ME 495 – Mechanical and Thermal Systems Lab

Department of Mechanical Engineering

Laser Vibrometry

Group E

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February 5, 2018
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Objective of the Experiment

The objective of this experiment is to use a laser vibrometer, specifically a Polytec PDV 100 Laser Doppler Vibrometer, to record the vibrations of a speaker playing first a high pitched tone, then a classical song and finally a hip hop song. By recording the displacement, velocity, and acceleration of the speaker cone, we can then find the damping coefficient and damping ratio, allowing us to know the mechanical limits of that particular system.

Almost every mechanical system undergoes vibrations from repeated loading or unloading of a force or weight. Be it jumping up and down on a table or the harmonic vibrations from a speaker cone, these vibrations can lead to understanding the mechanical limits of a system. The vibrations from a speaker are characterized by their natural frequency, which is dependant on the mass of the system, the spring constant, and the damping ratio, when there is one. When damping is introduced into the system, the oscillations from the vibrations will eventually die down, meaning that the materials of the system will last longer. So by taking the natural frequency of a system into account, a damping ratio can be designed to increase the life of the materials.

The laser vibrometer uses the Doppler Effect to find the velocity of the vibrations. Then by using Fourier transforms, we can then find the displacement and acceleration of those vibrations.
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 ratio is related to the damping coefficient by the equation:

$$\xi = \frac{c}{2\sqrt{km}}$$  \hspace{1cm} (2)

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

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

$$\beta = \tan^{-1}\left[\frac{\xi}{\sqrt{1 - \xi^2}}\right],$$  \hspace{1cm} (3)
Where $\omega_{nd}$ is the natural frequency.

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

$$\frac{P}{P_s} = \frac{-\xi - \sqrt{\xi^2 - 1}}{2\sqrt{\xi^2 - 1}} e^{(-\xi - \sqrt{\xi^2 - 1})\omega_{nd}} + \frac{\xi - \sqrt{\xi^2 - 1}}{2\sqrt{\xi^2 - 1}} e^{(-\xi + \sqrt{\xi^2 - 1})\omega_{nd}} + 1.$$  \hspace{1cm} (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](image)

For a harmonically excited system:

$$f(t) = f_0 \sin(\omega t)$$

And thus, the solution to equation (1) becomes

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

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

Below is the list of equipment that was used for this experiment:

- 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
- Computer

A laser Doppler Vibrometer (LDV) is a scientific instrument used to measure vibrations through a laser. The PDV-100 Vibrometer measures the vibration velocity of a system using Doppler-shifted, retro-reflected laser light. This non-contact technique monitors and measures a system’s natural frequency.

![Diagram of a laser Doppler vibrometer](image)

**Figure 4: Basic components of a laser Doppler vibrometer**
Between the PDV 100 and the computer is the Polytec VIB – E – 220 Data Acquisition System. The following are the features and benefits of the VIB – E – 220 Data Acquisition System:

- 2 channel, 20 kHz
- ± 10V input
- IEPE (ICP) support for reference channel
- Up to 204,800 FFT lines
- Export filters and macro programming
- No driver installation
- 64 MSamples continuous sampling

The specifications on the speakers include:

- Total output: 2 watts (1W per channel)
- Speakers have 2x1.5" full-range drivers and frequency response of 200Hz - 18kHz
- Power source: USB
- Size: 5.9"H x 2.17"W x 3.93"D
- 3.5mm Stereo Input Connection

Here is what the setup should look like:
Experimental Procedure

Before beginning the experiment, ensure that all equipment is working properly, and all systems are turned on. The computer was turned on and the lens from the Laser Vibrometer was removed. The laser was aligned along the center of the speaker. Both experiments were executed with the data being recorded and measured on the computer.

In the first experiment, VibrSoft software was opened to measure displacement. Following the procedure, FFT, Magnitude, and Cursor, was also opened. The vertical line was moved and set to a frequency of 1 kHz. To start recording data, the F8 was pressed when the Displacement window was on screen. Under the Settings menu,
“Channel” was selected on the pop-up window. To set the Vibrometer channel, the Active box was selected, and the direction was set to Y+, the Coupling was set to DC, ICP was clicked, and the Quantity to Displacement was set. “Peak” was selected under the General tab. Audacity was opened, “Sine” was set as the waveform, the Frequency was set at 1000 Hz, the Amplitude was set at 1, and the Length was set for 30 seconds. Audacity was used to generate the waveform output.

Once all the settings were set up, the “Generate Tone” and the Play buttons were pressed to begin the first run of the experiment. The run lasted ten seconds, with F10 being pressed to end the run. The magnitudes of each run were recorded in the log book. VibrSoft was used to change the graph to a Time Domain.

The above procedure was repeated for the second experiment. The second experiment determined the acceleration of the speaker cone. The Signal was set to Acceleration to record the acceleration of the speaker cone. In the vibrometer channel, Quantity was set to Acceleration. F8 started the run, F10 ended the run after five seconds. The magnitude was then recorded. The graphs and data were then exported. The VibrSoft software was used to graph the recorded data in both the time and frequency domains.

The procedure was repeated again to record the velocity of the cone of the speaker. During the run, the Signal and Quantity were set to Velocity. The tone played for five seconds, using F8 to start the run, and F10 to end the run. The data was exported to excel, and once again, the VibrSoft data was graphed in both the time and frequency domains.
The second stage of the experiment was similar to the first stage, however, as opposed to generating a sine wave, two different types of music were played through the speakers. One being a classical piece, the other being an electronic piece. Each song was played separately for 25 seconds, and the displacement of the cone was recorded. The data of each song is to be exported and individually compared to each other.

**Experimental Results**

Constants: assume spring constant is \( k = 63 \frac{N}{mm} \times 9.81 \frac{m}{s^2} = 618 \frac{N}{m} \) and mass of speaker cone is \( m = 7 \ mg \).

<table>
<thead>
<tr>
<th></th>
<th>Displacement (m)</th>
<th>Velocity (m/s)</th>
<th>Acceleration (m/s^2)</th>
<th>Damping Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>8.11e-5</td>
<td>1.3547</td>
<td>3200.3</td>
<td>0.22481</td>
</tr>
<tr>
<td>Beethoven</td>
<td>1x10^-5</td>
<td>2.4976</td>
<td>38.98</td>
<td>0.22456</td>
</tr>
<tr>
<td>Imagine Dragons -Believer</td>
<td>1x10^-7</td>
<td>2.3752</td>
<td>13.97</td>
<td>0.22448</td>
</tr>
</tbody>
</table>
Figure 5: 1 kHz Sine Tone

Figure 6: Beethoven’s 5th Symphony
Discussion of Results

After all the data was collected, as seen in figures 5, 6, and 7, the results were analyzed. Using equations 1, 2, 5, and 6, the damping ratio for the 1kHz sine tone was 0.22481. With $\zeta < 1$, this shows that the speaker was underdamped. For experiment 2, the damping ratios calculated for the classical and loud bass music were both 0.22456. These damping ratios clearly how a similarity and consistency to the result seen in experiment 1. The results reflect an underdamped speaker, which means the speaker is blown out. Use of the speaker brings wear to it components, thus its functionality, losing the efficiency of the speaker. The spring coefficient, $k$, is lowered throughout the period.
of use. Reexamining the calculation process, the actual spring constant of the speaker cone is less than 618 N/m, the value used in the calculations.

Some possible sources of error may have been human error. The laser may have been off from the absolute center of the speaker cone and may have affected the data collected. Another source of human error may have been outside vibrations. There were machines running and individuals talking that may have affected some of the data collected as well. The last possible source of error may have occurred is miscalibration of the laser. Lasers are particularly very accurate with their readings, yet is possible the laser may have not functioned properly.

The results seen in Table 1 correlate with the theory discussed in the Objective of the Experiment. The vibrations recorded reflects how the damping ratio relates to the mechanical performance and limitations of the speaker. The damping ratio calculated is considered underdamped and the vibrations of the speaker are not as easily controlled if the speaker was overdamped. Underdamped speakers cannot control the vibration of the frequency emitted well, and as a result, the quality of the sound coming from the speaker cone is hindered.

**Questions**

1. Determine the phase angle for the data from the first experiment.

With the damping ratio of 0.2245, and \( \frac{\omega_n}{\omega} = 0.668 \)

\[ \phi = \tan \left( \frac{2 \pi \frac{\omega}{\omega_n}}{1 - \left( \frac{\omega}{\omega_n} \right)^2} \right) = 29 \text{ degrees} \]
2. Find c when the system is critically damped.

Knowing that the system is critically damped ($\zeta = 1$), we can solve for the damping coefficient, c, via the equation for the damping ratio.

\[
c = 2\zeta \sqrt{\frac{k}{m}} = 2(1) \sqrt{(618)(10E - 3)} = 4.1598 \ \frac{Ns}{m}
\]

3. What can you say about the frequency contents of the two music pieces in Experiment 2?

The classical song displayed a much higher frequency range due to the different instruments were played in the song. The song by Imagine Dragon displayed a much lower frequency range which reflects the type of music being played. This song contained a large amount of lower frequencies which directly relate to what we know as bass in this case. However, this can be an experimental issue with the noise from the other experiments going on at that time.

4. How is 'bass' of music related to frequency?

The beat of music is related to frequency because when two different interfering sound waves approach the ear, they interfere with each other which produce noise. The two frequencies are constructive and destructive interferences, which when subtracted from each other, the magnitude of the two values is equal to the frequency. Bass is
considered the lower frequency ranges while treble is considered the higher frequency range.

**Conclusion**

The Laser Vibrometry experiment brought the conclusion of the damping ratio of the speaker cone under analysis. The passing of time and use on the speaker affected the damping ratio, resulting in the speaker being blown. It is hard to really tell if the speaker was actually blown due to no theoretical damping ratio of the speaker given. Even so, the process of achieving the damping ratio deepened our knowledge as a group on this engineering analysis. The difficult thing about engineering is that sometimes theoretical practices or ideal states can overbear reality and the practical and real world use of engineering. This experiment was practical and mixed both the theory and real-world application of the material to achieve a result, a result that can be replicated consistently and seen through this lab report.
References


<https://blackboard.sdsu.edu/webapps/blackboard/content/listContent.jsp?course_id=_307459_1&content_id=_3826181_1&mode=reset>