_n)^2} \right] = \text{the phase angle,}$$

$$s_s = F_0/k,$$

(6)

One method to estimate the damping is to harmonically excite the system through a series of frequencies, plot the amplitude ratio vs frequency ratio to obtain a curve like the one shown in figure 1. A precise determination of damping ratio can be obtained by also measuring the amplitude of the velocity, acceleration, and displacement at one frequency and using equations 1 and 2 to calculate the damping ratio.

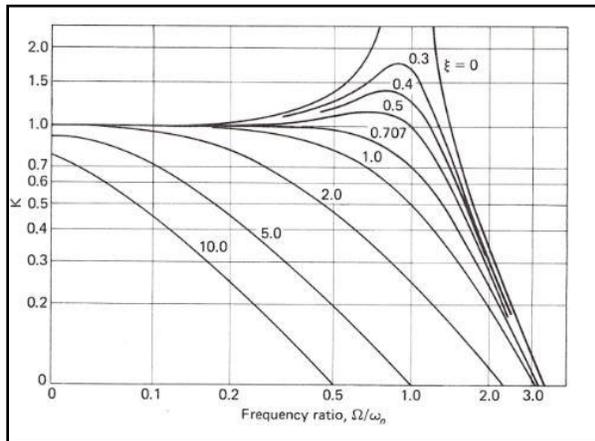


Figure 3: Theoretical damping curves [1].

Equipment

- PDV 100 Portable Digital Vibrometer Sensor
- BNC Cable
- USB Polytec Hardlock
- PDV 100 Portable Digital Vibrometer Power supply
- ArtDio Portable Computer Speaker
- USB Cable
- Polytec VIB – E – 220 Data Acquisition System
- Tripod
- Laptop Computer

Procedure

System Set-Up

1. Assemble the PDV 100 Portable Digital Vibrometer Sensor on top of a tripod
2. Connect BNC cable to “Analog Out” connection on the PDV 100 Portable Digital Vibrometer Sensor
3. Connect the other end of BNC cable to “Velo” on Polytec VIB – E – 220 Data Acquisition System
4. Connect Polytec VIB – E – 220 Data Acquisition System to a laptop using USB cable
5. Plug portable speakers to the headphone jack on the computer
6. Plug the PDV 100 Portable Digital Vibrometer Power supply to an outlet and the other end; plug it into PDV 100 Portable Digital Vibrometer Sensor that reads “12V, max. 15W.”
7. Plug the USB Polytec Hardlock to one of the USB ports of the computer.
8. Open the Laser lens cover. (Caution: Laser light is damaging to eyes. Do not look into the Laser light and make sure you close the lens cover when the Laser is not in use.)
9. Turn the dial on the front of the laser as shown below to focus the Laser light on the speaker cone.



Figure 4: System set-up.

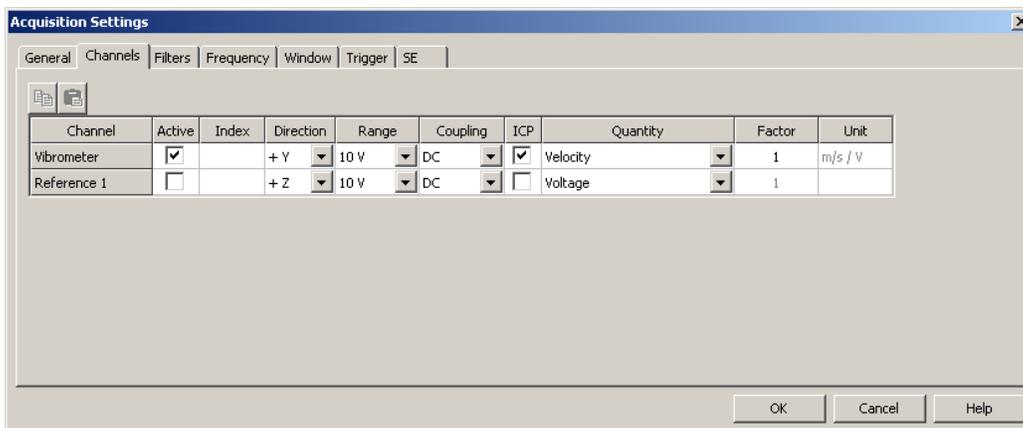
Experiment 1: Harmonic Input into Speaker Cone ($\Omega=2\pi*1\text{kHz}$)

In experiment 1, you will find the amplitude of the frequency response of the speaker cone to an input $F(t)=1\sin(\Omega t)$ where $\Omega=2*\pi*1\text{kHz}$. Record the frequency response amplitude at 1 kHz for displacement, velocity, acceleration, and export the graph.

1. Open VibrSoft Software
2. From the menu bar, select Acquisition → Settings

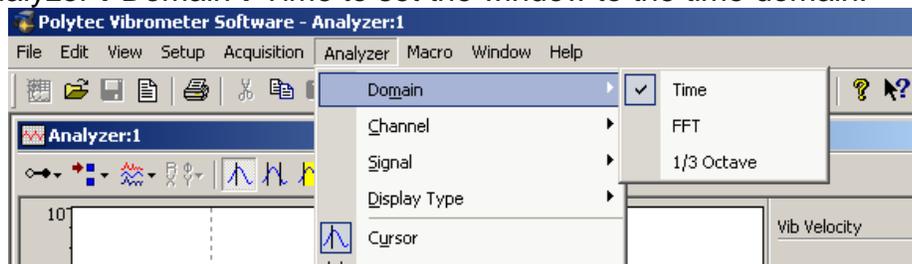


- a. A menu should pop up. Click the “**Channel**” tab and ensure settings are as shown in the image below.



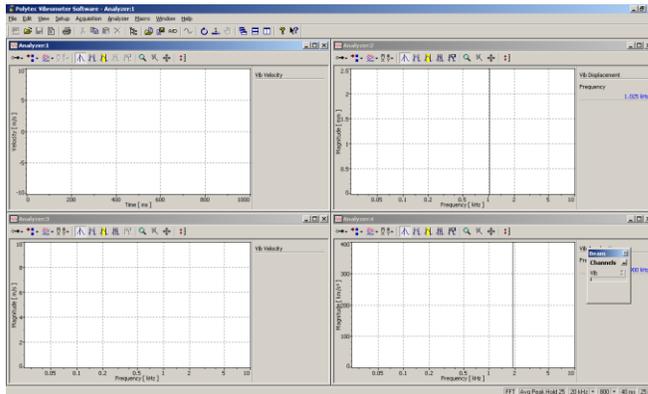
- b. Click on the ‘**General**’ tab and ensure that “peak” is selected

3. Ensure that ‘**Analyzer 1**’ window is highlighted (top should be blue not gray)
4. Select Analyzer→Domain→Time to set the window to the time domain.



5. Ensure that the analyzer records in magnitude rather than dB by selecting Analyzer→Display Type→Velocity
6. Turn on the cursor by selecting Analyzer→Cursor
7. To view displacement signal in this window, select Analyzer→Signal→Displacement
8. Move the blue cursor to 1000 ms (or 1kHz if in the frequency domain).

9. Now Select Window→New Window. This opens up a new analyzer window. Do this twice more so that 4 analyzer windows are open as shown below.



Repeat steps 3-8 with the but ensure the settings are as shown in the table below:

Analyzer Window Number	Analyzer Domain	Analyzer Signal	Analyzer Display Type
1	Time	Velocity	Magnitude
2	FFT	Displacement	Magnitude
3	FFT	Velocity	Magnitude
4	FFT	Acceleration	Magnitude

10. Open Audacity
 - a. A menu would pop up now. Under the drop down menu for the waveform, choose “Sine.”
 - b. Frequency/Hz setting: 1000
 - c. Amplitude: 1
 - d. Length (seconds): 30 (Set length longer if necessary.)
 - e. Click “Generate Tone.”
 - f. Click the “**Play Button.**”
11. Then click “Acquisition” → “Continuous” (F8).
12. Let it run for least 5 seconds then stop the data collection. Click “Acquisition” → “Stop” (F10).
13. Stop the sound in the Audacity.
14. Record the magnitude at 1 kHz in each analyzer screen. Use right click on the mouse to get the “auto scale” on each screen to make the graph more visually proportional.
15. Highlight Analyzer 1 screen and select File → Save Graphic
16. Save Graphic as Group_Letter_Image_Displacement_1kHz_TimeDomain.JPEG
17. Export → ASCII and save as: Group_Letter_Displacement_1kHz_TimeDomain.xls
18. Repeat Steps 12-16 for the other three analyzer windows. Ensure that file names reflect data collected in the window:

Analyzer Window No.	Image File Name
1	Group_Letter_Image_Displacement_1kHz_TimeDomain

2	Group_Letter_Image_Displacement_1kHz_Frequency Domain
3	Group_Letter_Image_velocity_1kHz_FrequencyDomain
4	Group_Letter_Image_acceleration_1kHz_FrequencyDomain

Experiment 2

In experiment 2, investigate the frequency contents of two sound sources in the frequency domain and make some qualitative observation about what frequency ranges are correlated with the melody and bass.

1. Repeat Steps 1 – 9 in the experiment 1.
2. Pick a **Classical** music piece from **YouTube** and play it for about 25 seconds.
3. Save the file using Export command.
4. Pick a music **rich in beats** (Electronic/Hip Hop) music piece from **YouTube** and play it for about 25 seconds.
5. Save the file using Export command.

Data Reduction:

Constants: assume $k=63\text{g/mm} \cdot g$, $g=9.81\text{m/s}^2$ and $m=7\text{ mg}$

Given that $\omega_n = \sqrt{k/m}$, use data gathered in experiments 1 and 2 and equations 1, 2, 5 and 6 to calculate ζ , the damping ratio. Use the time domain graph to ensure that your t in equation 1 is correlated to the peak amplitude (acquisition settings ensure that the magnitude shown in the frequency domain is at peak amplitudes).

Questions:

1. Determine the phase angle for the data from the first experiment.
2. Find c when the system is critically damped.
3. What can you say about the frequency contents of the two music pieces in Experiment 2?
4. How is '**beat**' of music related to frequency?

References

[1] Beckwith, T. G., Roy D. Marangoni, and John H. Lienhard. *Mechanical Measurements*. Upper Saddle River, NJ: Pearson/Prentice Hall, 2007. Print.