System Design and Analysis of Turbulence to Determine Effect of Valve Stenosis on Blood Flow for Heart Murmur Application

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Abstract

Heart murmurs are abnormal sounds due to turbulent flow in the blood arising from abnormalities in one or more of the four heart valves in a human’s heart. There are many potential causes of heart murmurs in humans, but the focus of this project was on stenosis: the narrowing of a heart valve which prevents it from fully opening and closing. Many studies have empirically analyzed murmurs using qualitative assessments; however, few studies have attempted to use experimental data to provide quantifiable measures of the severity of a heart murmur. We constructed a physical system analogous to pulsatile blood flow through a heart with valve stenosis, using water pumped at a rate of 1Hz through a tube with a narrowed component that partially restricted the flow. Contact microphones were placed on the tubing near the restriction to collect vibration data from the flow. The power spectra of the vibration data from different severities of narrowness were compared to the power spectrum of the baseline measurement with no restriction. When the tube was restricted to about 20% of its initial cross-sectional area, energy was found to have been injected in the flow in the range of 40-60 Hz and 80-90 Hz. For a restriction in the tube to about 30% of its initial cross-sectional area, energy was found to have been injected in the flow in the range of 30-40 Hz, 70-80 Hz, and 90-110 Hz. This provides quantifiable evidence that an increase in the energy of the flow at certain frequencies indicates narrowing in the flow and can provide insights on the severity of the narrowing. More research is needed to determine why these peaks occur at these frequencies and to compare these results to a system that more closely resembles a heart with a murmur.

Introduction

Heart disease affects thousands of people each year, and one indication of an underlying heart issue is a heart murmur. Caused by abnormal sounds due to turbulent blood flow in or near a person’s heart, heart murmurs have many possible causes, but the focus of this project was on stenosis. Valve stenosis is the narrowing of a heart valve (Figure 1), preventing it from fully opening or closing. Previous studies have been done trying to analyze and quantify murmurs based on heart sound data, and many of these studies have used the Fast Fourier Transform (FFT) in this analysis[1-3]. However, in these cases, researchers are analyzing heart murmurs from patients and therefore it is difficult to draw conclusions about heart murmurs in general. Few studies have looked experimentally at the relationship between stenosis narrowness and energy of the flow.

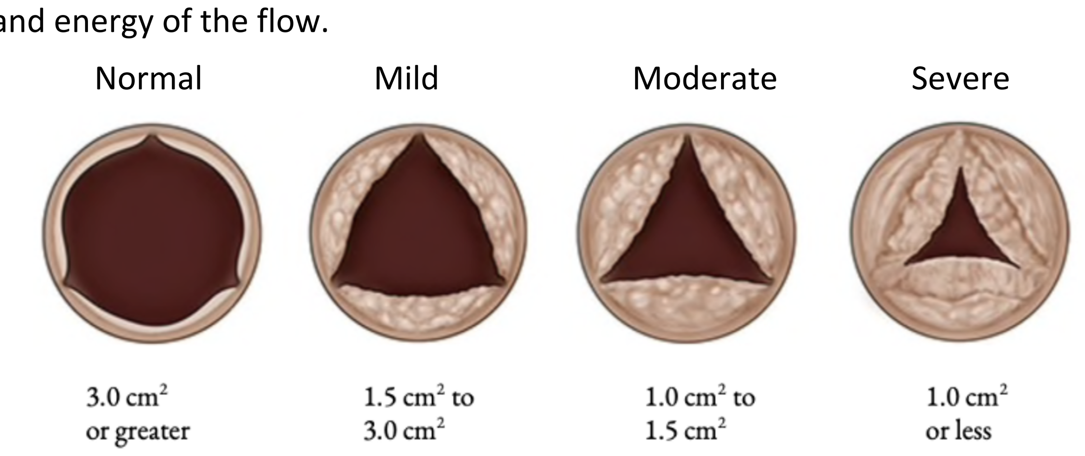

Figure 1: Stenosis severity levels in the aortic valve and the area of the opening [4]

Project Overview

- Project Goal: Determine a quantitative measurement of turbulence in the system relating to the severity of narrowness in the tube.
- Hypothesis: Increasing the severity of stenosis (narrowness) will cause an increase in turbulence, increasing energy and ranges of frequencies in the flow.

Methods

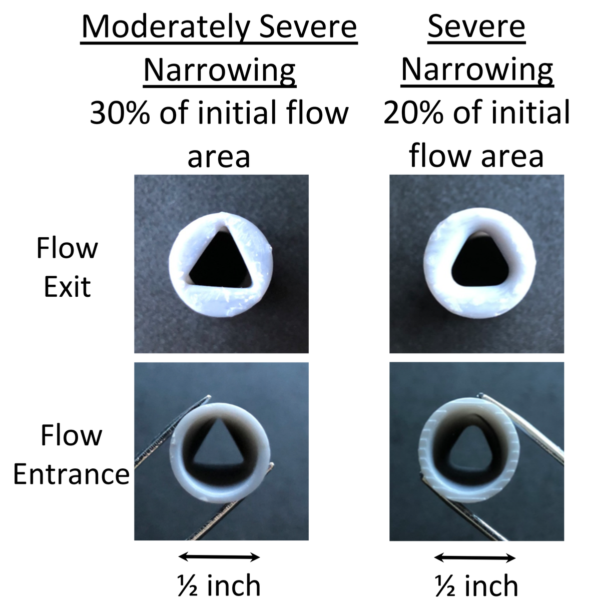

Figure 2: 3D-printed narrowings based on shape of heart valves (Figure 1)

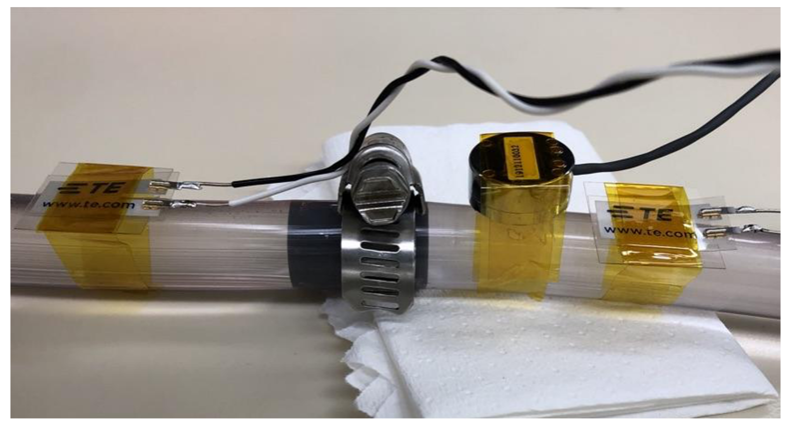

Figure 3: 3D printed narrowing secured by a hose clamp in the flexible tubing, surrounded by contact sensors on the tubing surface.

A closed-loop system was constructed with a water reservoir, ½” flexible tubing, a narrowed component, and a pump. Rigid “heart valves” were designed in SolidWorks based on the shape of actual aortic valves with stenosis and 3D printed (Figure 2). Each piece was ½ inch in diameter, 1 inch long, and had a tapered entrance to more closely resemble the aortic valve. These pieces were used to restrict flow, analogous to a heart valve with stenosis. For each type of narrowing, the piece was inserted into the tubing and contact sensors were placed on the surface of the tubing near the restriction (Figure 3). Four thirty-second trials were conducted for each narrowing, with water manually pumped at 1 Hz to mimic a heart beat of 60 bpm and keep a similar Reynolds number to the turbulent blood flow in the aorta. Vibration data of the flow was taken using a MATLAB code from the contact sensors at 1000 Hz.

Data Analysis and Results

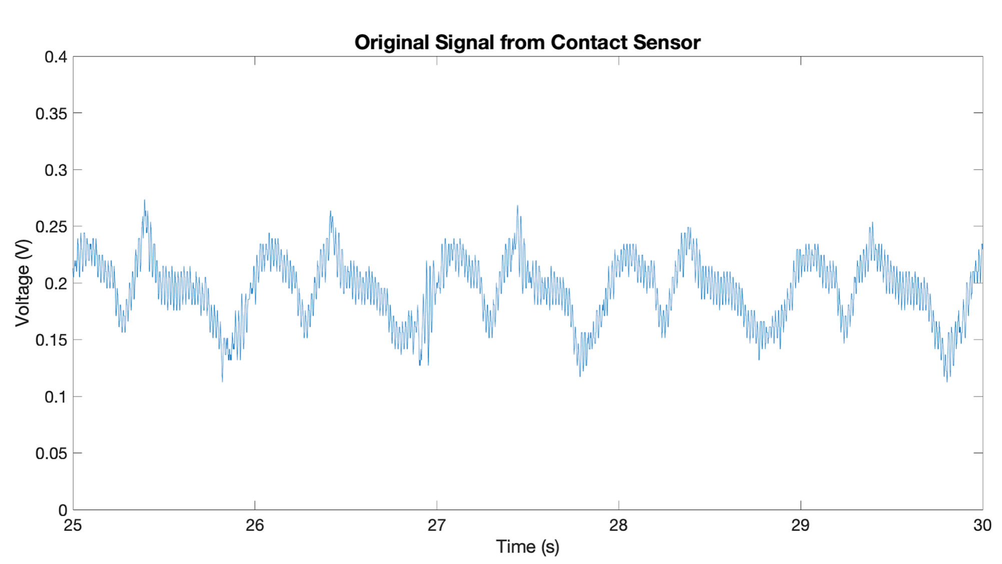

Figure 4: Voltage outputted by the contact sensors as water was pumped through the system

From the contact sensors, voltage was outputted with respect to time. Figure 4 is the last five seconds of a thirty-second trial, and shows the pulsatile motion of the pump. The 60 Hz electrical noise from the signal was removed using a MATLAB code. To analyze the frequencies present in the flow, the power spectra of the signals from each type of narrowing was found and plotted. This was done in MATLAB by finding the Fast Fourier Transform of the signal, which resulted in the relative energies at each frequency in the signal. The sum of the power spectra magnitudes for overlapping frequency intervals with a width of 10 Hz was found in order to compare the power spectra distributions for the non-restricted, severe restriction, and moderately severe cases (Figure 5). The non-restricted distribution is expected for turbulent flow, with most of the energy in the lower frequency regions due to the pumping rate of 1 Hz and then a gradual decline in the energy at each frequency as frequency increases. There are distinct peaks for both the severe and moderately severe cases that were not seen in the non-restricted case. Based on Figure 5, frequency intervals were selected that had noticeable peaks in the restricted cases. The sum of the power spectra for each restriction was plotted versus the non-dimensional area of flow, for each frequency interval (Figure 6). The frequency intervals of 40-60 Hz and 80-90 Hz were found to have an inverse relationship between the energy of the frequencies and the non-dimensional area of the flow opening. On the other hand, the frequency intervals of 30-40 Hz, 70-80 Hz, and 90-110 Hz were found to have the highest energy for the 30% restriction, resulting in a non-linear pattern.

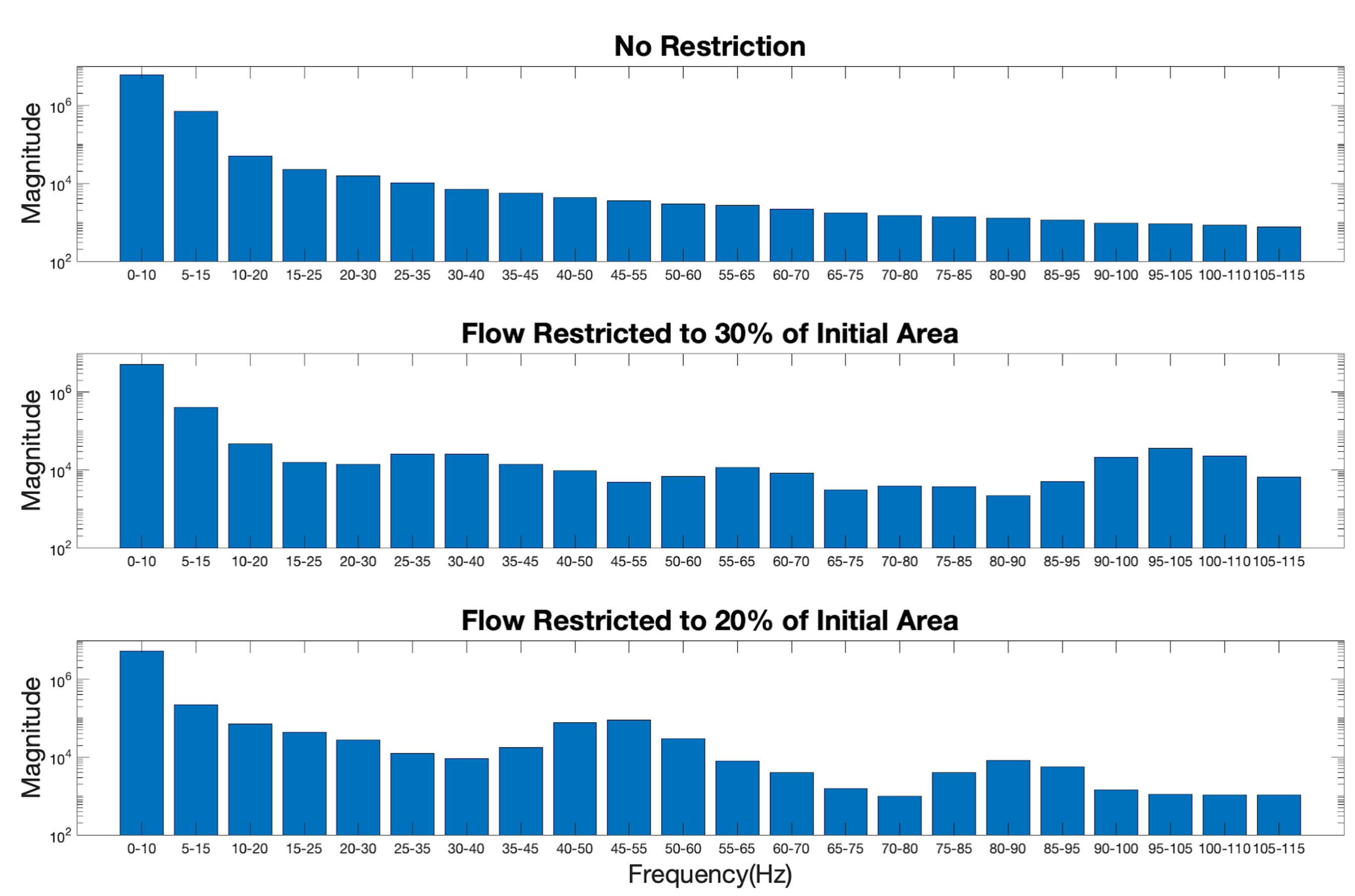

Figure 5: The magnitude of the sum of the power spectra for each frequency interval, up to 115 Hz. A larger magnitude indicates a high amount of energy in the water flow in that frequency interval. The top plot is from the case with no restriction, the middle plot is from the case with the flow restricted to 30% of the initial area, and the bottom plot is from the case with the flow restricted to 20% of the initial area.

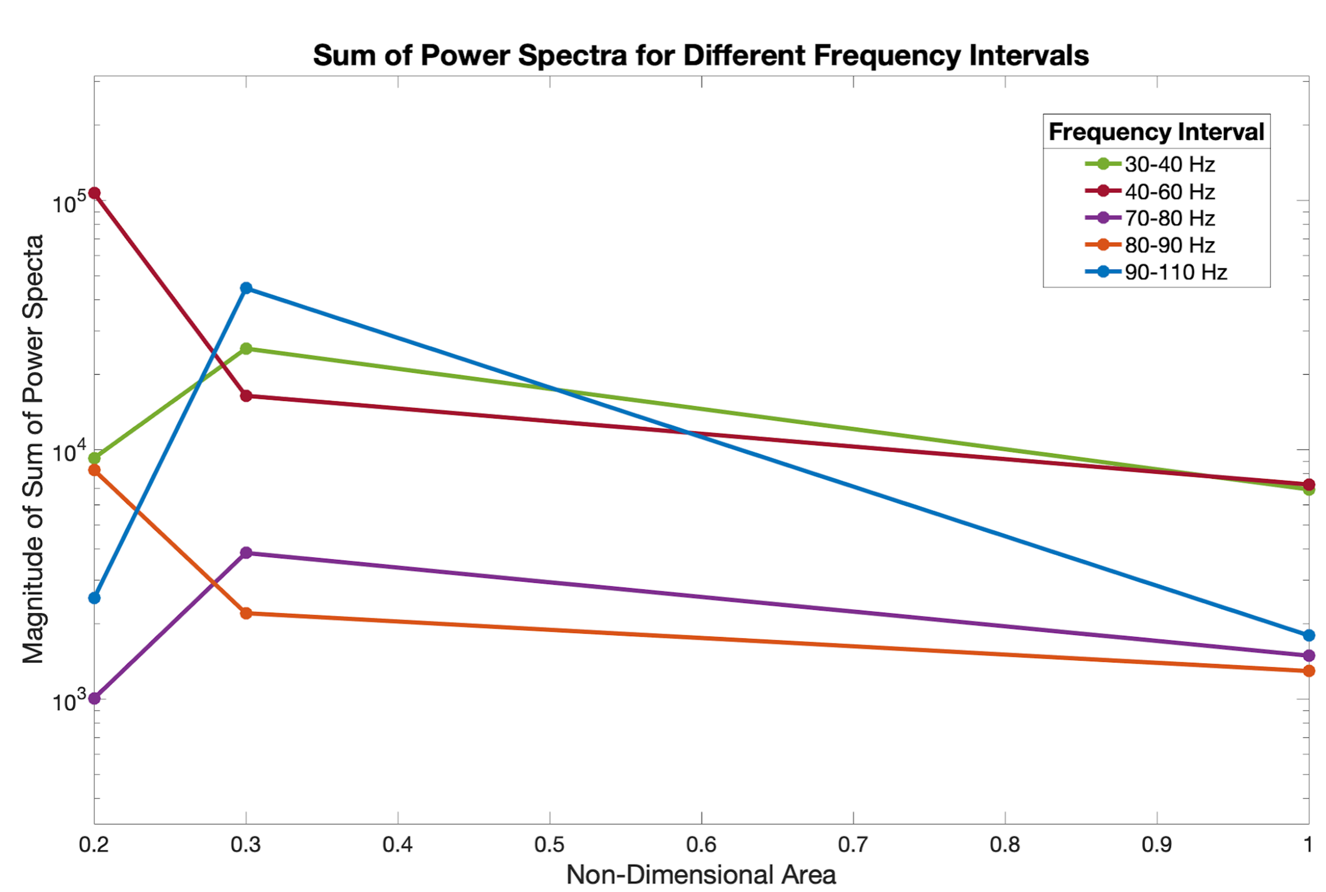

Figure 6: The magnitude of the sum of the power spectrum for the frequency interval versus the non-dimensional area of the restriction opening. A lower non-dimensional area indicates a higher severity of stenosis.

Discussion

It was shown in Figure 6 that there is a relationship between narrowness severity and the energy and ranges of frequency in the flow; however, that relationship was not uniform across different frequency intervals. Some frequency intervals had higher energies in the most severe narrowing, while others had higher energies in the moderately severe narrowing. More research is needed to determine why peaks in the energy of the flow were found at those frequencies. This could have been due to variations in Reynolds numbers for the flow through different severities, changes in pressure in the system, or differences in the shape of the 3D-printed parts. While the system constructed in this experiment did not closely resemble a heart, it provided quantifiable evidence that as the severity of narrowness in a tube increases, energy is injected into certain frequency bands, supporting the hypothesis. Blood flow in the aorta is already turbulent, but this project indicated that stenosis injects energy into the flow at specific frequencies. In addition, it was shown that contact sensors can be used to non-invasively collect vibration data that can be used to make meaningful conclusions about the flow. With more research, the energy distribution of the frequency domain could be used to make predictions about the stenosis severity, supporting previous research that found certain frequencies were characteristic of aortic stenosis[1-3]. By relating peaks in the frequency domain to the stenosis severity in a patient, this work would help doctors determine a patient’s heart condition.

Main Takeaways

- Evidence supporting the hypothesis.
- Quantitative evidence was found that as narrowing occurs, energy increases in certain frequency bands.
- Demonstrates the potential for the severity of stenosis to be estimated non-invasively based on the energy distribution in the frequency domain of the flow.

Future Steps

- Test more ways to represent stenosis
  - Wider range of severities and shapes
  - Flexible material
- Compare how other data change with narrowed flow
  - Pressure, velocity
- Build system more similar to a heart

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References

[1] P. D. Stein, H. N. Sabbah, J. B. Lakier, and S. Goldstein, “Frequency spectrum of the aortic component of the second heart sound in patients with normal valves, aortic stenosis and aortic porcine xenografts,” *The American Journal of Cardiology*, vol. 46, no. 1, pp. 48–52, Jul. 1980, doi: 10.1016/0002-9149(80)90604-9.

[2] G. R. Johnson, R. J. Adolph, and D. J. Campbell, “Estimation of the severity of aortic valve stenosis by frequency analysis of the murmur,” *Journal of the American College of Cardiology*, vol. 1, no. 5, pp. 1315–1323, May 1983, doi: 10.1016/S0735-1097(83)80146-6.

[3] S. M. Debbal and F. Bereksi-Reguig, “Computerized heart sounds analysis,” *Computers in Biology and Medicine*, vol. 38, no. 2, pp. 263–280, Feb. 2008, doi: 10.1016/j.compbiomed.2007.09.006.

[4] Mayo Clinic Staff, “Aortic valve stenosis,” *Mayo Clinic*, 2018. https://www.mayoclinic.org/diseases-conditions/aortic-stenosis/symptoms-causes/syc-20353139.