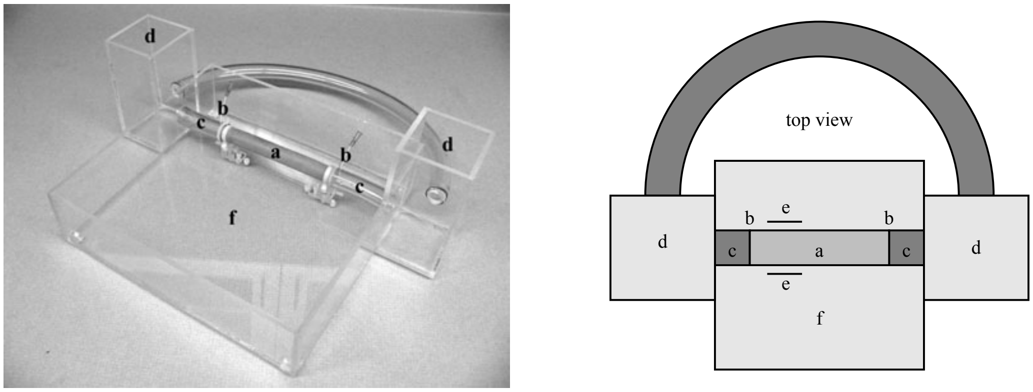
Chapter 2

Experimental Methods and Materials

Prior efforts have focused on analytical and computational approaches to explaining valveless pumping. With limited experimental data, the studies prior to this work hoped to predict the flow behavior of an impedance pump system. For this thesis, an experimental approach was chosen such that the pump's behavior could be explicitly measured prior to creating a model. Specific goals for the experiments included cataloging the pump's bulk behavior under a large range of parameters in order to identify those that are principal in the pump's performance and their effects. Further experiments were conducted to examine the pump's internal behavior including flow, pressure, and wall motion in time.

2.1 Experimental Flow Loop

A flow loop was constructed to test the impedance pump (figure 2.1). In its design, considerations were made to accommodate assorted tube geometries including changes in length, diameter, and thickness. This was accomplished using an interchangeable test section. It can hold horizontally an elastic tube of up to 6 inches in length and 3/4 inches in diameter. An additional 3 inches of length on each side are available for the tubing of mismatched impedance. The inlet and outlet flow rates, as well as the inlet and outlet pressures can be measured at this location. Two reservoirs are located at either end of the test section. An additional rigid tube connects the



(a) (b)

Figure 2.1: Experimental Flow Loop: a - elastic section, b - pressure ports, c- flow measurement location, d - reservoirs, e - pinchers, f - secondary reservoir.

reservoirs creating a closed loop. This connection can be modified to adjust the resistance to the flow or be removed completely to create an open loop setup. The reservoirs have two purposes: to reduce the momentum of the flow exiting the pump such that the flow through the connecting loop is pressure driven, and to allow the system to be pressurized to different values with respect to the external pressure on the pliant section. A secondary reservoir surrounds the test section. Filling this allows ultrasound imaging of wall motion in both radial and axial slices.

2.2 Tubing Materials

Both elastic and inelastic tubing was tested. The elastic tubing used for the experiment was an amber latex tube, 1/32 inch in thickness with varying length. It has a tensile strength of 3500 PSI and a Shore A hardness rating of 35. The inelastic tubing used was a polyethylene tube, 3/4 inch in inner diameter, approximately 2 x 10^{-3} inches in thickness and 6 inches in length. In all cases, the ends were connected to a Tygon S50-L tubing 3/4 inch in inner diameter and 1/8 inch in thickness. The size scale and materials were chosen to be readily imaged by an ultrasound machine, which permits imaging of the flexible tube wall motion and flow profile within the tube while pumping.

2.3 Compression Mechanism

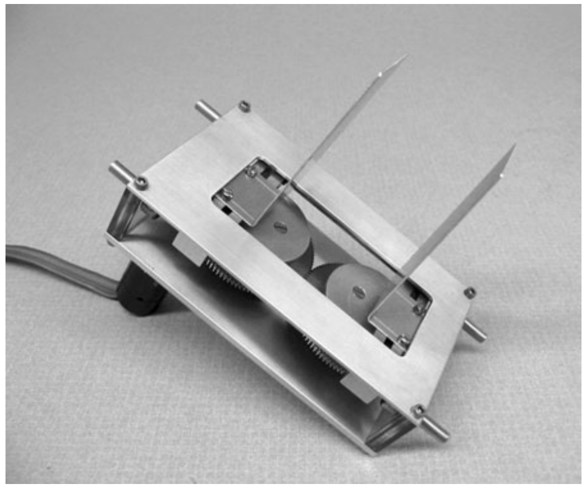
There was no mechanism readily available to pinch the tube in a prescribed manner. Ideally, the compression mechanism would be capable of a fully controllable compression profile including variable amplitude, frequency, and duty cycle. However, physical limitations in force require compromise of such qualities as amplitude and frequency.

2.3.1 Motorized

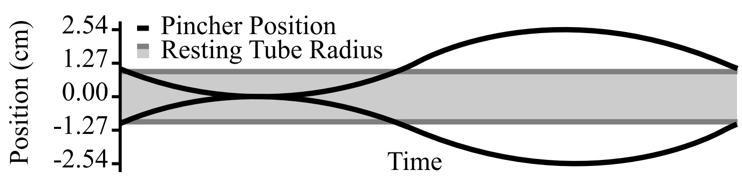
A device was constructed that relied on a motor to turn two geared wheels (figure 2.2). These wheels each have a pin on them that slides in a groove on the pinchers, creating a sinusoidal motion. It had been the intention to use a servo or stepper motor to control the pinchers. However, it became apparent that a motor could not provide a controlled motion at frequencies of interest. The pinchers followed a sinusoidal motion with a 1 inch diameter each. A maximum pinching frequency of 8 Hz was achievable with no further control over waveform of the compression.

2.3.2 Solenoid Activated

A second compression mechanism was built utilizing a solenoid (figure 2.3). The solenoid directly activated one pincher while another was mechanically linked to pinch from the other side of the tube. Though full control over the pinching profile was still not possible, this design allowed for variation in frequency, duty cycle, and amplitude with the use of a blockage. The duty cycle is defined as the fraction of the compression period during which the solenoid is active corresponding to an open tube. A maximum pinching frequency of 10 Hz and a duty cycle as short as 5% with complete closure from 3/4 inches was achieved.



(a) Compression mechanism



(b) Compression profile in time

Figure 2.2: Motorized compression mechanism and path

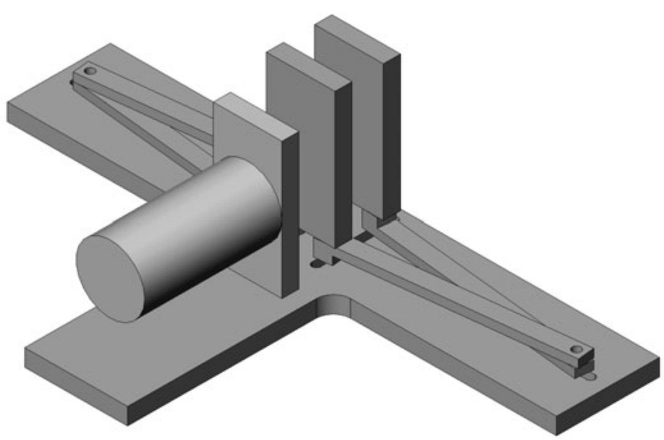


Figure 2.3: Solenoid activated compression mechanism

2.4 Measurement

The acquired data consisted of pressure and bulk flow measurements at the ends of the pliant tube. Additionally, ultrasound images were concurrently taken to capture the motion of the tube walls and fluid within the tube. The data were acquired using a National Instruments (Austin, TX) PCI-6035E data acquisition board.

2.4.1 Material Properties

Measurement of the compliance of the elastic tube was performed by filling an isolated section of tubing with different volumes and measuring the change in transmural pressure [31]. We selected a normalized definition of the compliance C as a function of cross-sectional area A, transmural pressure P, and cross-sectional area at rest of A_0. The change in diameter was inferred by assuming uniform expansion of the tube based on the volume added:

$$C = \frac{\partial A/\partial P}{A_0}$$

2.4.2 Pressure

Two diaphragm pressure transducers, Sensotec (Columbus, OH) 060-E067-02, were used to measure the pressure in time at both ends of the pliant section. The transducers have a range of 5 PSI, and an accuracy of 0.1%. They were connected to the system via a long semi-rigid tube. To verify that the connection does not interfere with the pressure reaching the transducer, we can calculate the natural frequency, damping ratio, attenuation and phase shift of the connecting system based on the equations presented by Holman [10].

Given the properties in table 2.1, we find that for a pressure signal, P_0, with a frequency of ω the natural frequency of the measurement system, ω_n, is

$$\omega_n = \sqrt{\frac{3\pi r^2 c^2}{4LV}}$$

Property	Symbol	Value
Volume of reservoir at pressure transducer	V	10^{-6} m^3
Length of tube	L	0.5 m
Radius or tube	r	0.001 m
Density of transmitting fluid	ρ	1000 kg/m^3
Speed of Sound in fluid	c	1500 m/s
Dynamic (absolute) viscosity	μ	10^{-3} kg/(m s)

Table 2.1: Parameter Values for Computing Pressure Transducer Dynamic Response

The damping ratio, h, is defined as

$$h = \frac{2\mu}{\rho c r^3}\sqrt{\frac{3LV}{\pi}}$$

The attenuation, defined as the absolute value of the pressure measured by the sensor, P, divided by the pressure signal, P_0, is

$$\left|\frac{P}{P_0}\right| = \frac{1}{\left(\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + 4h^2\left(\frac{\omega}{\omega_n}\right)^2\right)^{1/2}}$$

And the phase shift, Φ, in the pressure signal, P_0, and pressure measured, P, is

$$\Phi = \tan^{-1}\frac{-2h\left(\frac{\omega}{\omega_n}\right)}{1-\left(\frac{\omega}{\omega_n}\right)^2}$$

The natural frequency is approximately 3300 Hz, corresponding to negligible damping, attenuation, and phase shift at the frequencies we interested are in.

2.4.3 Flow

A Transonic (Ithaca, NY) HD01 flow meter system is used to measure the dynamic flow rate. It has a sample rate of 0.9 MHz, range of ± 50 L/min, and a resolution of .025 L/min. The sampling frequency far exceeded the needs of the experiments. The meter functions using Doppler ultrasound with a cuff around a calibrated tubing material. In the case of this study the materials are Tygon R-3603 and Tygon S50-L.

The probe was placed just past the ends of the primary pliant section.

2.4.4 Ultrasound Imaging

Ultrasound allowed for the high speed imaging of the tube wall for various slices. Provided that the flow was seeded with particles, it is also capable of capturing the fluid motion. The ultrasound machine available to the project was a General Electric (GE) Vingmed System FiVe. It is equipped with three different probes:

- The FPA 10 MHz 2A is a pediatric cardiac probe capable of acquiring data at frame rates up to 297 frames per second. It has a depth resolution of 0.015464 cm and 0.011001 rad. The maximum depth of penetration is 14 cm. The frame rate is dependent on the width and depth of the measurement.

- The FPA 2.5 MHz 1C is an adult cardiac probe capable of acquiring data at frame rates of up to 212 frames per second. The maximum depth of penetration is 30 cm. The frame rate is dependent on the width and depth of the measurement.

- The FLA 10 MHz 1A KZ314118A is a linear phase array probe that is capable of acquiring data at frame rates of approximately 17 frames per second. This probe has the highest spatial resolution but the frame rate is significantly lower than that of the other two probes.

The pediatric probe is the most suitable for the project because of its spatial and temporal resolution.

Ultrasound imaging was used for the measurement of wave speed on the surface of the tube. To accomplish this, the secondary reservoir was filled with water. An ultrasound probe was placed in the water to image axial slices of the tube. The edges of the axial slices were outlined and the cross-sectional width was measured along the length of the tube. By determining the positional shift of the cross-sectional width at a known frame rate, the wave speed was determined.

To determine the natural frequency response and behavior of the impedance system a single waveform response was measured. The system was pinched once 1 inch from one end of the tube with a profile equivalent to that of pinching at a frequency of 4.7 Hz. Pressure, flow, and ultrasound images were simultaneously acquired.

Chapter 3

Experimental Results

3.1 Basic Systemic Behaviors

The basic systemic behaviors of the experimental setup were first measured to characterize its properties. Included are the compliance of the primary latex tubing used in the experiments and the wave speed on the surface of the elastic tube when filled with water to a fixed pressure.

3.1.1 Compliance

The compliance of the elastic tube used was measured by the method outlined in section 2.4.1 to be constant at 0.002525 mm Hg^{-1} within the pressure ranges observed during operation (figure 3.1). The maximum change in cross-sectional area due to elastic expansion for this compliance was under 1% suggesting that elastic forces are not essential to the pumping mechanism.

3.1.2 Wave Speed

For one typical configuration, the average wave speed observed on the surface of the tube was approximately 59 cm/sec when pressurized with water to 2.8 mm Hg (figure 3.2). In response to a single compression, the tube resonated at integer multiples of 8.8 Hz. This frequency is equivalent to the rate at which a single wave would travel half the length of the elastic tube at 59 cm/sec. However, the wave speed is

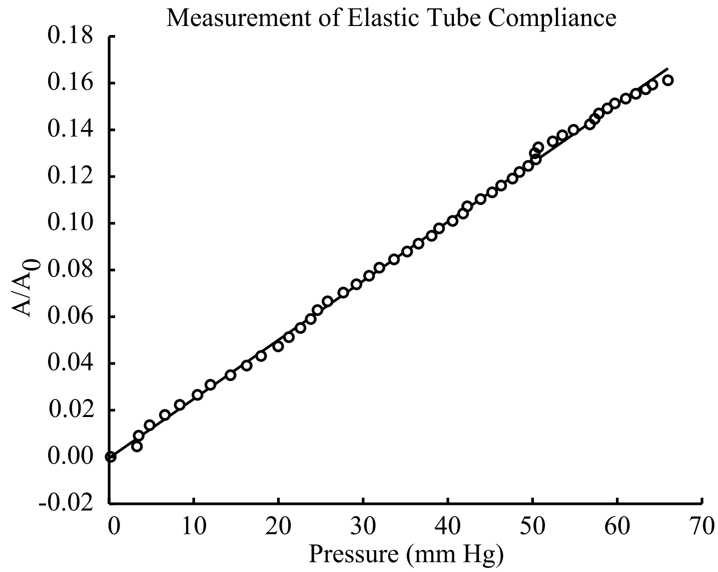


Figure 3.1: Measured compliance of amber latex tube 3/4 inch in inner diameter, 1/32 inch in thickness, with a tensile strength of 3500 PSI and a Shore A hardness rating of 35.

unique to each data set. When the tube is attached to the flow loop, the tension and other factors affecting the wave speed, and consequently the resonant frequency, are modified.

3.1.3 Reservoir Natural Resonant Frequency

In an effort to separate the behavior of the impedance pump with that of the flow loop including the reservoirs, the natural frequencies associated with the reservoirs and flow loop were measured with the pump removed. In its place was a short rigid tube of the same diameter. The reservoirs and adjoining tubing were filled to the same height used in all the experiments except for those where the height was deliberately changed to increase the transmural pressure across the elastic section. The setup was then lifted and quickly lowered to create an imbalance in the fluid level between the two reservoirs. The flow rate was subsequently measured through the short tube section whenever the short section was not occluded and through the long section when the short section was occluded. A Fourier transform of the resulting data