System Design and Spectral Analysis of Turbulence for Aortic Valve Stenosis

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Abstract

A model experiment is used to investigate the relationship between a narrowing in a pulsatile flow and the relative energy contained in the measured acoustic spectrum. Inspired by studies of aortic stenosis, this experiment models increasingly severe narrowings in an internal flow with a semi-triangular opening to mimic the shape of an open tricuspid valve. A baseline case is attained through use of dynamic similarity to the average flow through an unrestricted aortic valve. Normalized spectra for each case provides an indication of relative energy in each frequency band which shows how the distribution of energy changes with each restriction. Increasing narrowness of the model valve opening results in enhanced energy content across all frequency bands up to 400Hz. Frequency bands identified as relevant to more extreme cases of stenosis in actual heart valves, such as the 40Hz - 80Hz band, show significantly increased overall energy in these model cases. While all restricted cases demonstrate a nominal amount of increased energy, there appears to be more significant changes when the narrowing exceeds an area reduction of 40%.

Introduction

Aortic valve stenosis is a common heart disease that occurs due to the narrowing of the aortic valve [1]. The severity of a heart murmur is diagnosed qualitatively by a doctor listening to the sound produced by the valve and its interaction with the blood flow [2]. We propose to investigate a quantitative analysis of the sound signals produced by a similar system, enabling a repeatable and unbiased diagnosis of the severity of a narrowing. The goal of this project will be to identify a relationship between the severity of valve stenosis and the frequencies of sound signals due to pulsatile flow through a model valve.

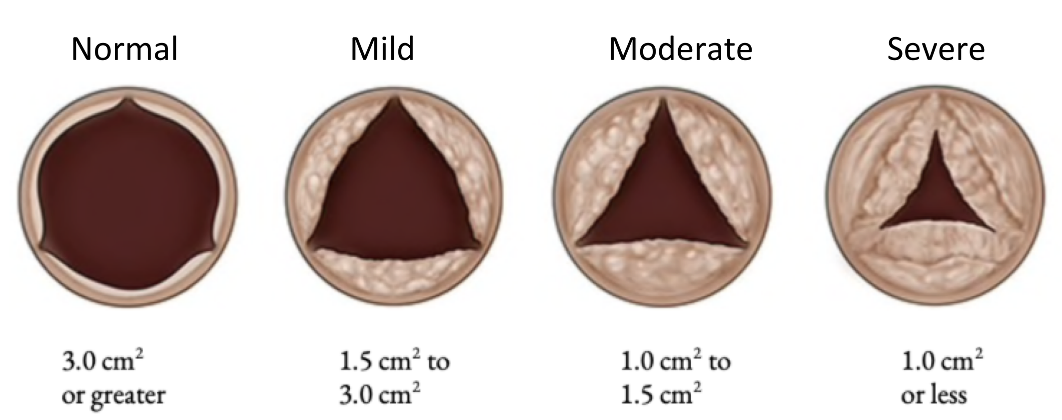

Figure 1: Schematic of a normal aortic valve to restricted valve due to stenosis used to model 3D printed valve restrictions [4]

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

Table 1: Test parameters for each restriction

Restriction (%)	d (mm)	Area (cm^2)	Re$_d$	Narrowness
0	12.7	1.143	5790	-
13	10.9	0.992	6360	mild
22	10.6	0.890	6864	mild
34	9.76	0.757	7450	moderate
39	9.41	0.703	7730	moderate
44	8.98	0.641	8090	severe
52	8.23	0.539	8830	severe

Figure 2: Top are the SolidWorks designs and bottom shows the 3D printed restrictions for the 13% (left) and the 52% (right).

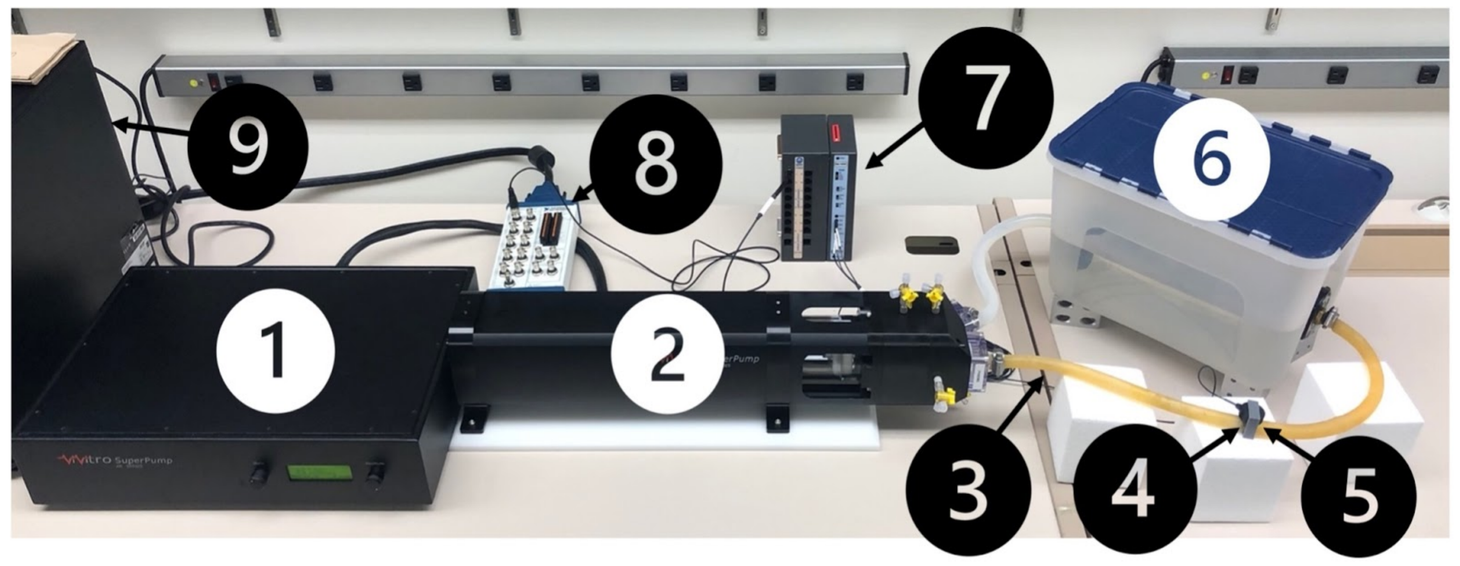

Figure 3: Physical Setup used for data collection which includes the following components: 1) Waveform Generator; 2) Pulsatile Pump; 3) Latex Tubing; 4) 3D printed restriction; 5) Contact Microphone; 6) Reservoir; 7) Signal Amplifier; 8) National Instruments NI-6123 and BNC-2110; 9) Computer.

The experimental setup was inspired by aortic valve stenosis and contains the components in Figure 3. The Reynolds number of 6360 was used to create dynamic similarity between the smallest restriction (13%) and the actual heart. The following restrictions and their stenosis characterizations can be seen in the table 1. Data was collected for each restriction at a sampling frequency of 10kHz for a duration of one minute. The pulsatile pump used a physio-70 waveform which models the heart volume ejection. The pump stroke volume was held constant at 40.20 mL/beat for each restriction. The pump is set at 70bpm. A low pass filter of 5kHz and gain of 1000 was used to improve signal collection.

Data Analysis and Results

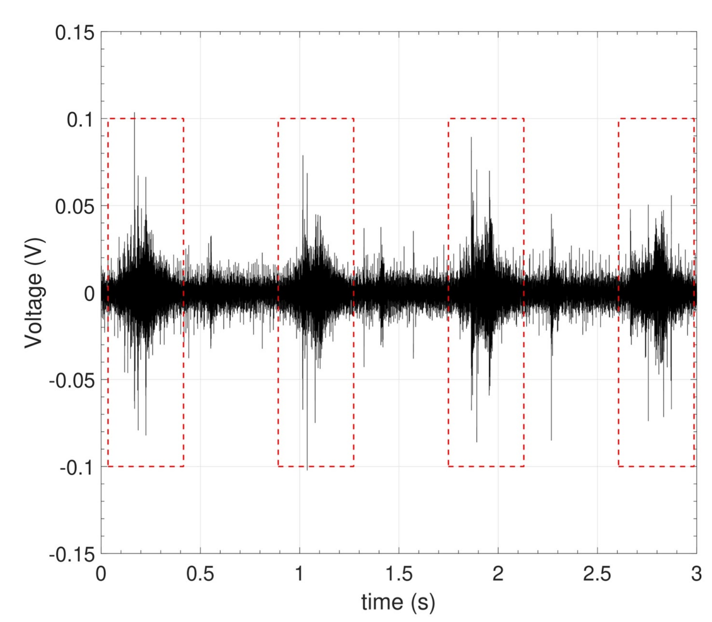

Figure 4: Example of raw data for 52% restriction. Dotted lines represent pulses extracted for data analysis.

To obtain the energy distribution of frequencies from the vibrational data, a power spectra analysis was performed using MATLAB. Individual windows, shown in Figure 4, depicts the “diamond-shaped peaks” caused by each pulse in the raw data. These 70 pulses are extracted for each of the five independent trials of data collection trials. The Fourier transform of these “sound bursts,” which traditionally would be associated with systole, are calculated and normalized, then averaged over all independent trials. The power spectrum is normalized by the variance of the raw data which removes any influence of the overall magnitude of the raw signal. This normalization results in an inability to discern the change in magnitude of particular frequencies between restrictions, but rather presents the relative change in frequencies. Additionally, a 60Hz electrical noise was removed from the raw data prior to the spectral analysis.

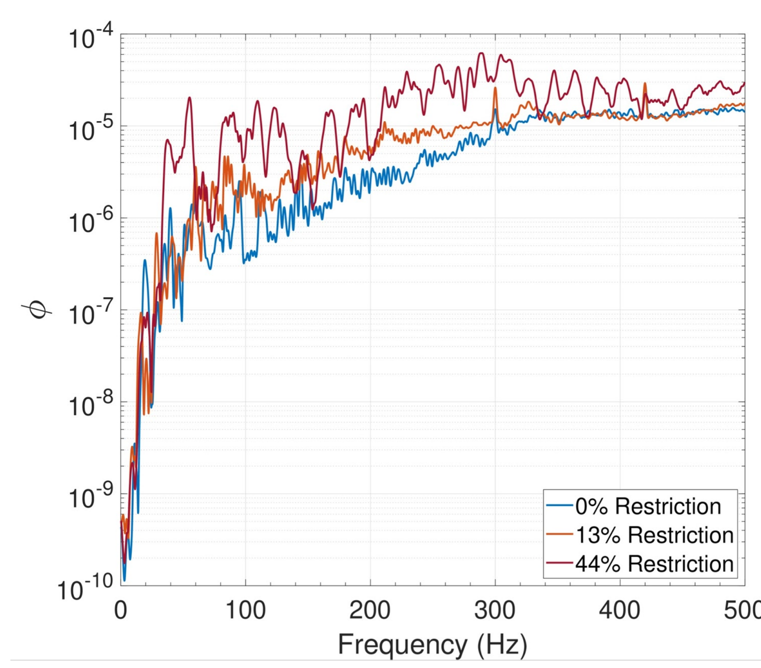

Figure 5: The normalized power spectra for three cases (0%, 13%, and 44% restrictions). Other restrictions show similar trends but are removed from this plot to improve readability.

Figure 5 shows the normalized power spectra for three restriction cases. Increased restrictions show higher energy content which is consistent with the hypothesis. Energy content in specific energy bands can be seen in Figure 6. There is increased energy in the 40-80Hz and 80-120Hz bands compared to the 0% restriction. More frequency bands of interest are compared in Figure 7. All restrictions show an increase in energy content relative to 0% restriction. The greatest change in energy can be seen in 40-80Hz range (squares). The greatest increase in energy is the most severe restrictions (44% and 52%). This agrees with the hypothesized relationship that increasing the restriction causes increased turbulence and consequently higher energy content.

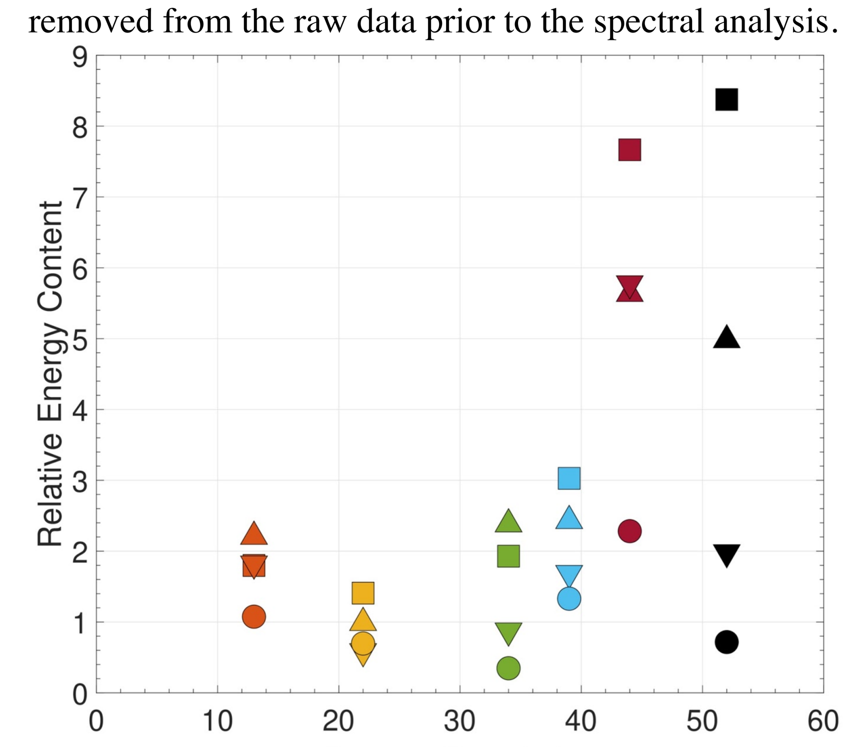

Figure 7: Integrated power spectrum relative to 0% restriction. Rectangle: 40 – 80Hz; Triangle : 100 – 200Hz; Inverted triangle:200–300Hz; Circle:300–400Hz.

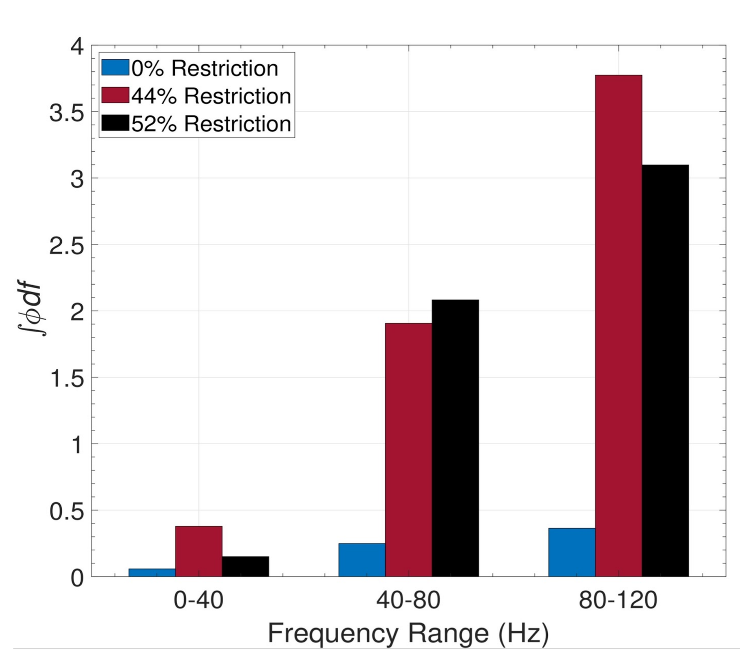

Figure 6: Integrated power spectrum for 0%, 44%, and 52% restrictions in three frequency bands.

Discussion

This model experiment demonstrates the proposed relationship between stenosis severity and frequency. The power spectra for each restriction generally shows increased frequency content with decreased flow area. The integrated power spectra allows for comparison between energy content in specific frequency bands of interest. Compared to the 0% baseline restriction, each restriction increased in energy content, most significantly in the 40–80Hz band. The most severe cases of 44% and 52% restrictions showed the greatest increase in energy content. This agrees with the hypothesized relationship that increasing the restriction causes increased turbulence and consequently higher energy content. As this research is inspired from aortic stenosis, future refinements to the experimental setup will aim to create a more realistic and biologically accurate setup. One step will include the removal of noise due to the pulsatile pump valve closure, which likely contributes to some of the baseline energy and noise seen in Fig. 4. Mechanical aspects of the aortic valve will be more closely replicated by using flexible 3D printed resins with geometries that more accurately mimic the shape of the valve. Additional analysis techniques can also be employed that aim to understand the more complex nature of turbulence, including bispectral analysis and dynamical analysis that uses parameters such as the correlation dimension of the sound signals. These approaches aim to provide a non-invasive and robust measure that allows researchers and healthcare providers to diagnose the severity of stenosis that compliments the spectral analysis.

Main Takeaways

- ➢ 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 to mimic valve restrictions
- ➢ Compare how other data changes with narrowed flow
  - ◆ Pressure, velocity
- ➢ Expand analysis techniques to better represent turbulence

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