Ratcheting fluid pumps:

A Valveless Pumping Technique Based on Insect Hearts and Geometric Asymmetry

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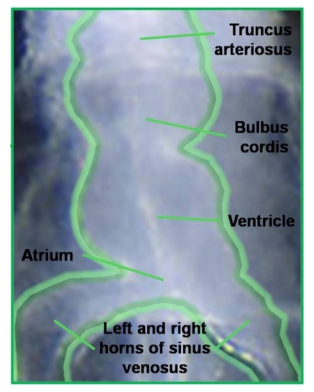
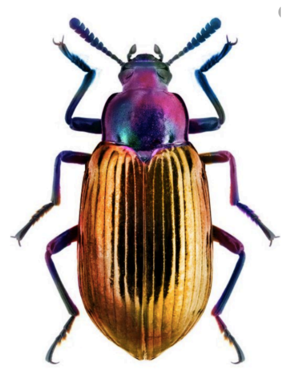
Introduction

In the early stages of heart morphogenesis, the heart is a tubular vessel that efficiently pumps embryonic blood throughout developing circulatory system.



embryology.med.unsw.edu

In invertebrates such as arthropods (insects) the heart is a tubular valveless structure made of successive chambers. Peristaltic contractions drive the mixing and bulk flow of hemolymph in the insect heart


pinterest.ca/ideas/beetles/

We developed a fluid structure interaction model to design a new biomimetic pump.

QUESTIONS: How can we maximize bulk volumetric flow in a bioinspired valveless pump, based on geometric asymmetry?

Immersed Boundary Method

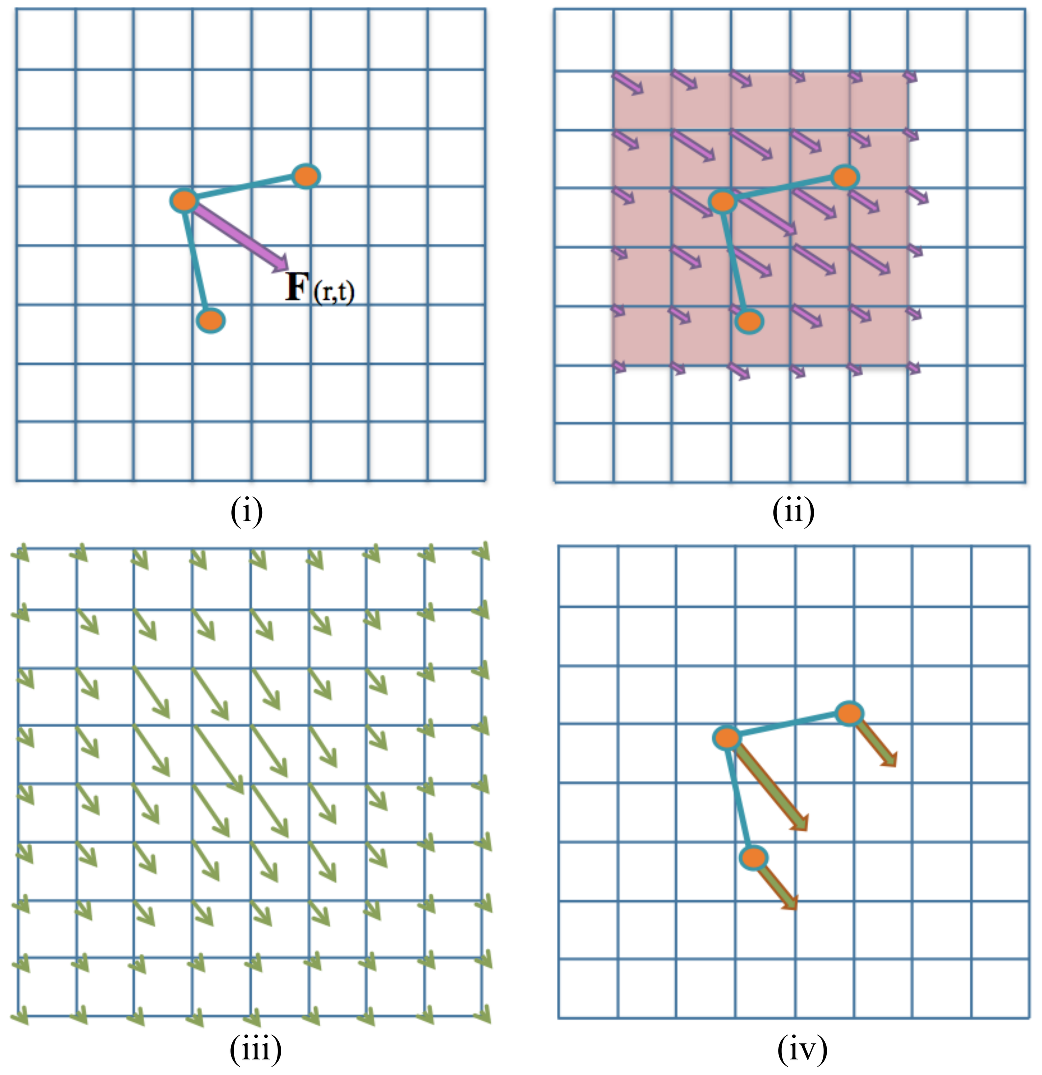


Figure: *Steps in Dr. Charlie Peskin's immersed boundary method [2,3].*

Conservation of Momentum

$$\rho\left(\frac{\partial \mathbf{u}(\mathbf{x},t)}{\partial t}+\mathbf{u}(\mathbf{x},t)\cdot\nabla\mathbf{u}(\mathbf{x},t)\right)=-\nabla p(\mathbf{x},t)+\mu\Delta\mathbf{u}(\mathbf{x},t)+\mathbf{f}(\mathbf{x},t)$$

Conservation of Mass

$$\nabla\cdot\mathbf{u}=0$$

Force Coupling Equation

$$\mathbf{f}(\mathbf{x},t)=\int\mathbf{F}(r,t)\delta(\mathbf{x}-\mathbf{X}(r,t))dr$$

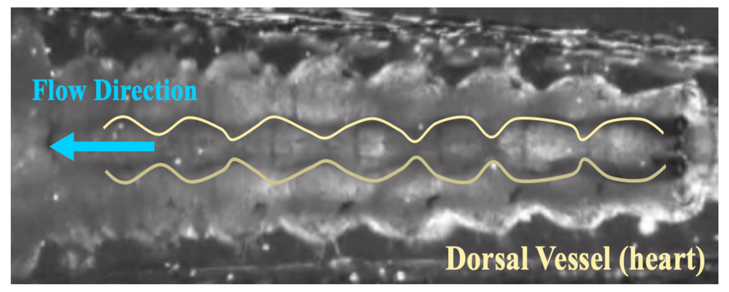
Velocity Coupling Equation

$$\mathbf{U}(\mathbf{X}(r,t),t)=\frac{\partial\mathbf{X}(r,t)}{\partial t}=\int\mathbf{u}(\mathbf{x},t)\delta(\mathbf{x}-\mathbf{X}(r,t))d\mathbf{x}$$

Sawtooth Model

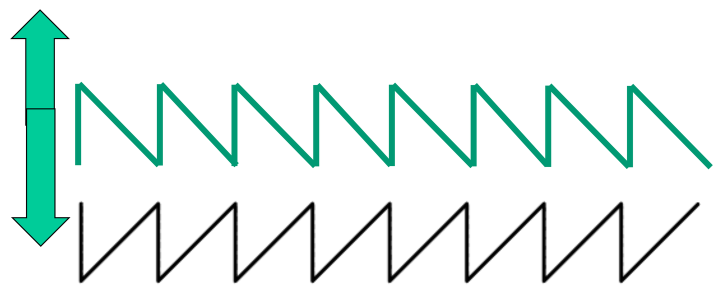
Model Idea:

- **Valveless pumping action**
- **Geometric asymmetry biases bulk fluid flow**



* Adapted from League et al., J. Exp. Biol. 2015

$Y(t) = a/2 \sin(2\pi ft)$



What is the Reynolds Number?

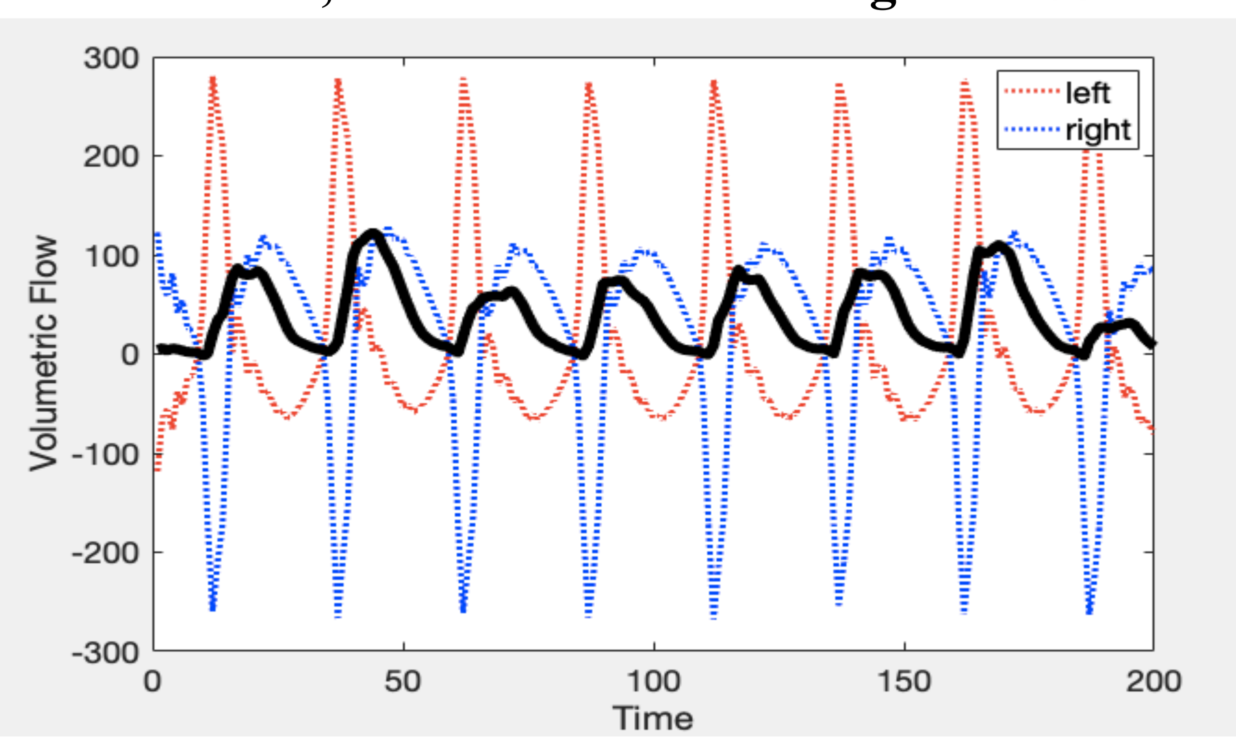
"The ratio of inertial forces to viscous forces"

$$Re=\frac{\rho LV}{\mu}=\frac{\rho fL^2}{\mu}$$

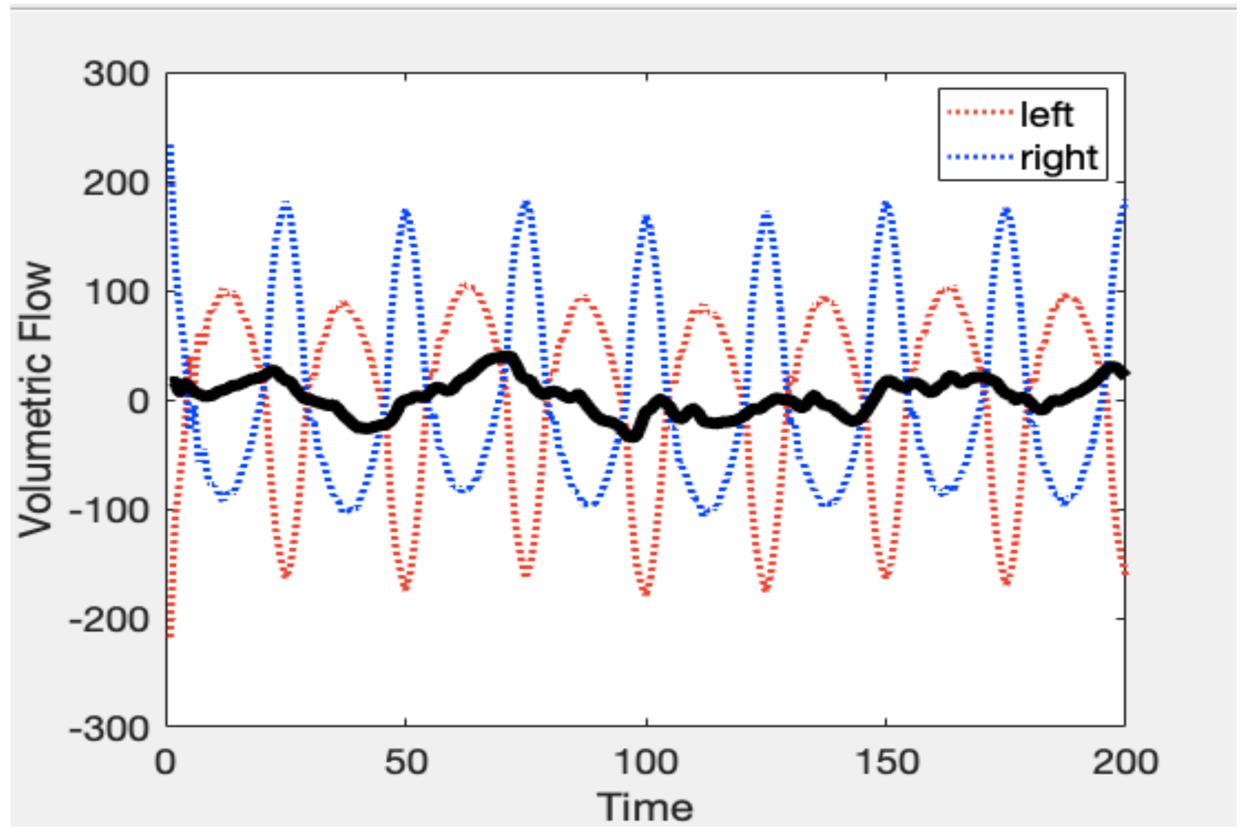
ρ : fluid density
L : characteristic length
V : characteristic velocity
μ : fluid viscosity

Volumetric Flow Vs Time

Re 450 , Contraction Percentage = 75%

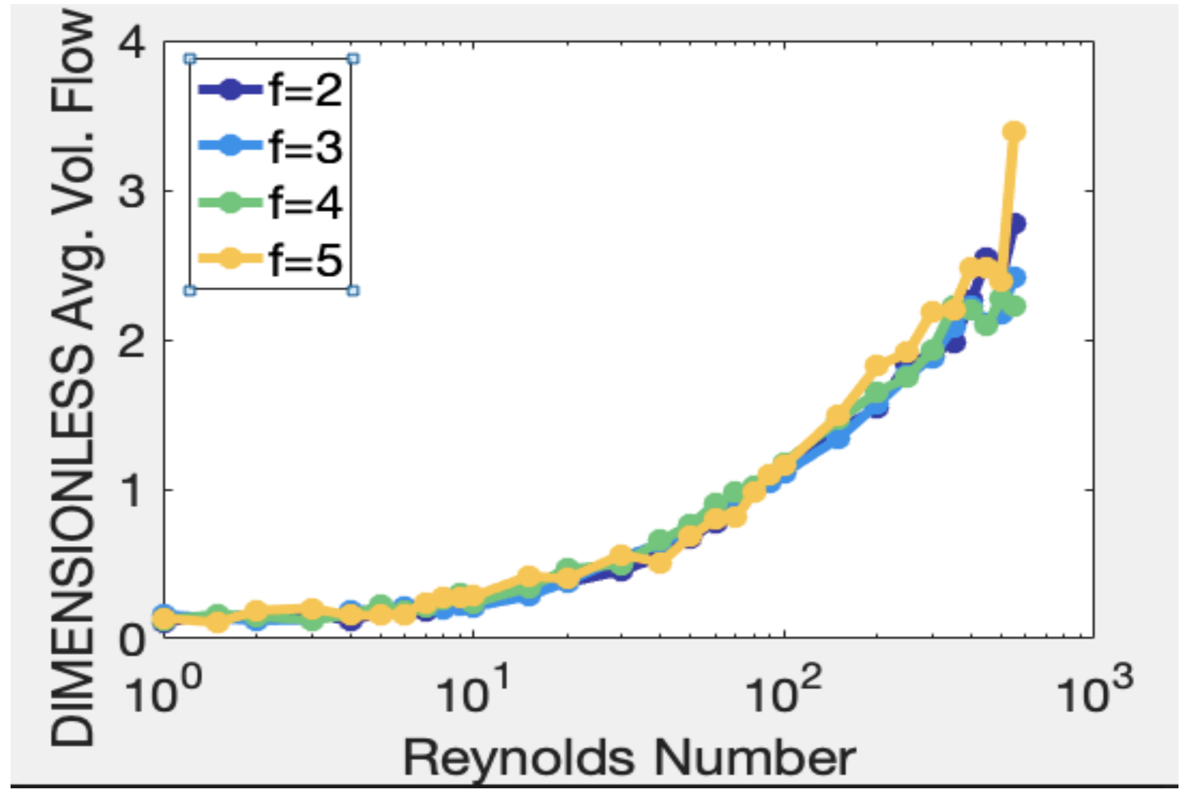


Re 500, Contraction Percentage = 35%



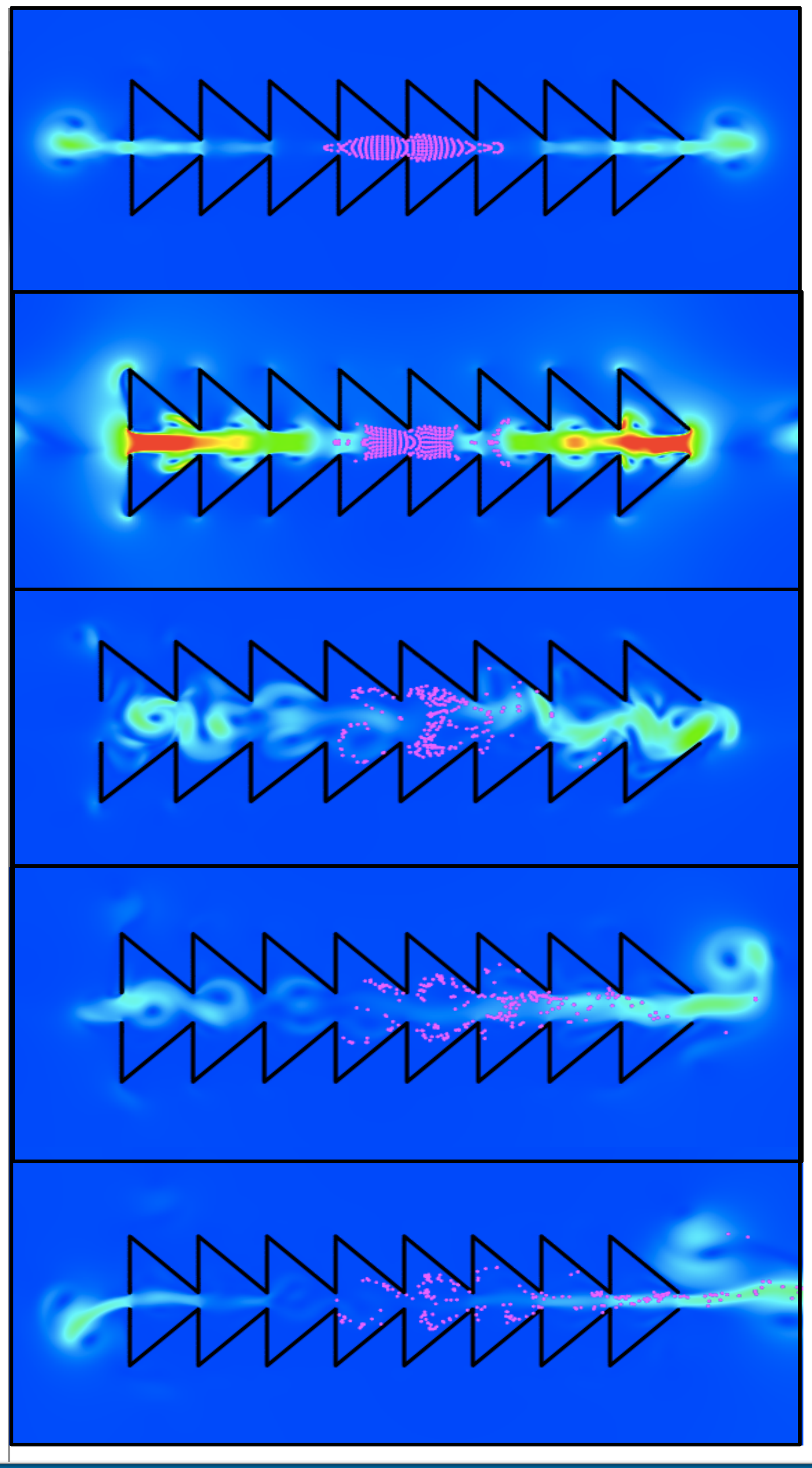
Reynolds Number Vs Volumetric Flow

How does Re influence the model's volumetric flow rate?



- **The data collapses when non-dimensionalizing the volumetric flow rate by dividing by characteristic velocity scale: *fL***
- **Allows for further analysis using only one pumping frequency**

Flow Visualizations with Tracers



25% of first cycle

50% of first cycle

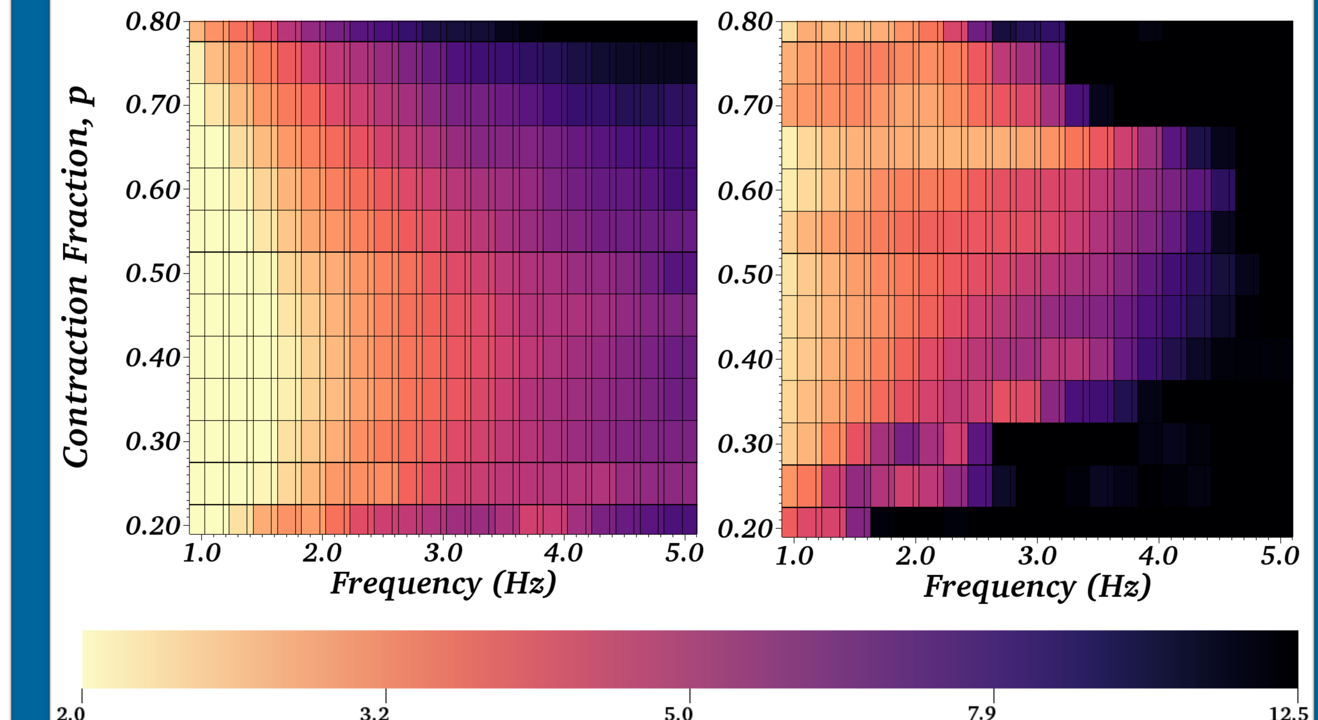
75% of first cycle

100% of first cycle

25% of second cycle

Frequency Vs Contraction Fraction

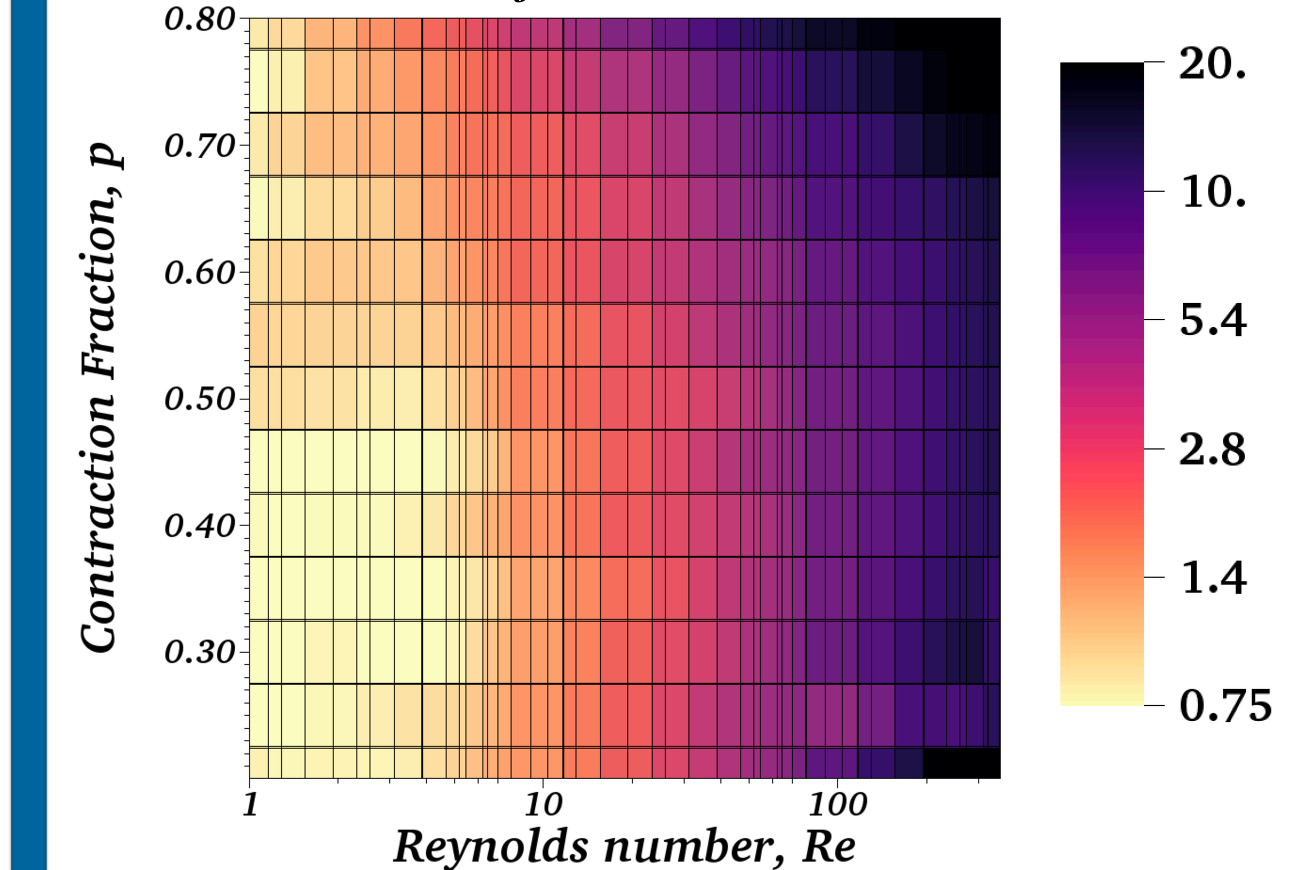
How does the Frequency of the Sawtooth oscillation effect the volumetric flow when it is not dimensionless?



- **Asymmetric contraction patterns correlates to a higher volumetric flow**
- **Higher frequencies result in higher bulk flow**

Reynolds Number Vs Contraction Fraction

How does the contraction percentage of each cycle affect the volumetric flow for different Re?



- **Higher *Re* and greater asymmetric contraction patterns lead to greater flow rates**

REFERENCES

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3. Battista, N.A., Strickland, W.C., Miller, L.A., *IB2d: a Python and MATLAB implementation of the immersed boundary method*. Bioinspir. Biomim. 12(3): 036003 (2017)
Software freely available at: http://github.com/nickabattista/IB2d

ACKNOWLEDGEMENTS

I would like to thank Dr. Battista for making this a fulfilling and enjoyable experience, the MUSE program at TCNJ for support, and the NSF OAC-#1828163 Grant for the ELSA HPC.