NON LINEAR METHOD OF ROUGHNESS EFFECTS ON PULSING RESTRICTED FLOW

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Abstract:

The study is inspired by the effect of aortic valve stenosis, where the tricuspid valve does not fully open or close due to thickening of the leaflets. A study of the influence of surface roughness on the acoustic spectrum in a pulsing restricted flow is performed over a range of roughness sizes, flow conditions. This study aims to develop a quantitative measure of how surface roughness influences the acoustic spectrum by finding potential relationship between the frequencies that strongly couple and the flow geometry.

Background and Hypothesis:

- Aortic valve stenosis is a medical condition in which the aortic valves does not fully open. Over 300,000 people in the United States are diagnosed each year.
- It is mainly caused by the buildup of calcium deposits on the valve surface forming bumps. These bumps introduces roughness inside and increase its overall narrowness.[2]
- Severity aortic stenosis restrictions ranges from mild stenosis: 25-49%, moderate: 50-69% and severe: 70% or more.[3]
- When blood flows through these restricted valves, an enhanced turbulence flow and recirculation occurs, producing heart murmur sounds.
- This project hypothesize that by modeling a normal heart valve and its flow conditions, changing percentage restriction and roughness intensity should produce distinct sound frequency spectrums.
- This study seeks to investigate the effect of roughness and valve restriction on the energy content in frequencies of the sound produced due to turbulence in these valves.

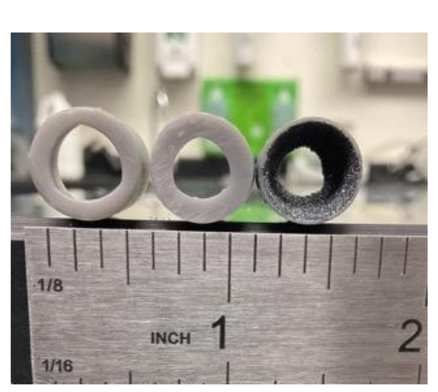
Valve Designs:

- Three different sizes of valve restrictions were created; 56%, 69% & 82% blockage.
- Reynold's number of a healthy human heart model was derived using dynamic similarity to inform the various volume flow rates utilised in the study. The mathematical expression for finding distinct Reynold's number is expressed below:

$$Re_D = \frac{UD}{\nu}$$

U = bulk velocity
D= hydraulic diameter
$\boldsymbol{\nu}$ = kinematic viscosity

- Roughness particles of different grit sizes were introduced in the inner layer of the valve; 120 grit (0.102 mm), 100 grit (0.122 mm) & 80 grit (0.165 mm)



3D printed valves; smooth case with two different restriction severities on the left, added roughness shown on right

Acknowledgements:

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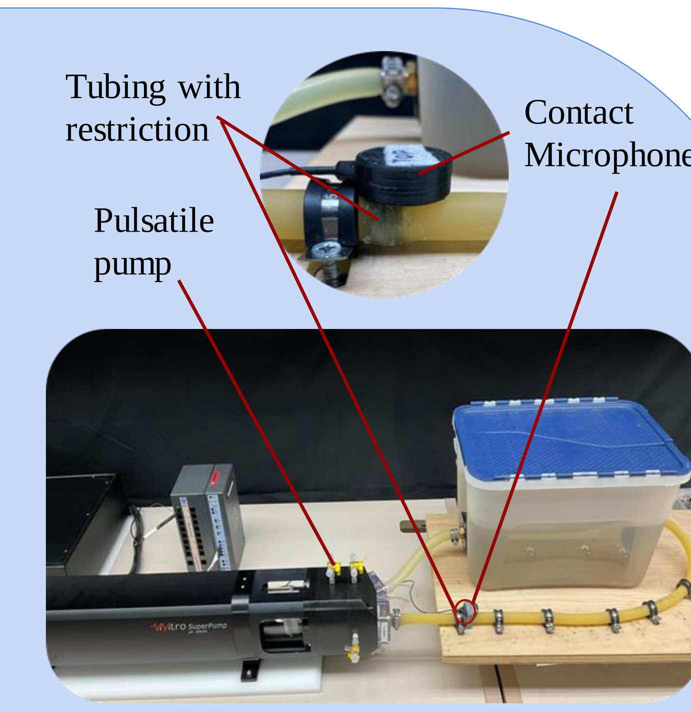
Experimental Methods and Setup:

- The pump is set at a frequency of 70 beats per minute and connected to the reservoir through the tubing which houses the 3D printed restricted valve. Water is forced through the tubing containing the 3D printed valves.
- A contact microphone is placed on top of the valve and collects the sound produced by pressure at the narrowing for different volume flow rates.
- The amplifier filters the signal and amplifies the collected signal.



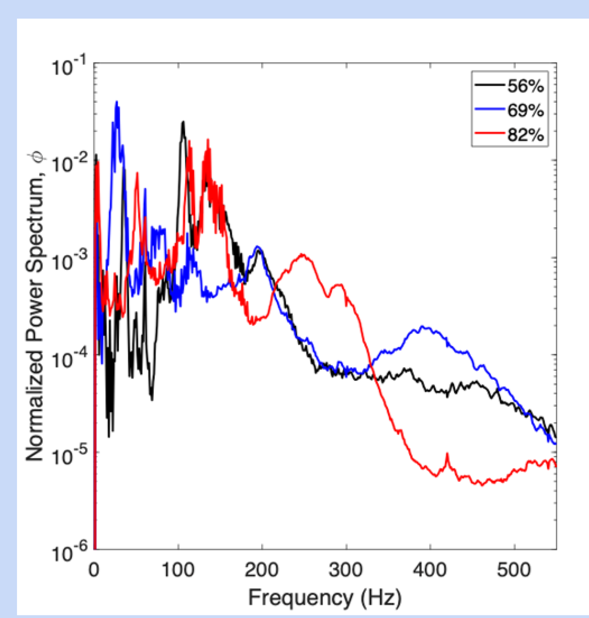
Power Spectrum:

- This linear method of analyses will decompose the voltage signal from the time domain to the frequency domain.
- A noise reduction algorithm is used to remove the unwanted 60Hz signal produced from the AC power-line.
- The power spectrum of the signal is normalized. This allows us to make comparisons of degree of roughness with increasing flow parameters. The normalization of the power spectrum is expressed as:

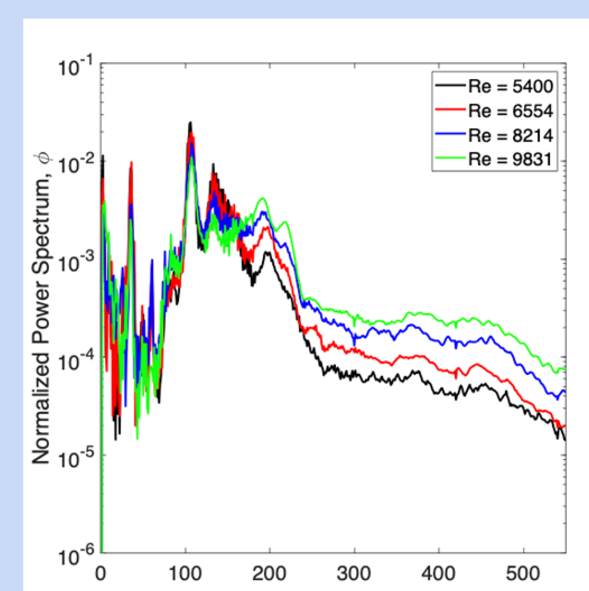
$$\boldsymbol{\phi(f) = \frac{P(f)}{\sigma^2}}$$

$\boldsymbol{P(f)}$ = power spectrum of voltage,
$\boldsymbol{f}$ = frequency,
$\boldsymbol{\sigma^2}$= variance of signal,
ϕ = normalized spectrum

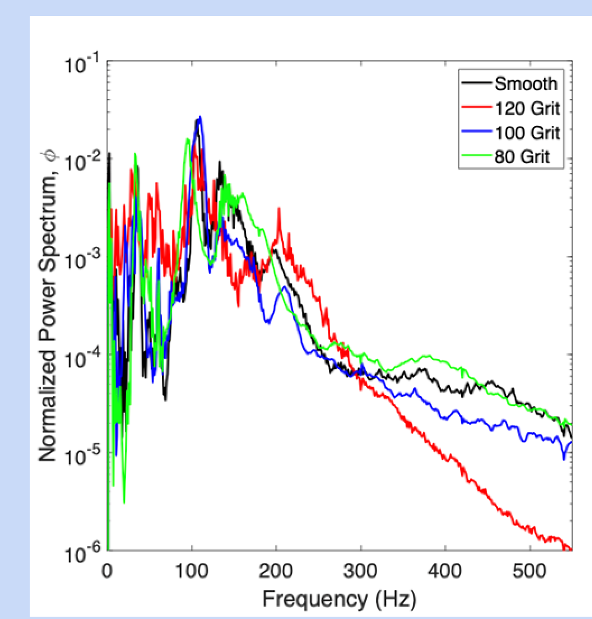
Results:



Normalized Power Spectrum For A Fixed Re = 5407, In A Smooth Case For Different Restrictions

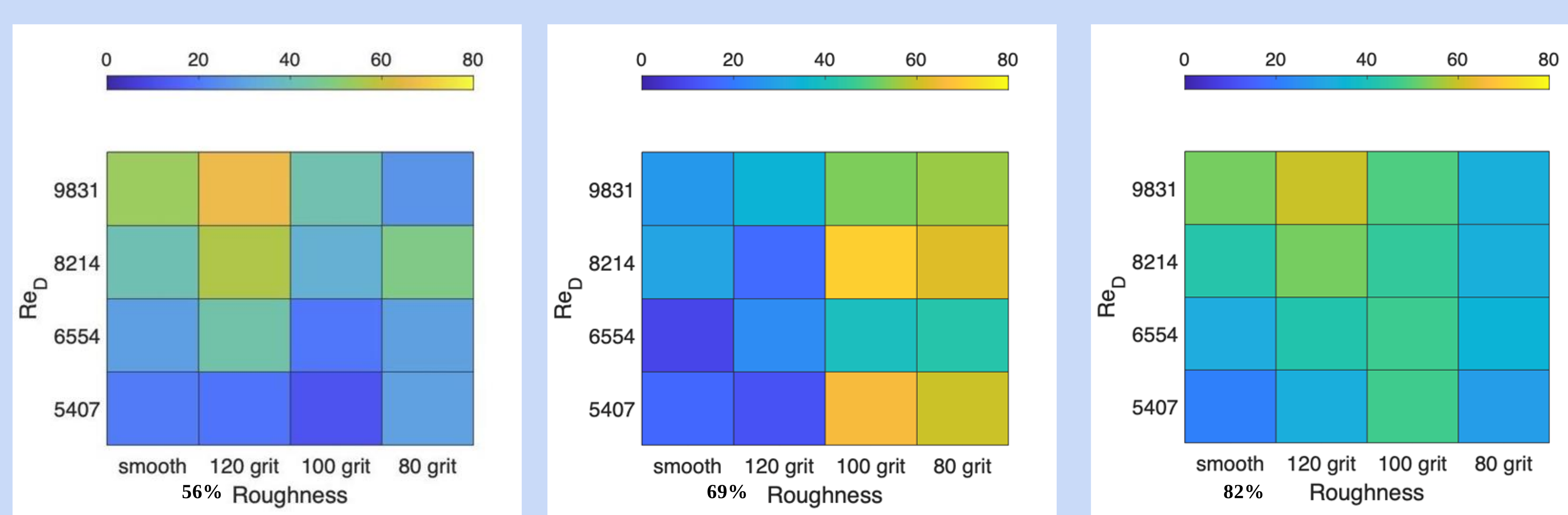


Normalised Power Spectrum For Different Re, In A Smooth Case For A 56% Restriction



Normalized Power Spectrum For Fixed Re =5407, In Changing Roughness For A 56% Restriction

- There is a significant shift in the spectral shape favoring higher frequencies as the restriction becomes narrower.
- For a given restriction and roughness, more energy is contained in higher frequencies as Reynolds Number increases.
- The distribution of energy changes when roughness is added to the valves by disrupting both low and high frequencies.
- The Normalized Power Spectrum is integrated to fully observe the effect of surface roughness, valve narrowness and Reynolds Number on the acoustic Spectrum.



Percentage of energy contained in the frequency bands of 150 - 300 Hz in all 48 cases.

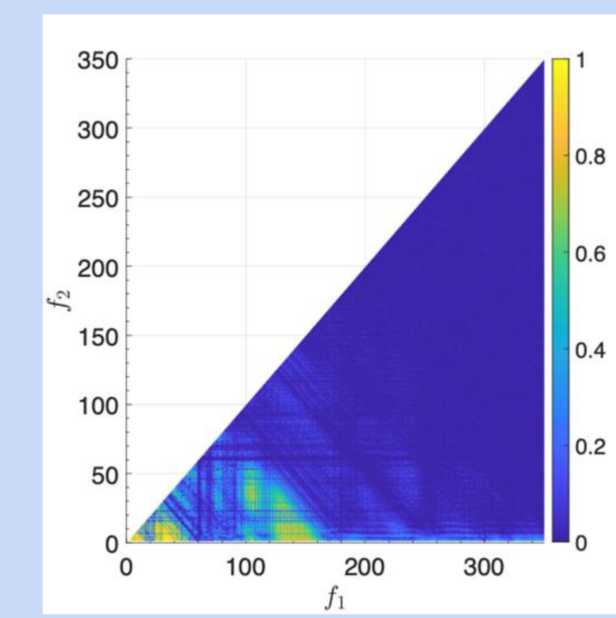
Bicoherence Analysis:

- The measure $b(f_1, f_2)$ provides a normalized assessment of frequency coupling between two frequencies f_1, f_2 in a flow.
- Mathematically defined as:

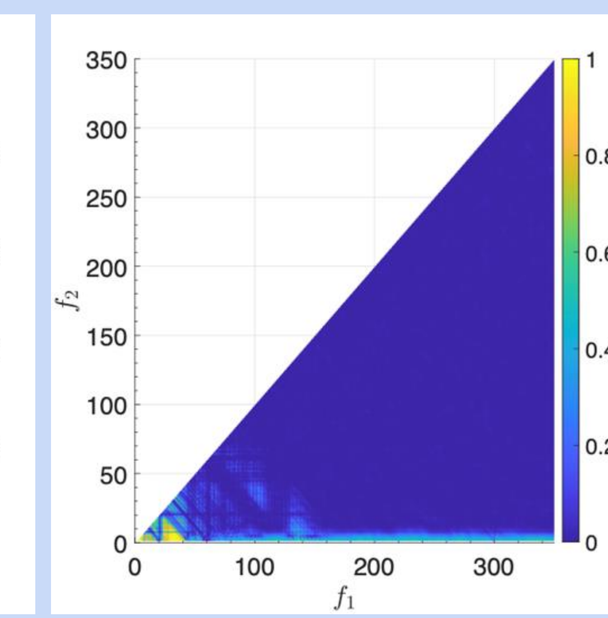
$$b(f_1, f_2) = \frac{\left|\sum_{i=1}^{L} X_i(f_1)X_i(f_2)X_i^*(f_1+f_2)\right|}{\sum_{i=1}^{L} |X_i(f_1)X_i(f_2)|^2 \left|X_i^*(f_1+f_2)\right|^2}$$

$X(f)$= Fourier transform of a time varying signal x(t)
X^*=complex conjugate of X
L= number of epochs over which this measure is averaged [1]

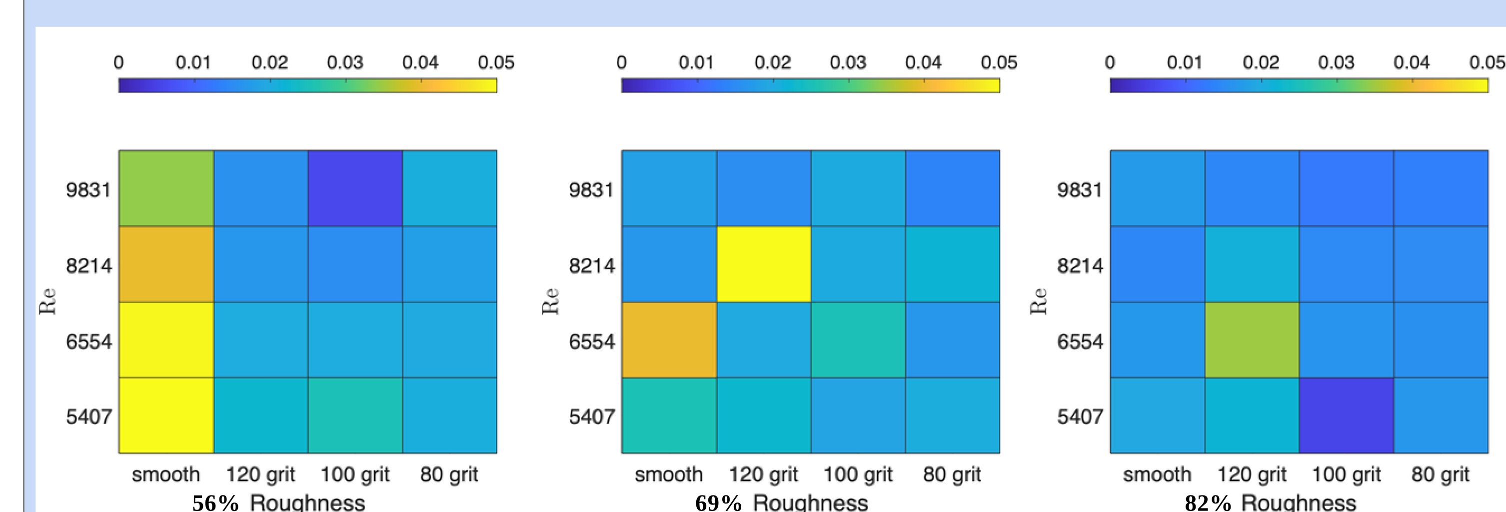
Bicoherence Results:



Bicoherence results for 56% restriction, **smooth case** and Re = 5407



Bicoherence results for 56% restriction, **80** grit and Re = 5407



Average Bicoherence contained in the frequency bands up to 350 Hz in all 48 cases.

Conclusions:

- The relative energy distribution in the acoustic spectrum is significantly impacted by the introduction of small roughness elements.
- Increasing the Re number showed an increase in the relative energy in the higher frequencies but was not associated with the shift in distribution of energy across the acoustic spectrum.
- Frequency bands of 21 to 40 Hz are heavily influenced by the 120-grit roughness and 80 to 120 Hz appear to be more strongly affected by the larger 100 and 80 grit.
- Enhanced roughness correlates with higher frequencies (150 - 300 Hz) becoming prominent in the spectrum. This trend follows with increasing restriction.
- As more roughness is introduced, frequency coupling diminishes across all restrictions and Reynolds numbers.

References:

[1]Sigl, Jeffrey C and Chamoun, Nassib G. "An introduction to bispectral analysis for the electroencephalogram." Journal of *clinical monitoring* Vol. 10 (1994): pp. 392–404
[2]Nkomo, Vuyisile T, Gardin, Julius M, Skelton, Thomas N,Gottdiener, John S, Scott, Christopher G and Enriquez-Sarano, Maurice."*Burden of valvular heart diseases: A population-based study*."The lancet Vol. 368 No. 9540(2006): pp. 1005–1011.
[3]Nishimura RA, Otto CM, Bonow RO."*Guideline for the Management of Patients With Valvular Heart Disease:"* A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines. Circulation. 2017