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

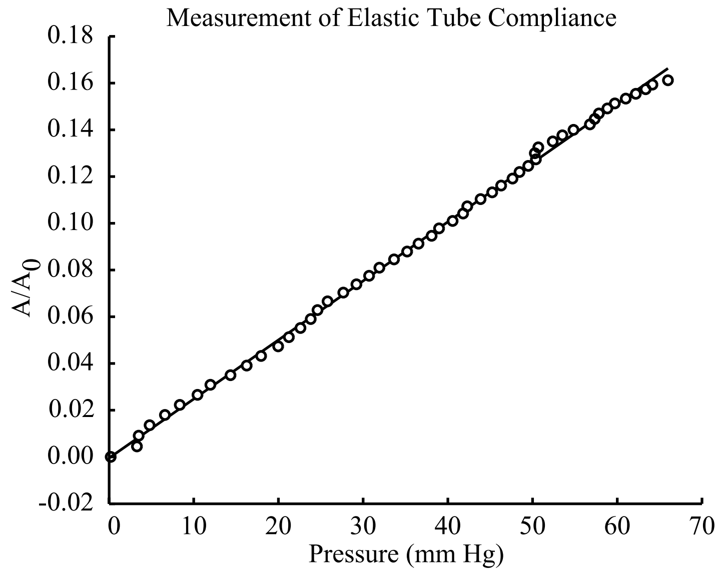


Figure 3.1: Measured compliance of amber latex tube 3/4 inch in inner diameter, 1/32 inch in thickness, with a tensile strength of 3500 PSI and a Shore A hardness rating of 35.

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

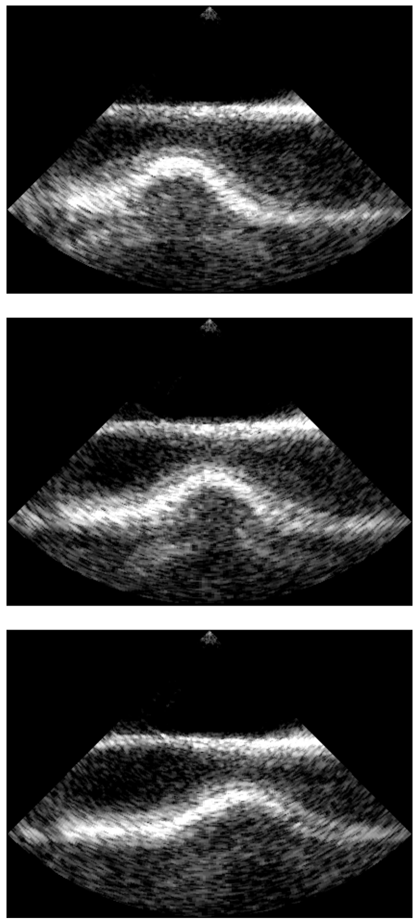


Figure 3.2: Ultrasound images of an axial slice of an elastic tube demonstrating wave motion used in the calculation of wave speed.

indicated the system, in this configuration, behaved as a simple harmonic oscillator with a resonant frequency of 0.300 Hz when allowed to flow through both the short rigid section and the long rigid section, 0.167 Hz when allowed to flow only through the long rigid section, and 0.234 Hz when allowed to flow only through the short rigid section.

3.2 Intrinsic Behaviors

The impedance pump is a remarkably robust system in its design. For every configuration we have built to date, an appropriate frequency has been found to drive significant net flow. Though the specific response of each configuration can be quite different, there are behaviors intrinsic to the impedance pump that can be observed in all configurations. In all cases, flow rates are considered positive when flowing from the short end to the long end of the elastic section.

3.2.1 Wall Motion

Imaging of the sectional slices of the impedance pump show the wave propagation along the length of the tube and reflection at the end. Also visible is that the tube is not expanding in diameter but rather functioning as a pliant tube that can buckle. This is because the pressures created in the system are not sufficiently high enough, given the compliance of the material used, to stretch the material beyond 1% of its resting diameter, as anticipated by the compliance measurement. This phenomenon is further discussed in section 3.2.5.

The configuration shown in figures 3.3 and 3.4 was a 6 inch long latex tube compressed with the motorized pinchers at 1 inch from the end. The compression is on the left of the images, at a frequency of 6.25 Hz. Cross-sectional slices were taken at 2, 3, 4, and 5 inches. One complete pinching cycle is shown. The pinchers remain in contact with the tubing material during the compression phase. As they begin to retract, the pinchers lose contact with the tubing and the ensuing tube motion is independent of the pincher motion. In the optimized case, we can see that the frequency of compression is matched with the frequency of refilling of the tube at the site of the compression such that just as the tube begins to relax following its refilling the pinchers begin to compress the tube again. This suggests that the impedance pump relies on resonance to build pressure and flow.

3.2.2 Role of Resonance

What role does resonance play in frequency response of an impedance pump? We first look at the flow response to an impulse and the corresponding fast Fourier transform (FFT) (figure 3.5). To do so, the solenoid pinchers were used on a 6 inch length of latex tubing. At first glance, the time response resembles a simple damped harmonic oscillator as does the envelope around the FFT. However, the FFT shows us that there are multiple frequency peaks within that envelope implying that the mechanics are of a more complex resonating system.

A look at the net flow rate as a function of frequency reveals that the resonant frequency of the system is also very near the frequency at which maximum positive net flow occurs. Maximum negative net flow occurs around the first multiple of the resonant frequency.

3.2.3 Transient Response

The resonant, pulsatile nature of the impedance pump leads us to ask about the transient nature of the pump. How long does it take to establish a net flow? Will the pump exhibit the same net flow when the forcing frequency is approached from different directions? Does the pump have different characteristics when approaching a negative net flow versus a positive net flow?

We look again at the data used to establish the resonant behavior of the impedance pump. This time, however, we inspect the development of the flow to reach a quasi-steady state. A comparison between the flow in time and the moving average of the flow in time are compared for each case: high positive net flow (figure 3.7), low positive net flow (figure 3.8), and high negative net flow (figure 3.9).

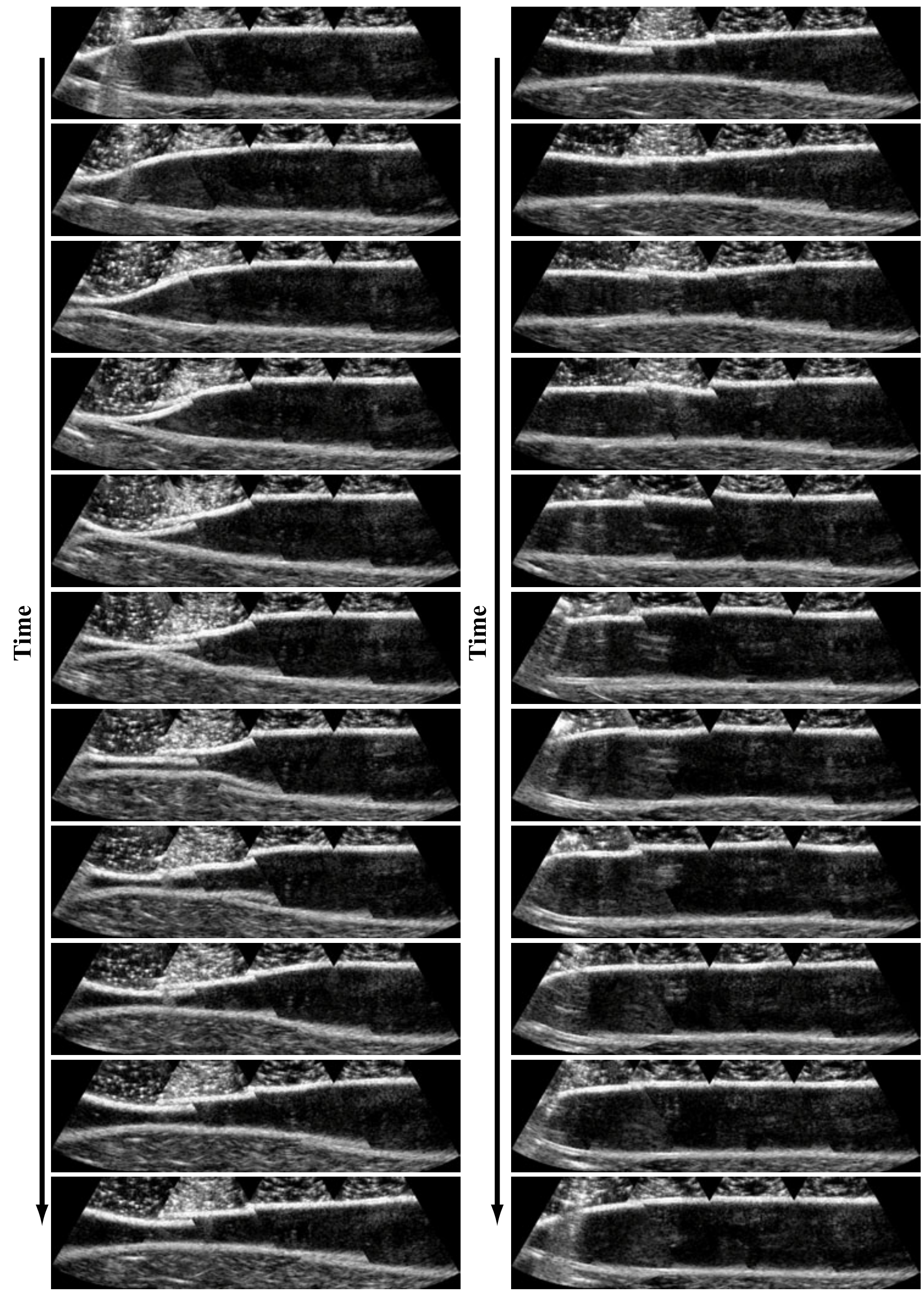


Figure 3.3: An axial section of impedance pump in time during highest net flow for a single compression cycle.

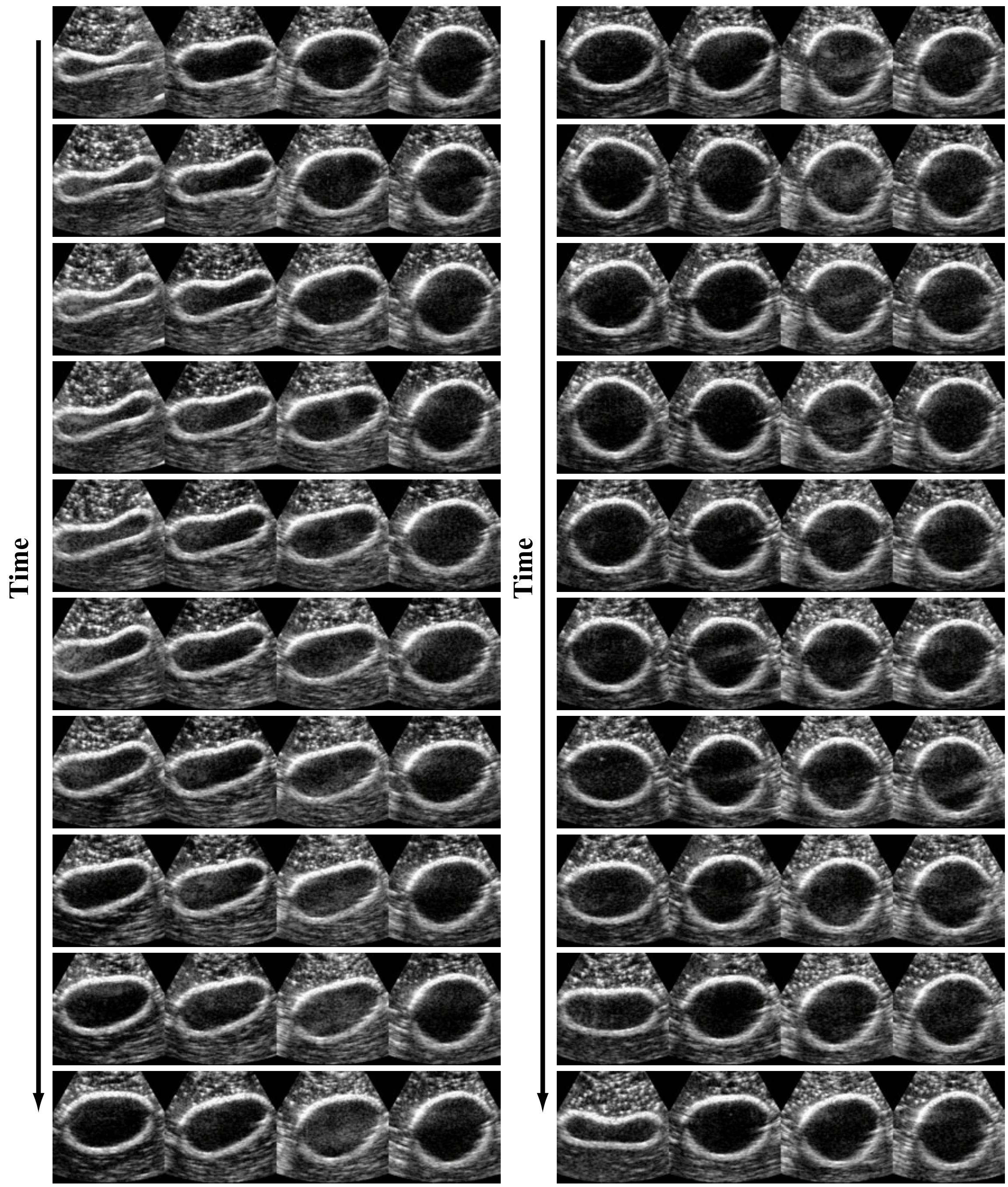
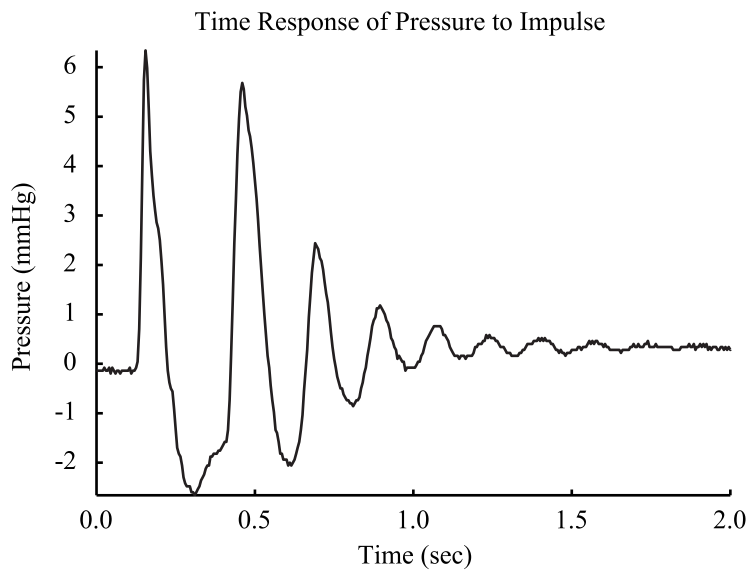
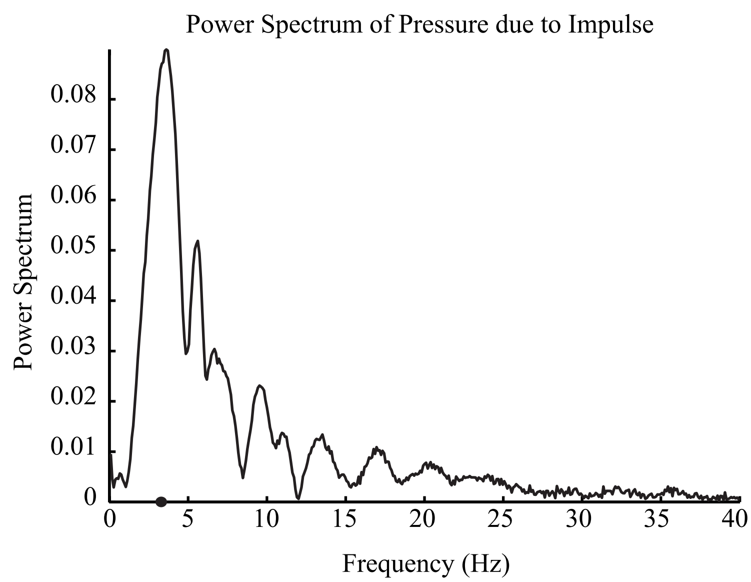


Figure 3.4: A cross section of impedance pump in time during highest net flow for a single compression cycle.



(a) Impulse response in time.



(b) Impulse response in frequency space and frequency of highest forward flow.

Figure 3.5: Response in time and frequency of pressure at exit interface to an impulse.

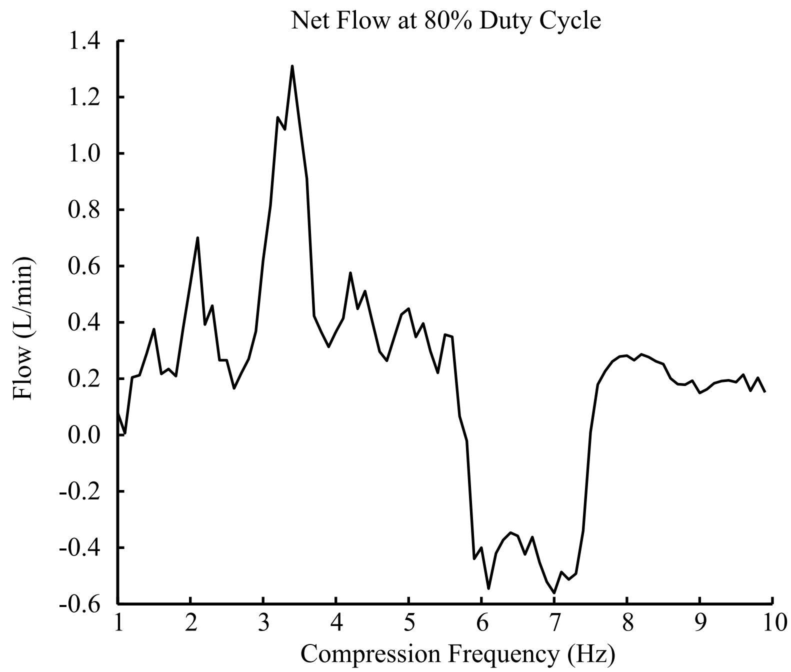


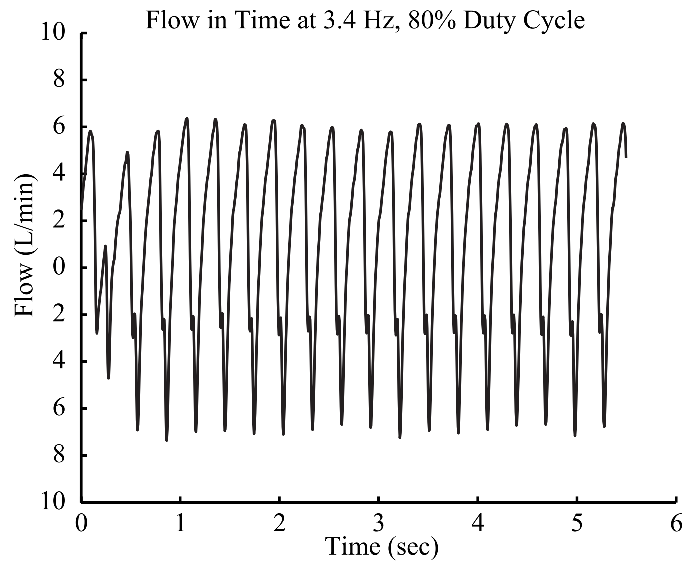
Figure 3.6: Sample mean flow as a function of frequency for a fixed configuration.

We find that for the high positive net flow case, an equilibrium is reached faster than for the low flow or negative flow cases.

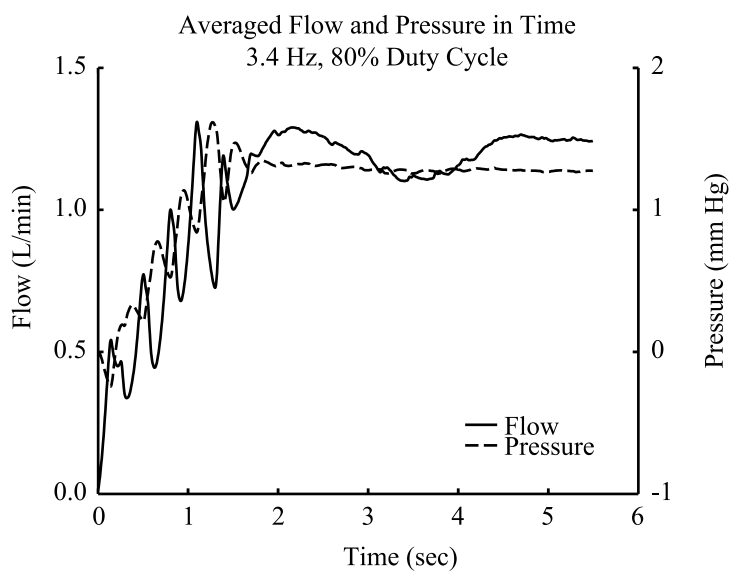
3.2.4 Pressure and Flow Relationship

We examine the relationship between pressure and flow at one end of the pliant section for cases of high positive net flow, low positive net flow, and high negative net flow. During the highest positive net flow, the pressure and flow appear to be locked in phase (figure 3.10). This is a direct result of activating the resonant frequency of the system.

In the low flow and negative flow cases, the flow-pressure profile moves counterclockwise in time (figures 3.11, 3.15). Just as the pressure drops, a flow forms filling in that area from a higher pressure region. The phase at which this occurs between the ends of the pliant tube can be coordinated in such a way as to select what the position of the higher pressure region should be, and in turn, inducing a unidirectional flow. This coordination is achieved by modifying the frequency and duty cycle. The same

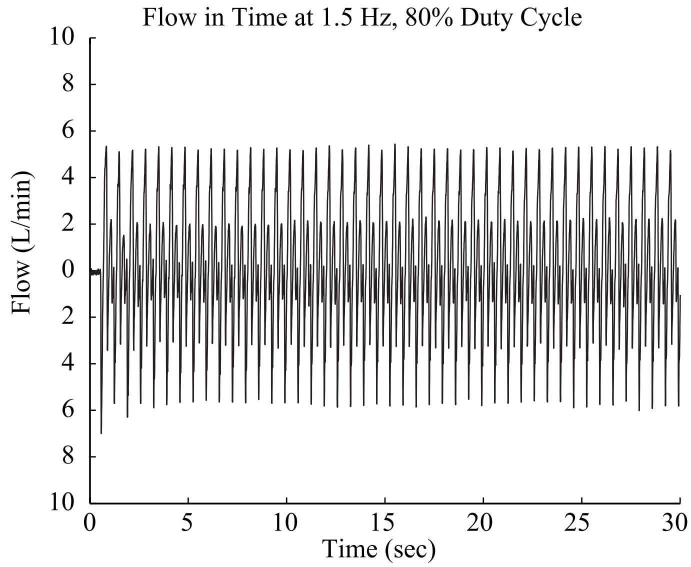


(a) Measured Flow

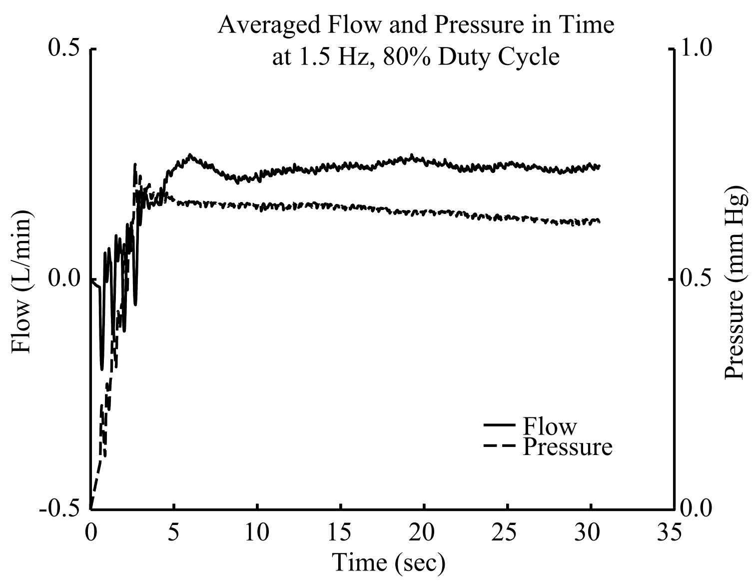


(b) Averaged Flow

Figure 3.7: Response of flow rate in time, both measured and averaged at highest mean flow rate.

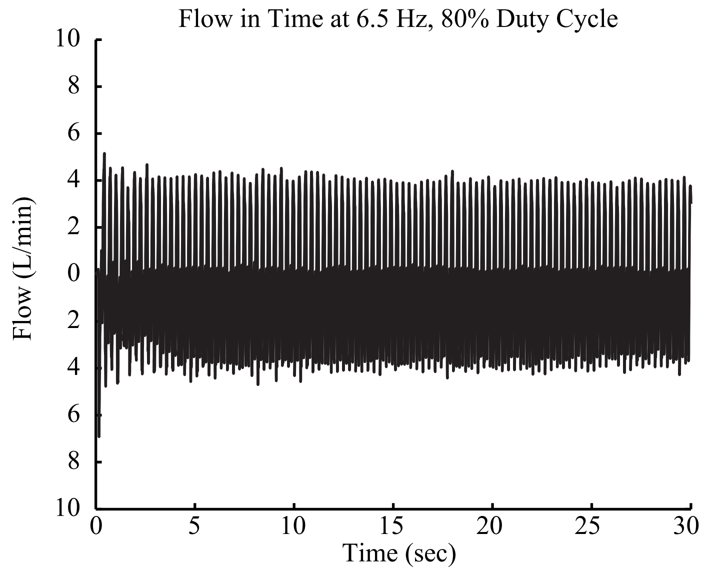


(a) Measured Flow

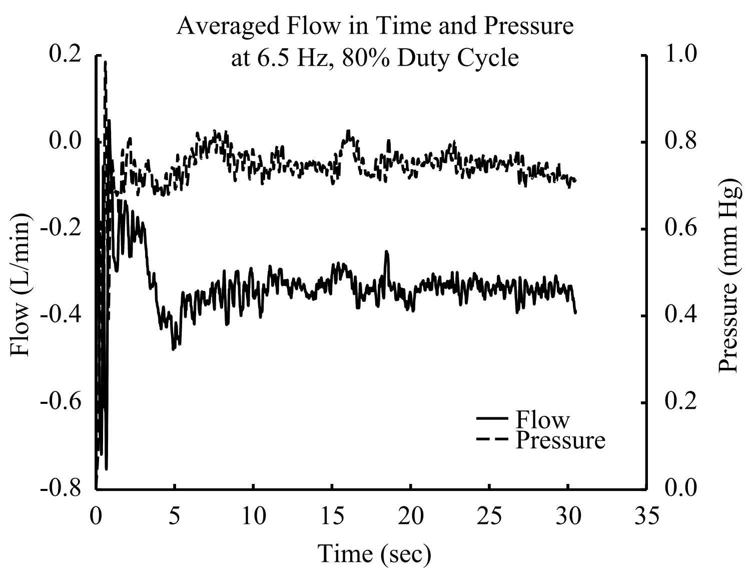


(b) Averaged Flow

Figure 3.8: Response of flow rate in time, both measured and averaged at low mean flow rate.



(a) Measured Flow



(b) Averaged Flow

Figure 3.9: Response of flow rate in time, both measured and averaged at high negative mean flow rate.

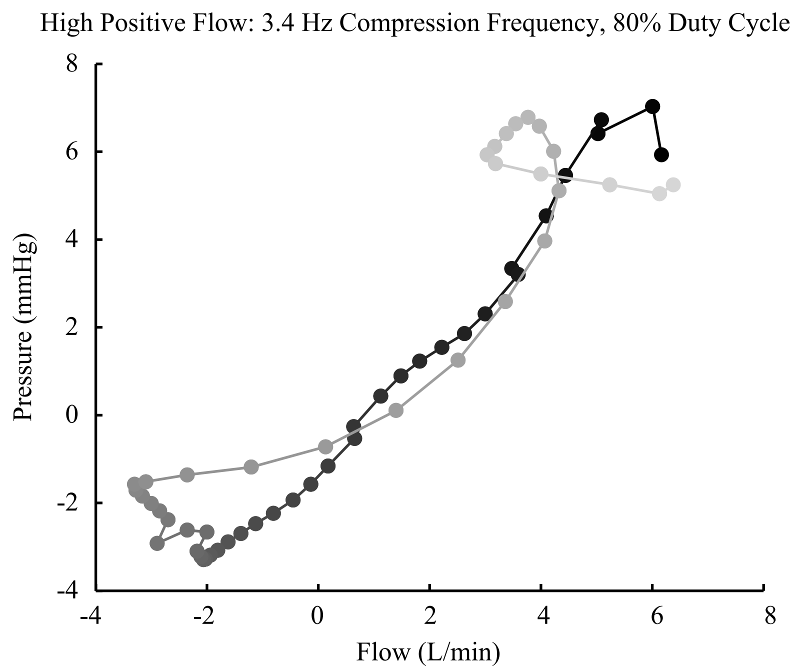


Figure 3.10: Pressure-flow relationship averaged over one compression cycle at end of long section during highest positive net flow. Points are equidistant in time. Color lightens forward in time.

phenomenon is observed when the flow is seeded in an axial slice ultrasound video. As the pressure decreases, the tube begins to collapse. When the traveling region of low pressure reaches the end it reflects off of the impedance mismatch causing the tube to open. Fluid immediately begins to fill in from behind the wave front. Once the section has expanded to its resting diameter, it begins to exert pressure back into the fluid. It reaches a critical threshold when the pressure differential can no longer drive the flow in the same direction and the flow reverses (figure 3.12).

We take a closer look at the pressure-flow profile for negative flow by comparing the results for many cycles (figure 3.13), phase-averaged with the compression frequency (figure 3.14) and finally phase-averaged by half the compression frequency (figure 3.15). Unlike the positive flow cases, both pressure and flow have periods double the duration of the compression period. However, this occurs at all higher compression frequencies and not only when the net flow is negative. Negative net flow, is caused by the same mechanism as forward flow. However, the frequency of compression is

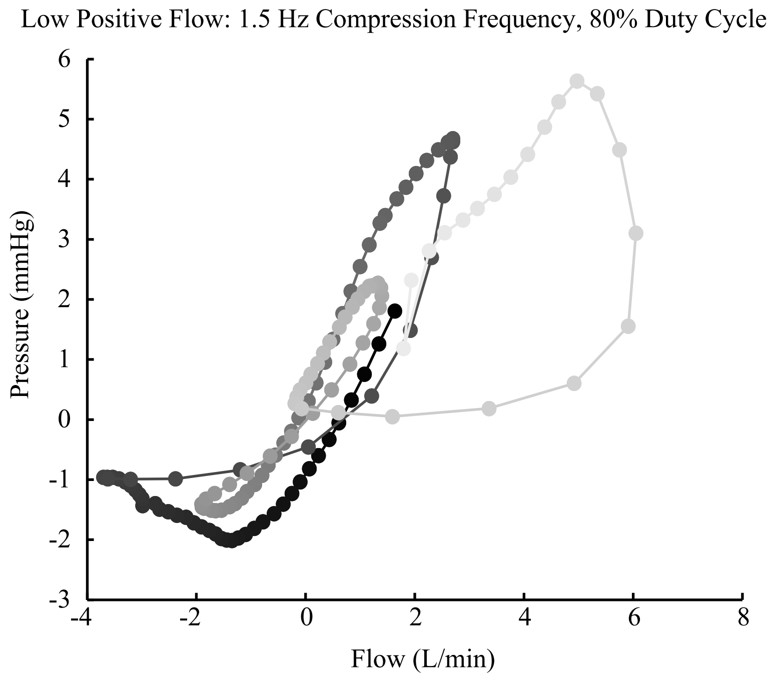


Figure 3.11: Pressure-flow relationship averaged over one compression cycle at end of long section during low positive net flow.

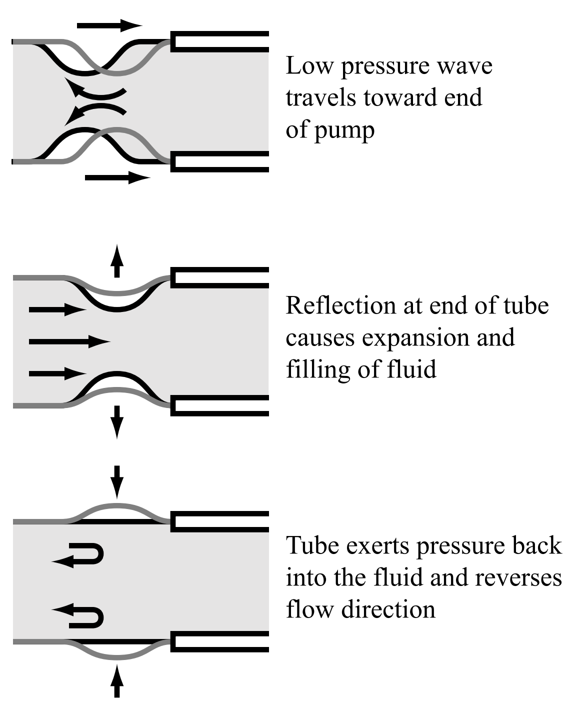


Figure 3.12: Illustration of pressure flow relationship near one end of the pliant tube.

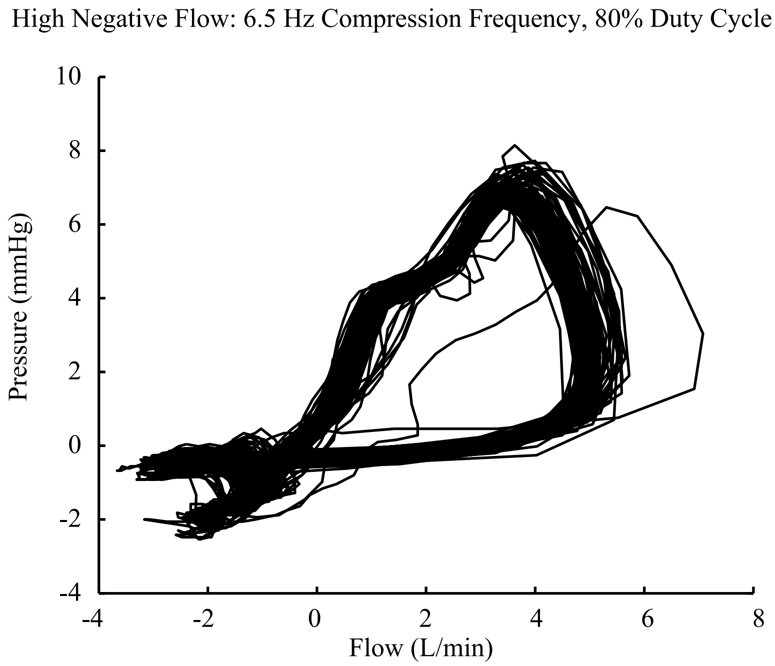


Figure 3.13: Pressure-flow relationship over all compression cycles at end of long section during high negative net flow.

such that the coordination between the pressures at the two ends of the pump result in a net negative flow.

3.2.5 Role of Elasticity

The compliance and range of pressures measured during the operation of the impedance pump show that the perimeter of the elastic latex tube used in the majority of the experiments did not expand past 1% of the resting perimeter whereas large changes in cross-sectional area were observed as the tube collapsed. To led us to evaluate the necessity of elasticity for the function of the impedance pump.

To test the hypothesis that elasticity is not required, experiments were conducted using a polyethylene, inelastic, pliant tube. When compressed manually at comparable frequencies to the previous trials, a net flow rate over 2 L/min was achieved, similar in magnitude to the elastic tube pinched under similar conditions. It follows that it is not the elastic properties of the tube that provide a restoring force to

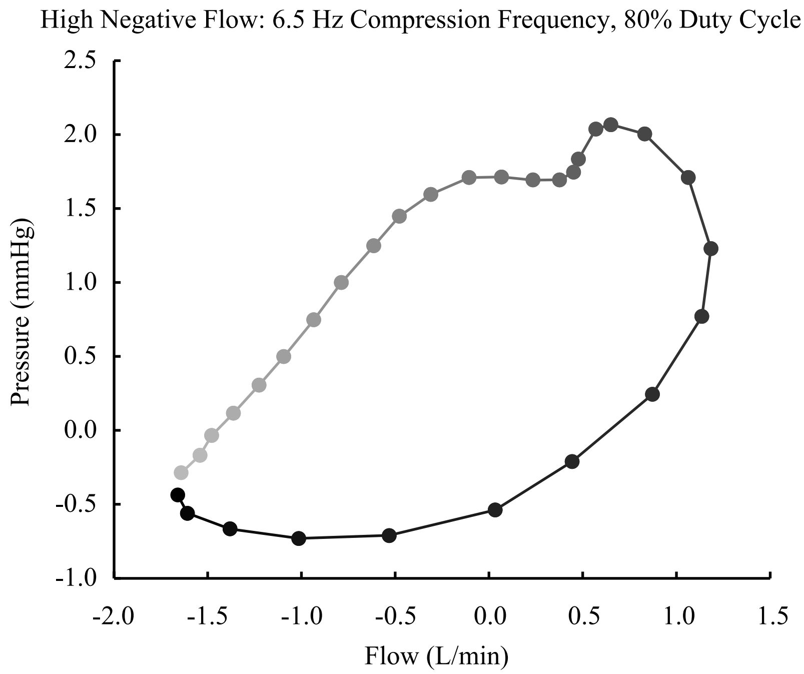


Figure 3.14: Pressure-flow relationship averaged over one compression cycle at end of long section during high negative net flow.

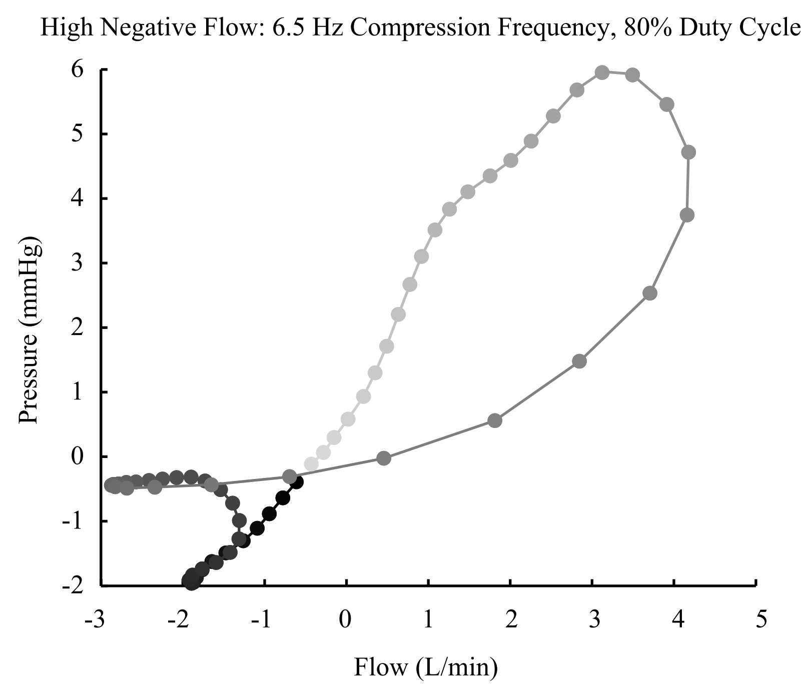


Figure 3.15: Pressure-flow relationship averaged over two compression cycles at end of long section during high negative net flow.

refill the tube and transmit waves but rather gravity that refills the tube from the reservoirs.

This expands the possible designs one might consider in the application of an impedance pump. In a neutrally pressurized environment elasticity may be used as the restoring force and the material would have to be chosen accordingly. However, for a pump loop that is naturally pressurized a wider range of materials and options are available. The arterial system, for example, is pressurized with respect to the body cavity. On a micro-scale, surface tension on a water droplet increases the pressure within the droplet with respect to the surrounding air. This pressure can also act as the restoring force for an impedance pump.

3.3 Bulk Flow Behaviors

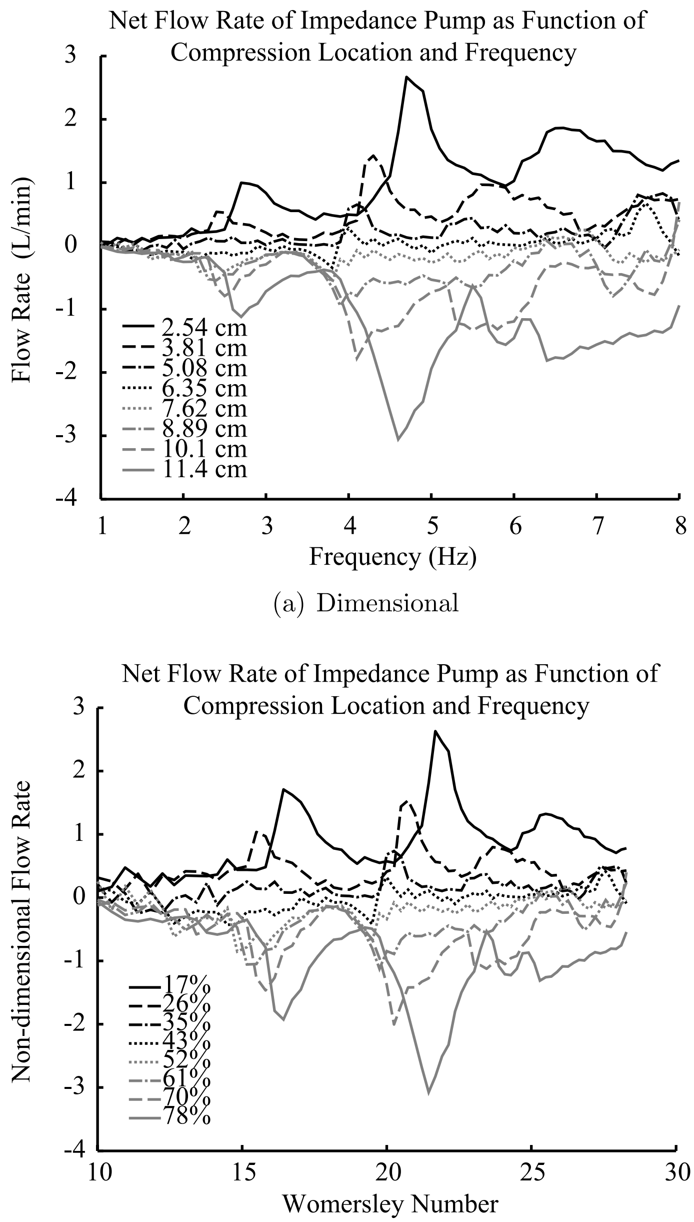
3.3.1 Frequency and Position

To test how the origin of the compression affects the net flow rate as a function of frequency, a set of measurements was acquired for frequencies ranging between 1 and 8 Hz using the motorized pinchers system (figure 3.16(a)). The location of pinching spanned the full length of the elastic tube. In all cases, the tube was 5 3/4 inches long and the compression was 1 inch wide unless explicitly mentioned.

To properly compare the results of this experimental setup with others, especially on different scales, the data can be made dimensionless. First, the flow rate is normalized by half the volume displaced by the pinchers times the compression frequency as suggested by Thomann [32]. Because we are concerned with a pulsatile flow through a tube, the Womersley number, α, arises as a useful tool to make the frequency of compression non-dimensional. The Womersley number is defined as $\alpha = r\sqrt{\frac{\rho\omega}{\mu}}$ where r is the resting radius of the pump, ρ is the density of the fluid being pumped, ω is the compression frequency, and μ is the dynamic (absolute) viscosity. The location of the pincher is measured as a percentage of the distance from one end of the elastic section to the center of the pincher width compared to the total length of the elastic section (figure 3.16(b)).

The net flow rate as a function of the non-dimensional pinching frequency, the Womersley number, maintains a similar trend between different pincher locations. In this trend we see a series of distinct peaks at which flow maxima occur. All the flow rates have been non-dimensionalized by half the rate of volume displaced by the compression. The unique frequency dependence of the net flow rate implies the occurrence of resonance, a consequence of wave propagation and reflection due to impedance mismatching. As the position of the pincher location moves toward the center of the primary elastic section, the location of those peaks shifts to slightly lower frequencies. Assuming a constant wave speed, these observations further our hypothesis of interfering waveforms, since an increase in the distance of the compression from one end increases the time necessary for a wave to travel that distance and back to the pincher location. This would result in a downshift of the frequency response. The magnitude of the net flow also decreases to zero as the pincher moves toward and becomes symmetric about the center. Increasing the distance of the compression from the ends further attenuates the wave, decreasing the pumping energy and flow rate. When the compression is in the center, the system is fully symmetric and no flow is expected. The highest non-dimensional net flow rate of 2.62 occurring at a Womersley number of 21.7 (4.7 Hz) exceeds the volumetric rate of fluid displaced by the compression. A peristaltic system non-dimensionalized in the same manner would result in a constant non-dimensional flow rate of 2. As a first approximation, this demonstrates that the impedance pump can be more efficient than a peristaltic system and is further discussed in section 3.3.7.

Flow rates as a function of time were further investigated at select Womersley numbers based on the net flow rates found in the trials (figure 3.17(a)). Womersley numbers of 16.4 (2.7 Hz), 19.7 (3.9 Hz), 21.7 (4.7 Hz), and 25.7 (7.1 Hz) compressed at a distance of 1 inch were chosen to compare the flow profiles at resonant peaks with a non-resonant flow profile. In all cases, significant backflow was observed. However, the non-resonant case had a longer semi-steady period of backflow whereas the resonant cases immediately began to accelerate forward after reaching their respective negative



(a) Dimensional

(b) Dimensionless

Figure 3.16: The net flow rate of the impedance pump as a function of compression position and frequency.

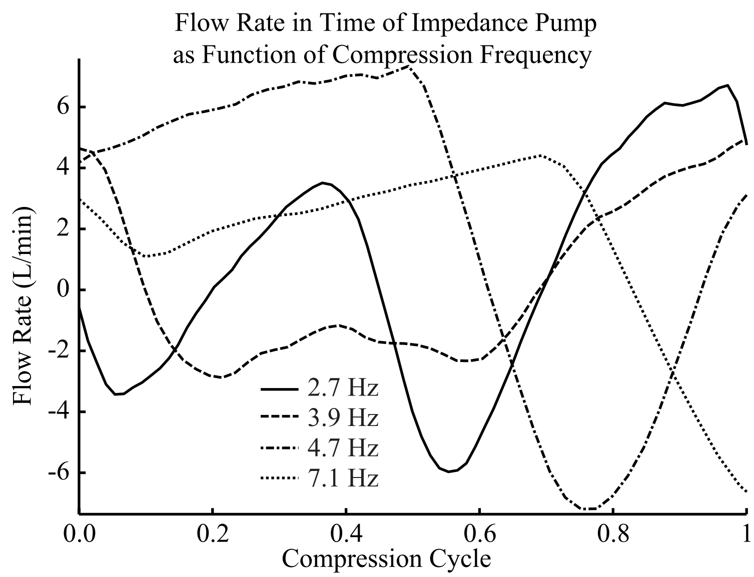
peaks. An FFT of the flow waveform has peaks at the forcing frequency plus an integer multiple of an unknown frequency that may be related to the natural frequency of the elastic section (figure 3.17(b)). What is interesting to notice is that the tallest FFT peak occurs at the same frequency as the highest net flow rate and the remaining FFT peaks decay in amplitude around the tallest. This further supports our hypothesis of resonating waves within an impedance chamber. By determining the resonant frequency of an impedance system, one may be able to predict the subsequent pump behavior under various compression profiles.

3.3.2 Frequency and Transmural Pressure

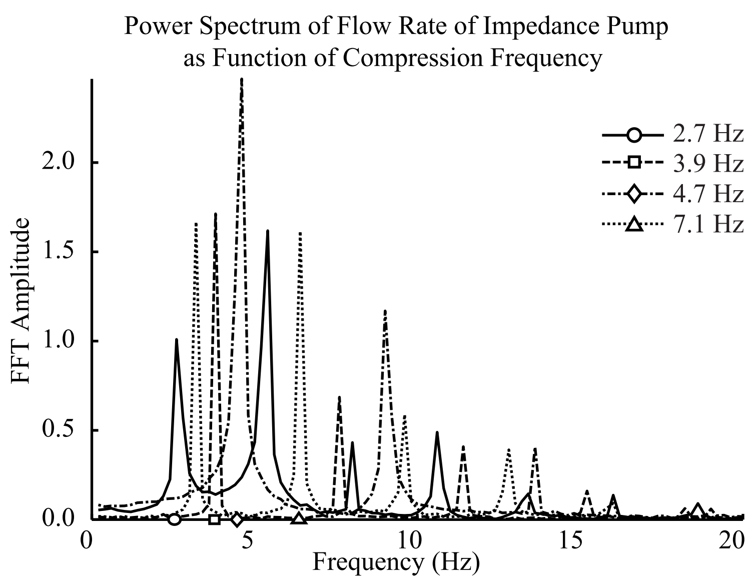
The experiment was repeated varying transmural pressure at rest across the wall of the elastic section with the pincher located at a constant position of 1 inch. Figure 3.18 shows that by increasing the internal pressure of the system, the peak net flow rate decreases and the frequency response shifted to higher values. One would expect this result from a shift in wave speed. This phenomenon is exaggerated by the method for non-dimensionalizing the net flow rate.

3.3.3 Frequency and Compression Width

To modulate the amount of energy imparted into the fluid, the experiment was repeated for varying pincher widths. In absolute terms, a wider pincher corresponds to a larger volume being displaced and therefore more energy being imparted into the fluid, and to higher flow rates (figure 3.19(a)). However, when non-dimensionalized against the rate of volume displacement by the compression, no clear pattern emerges (figure 3.19(b)). As the width of the compression approaches the distance from the end of the elastic section, other behaviors will begin to dominate. No longer is just the volume displaced changing, but also the distance the waves travel from the pincher to the end of the elastic section and back. Flow reversal is also observed when the pincher width is narrowed to 4.3% and 8.7% of the total length of the elastic tube. The magnitude of the reversed flow in this case is significantly lower than the forward

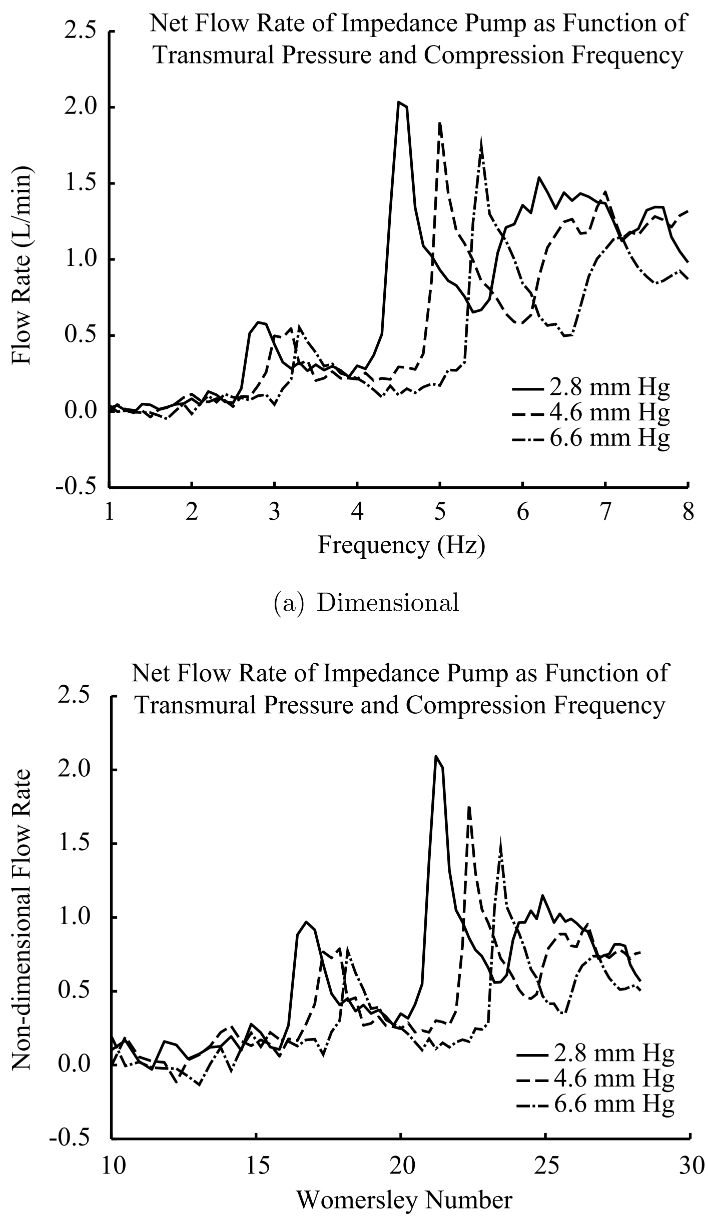


(a) Flow Rate



(b) FFT of Flow Rate

Figure 3.17: The flow rate in time and its Fourier transform for selected compression frequencies.



(a) Dimensional

(b) Non-dimensional

Figure 3.18: The net flow rate of the impedance pump as a function of transmural pressure and compression frequency.

direction.

3.3.4 Frequency and Systemic Resistance

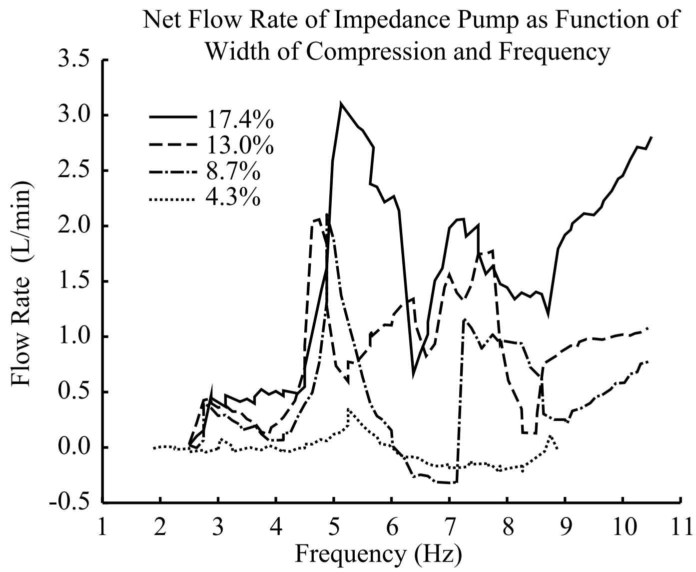
The resistance to flow of the system was also adjusted far from the elastic section by applying a constriction of varying diameter (figures 3.20, 3.21). As the resistance went up, the flow rate went down, and the pressure head went up as is typical in a pump. The pressure head as a function of frequency maintained a similar profile to the flow rate as a function of frequency with the peaks in pressure occurring at the same frequencies as the peaks in net flow rate. The power converted toward pumping the fluid therefore also has this non-linear profile.

3.3.5 Frequency and Viscosity

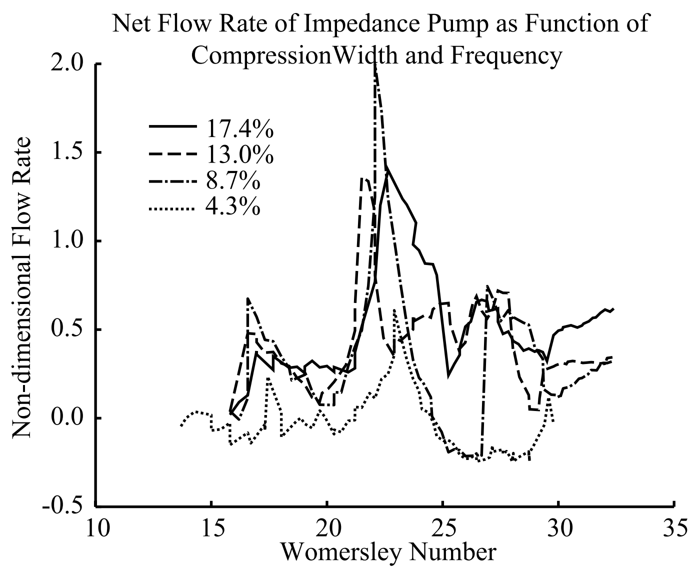
The effects of viscosity on the performance of the impedance pump were tested by preparing glycerol solutions with different fractions of glycerol to water. The solutions tested were 0%, 12%, 23%, 32%, and 47% glycerol by mass corresponding to relative viscosities of 1.0 cP, 1.3 cP, 1.8 cP, 2.4 cP, and 4.6 cP respectively. The resulting frequency response curve (figure 3.22(a)) shows little change for different viscosities. The non-dimensionalized response curve (figure 3.22(b)) on the other hand, shows peaks at dramatically different locations because the Womersley number incorporates the relative viscosity. These results demonstrate that the resonance phenomena is unaffected by relative viscosity within this range. It would seem, that the wave speed also remains unaffected.

3.3.6 Frequency and Duty Cycle

To study the effect of duty cycle, the solenoid-driven pinchers were used on a 6 inch long latex tube. A quantitative look was taken on the effects of duty cycle on the direction of the flow rate (figure 3.23). The duty cycle is defined in section 2.3.2 as the fraction of the compression period during which the solenoid is active corresponding to an open tube. When the duty cycle is modified, two things happen: the flow is

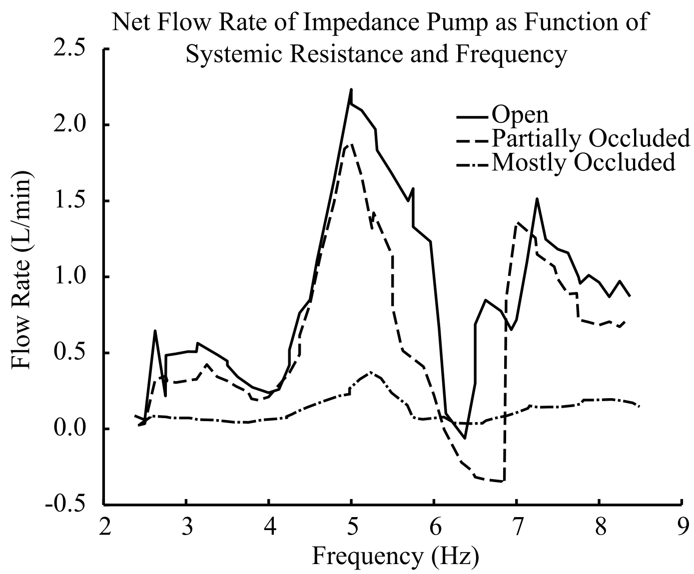


(a) Dimensional

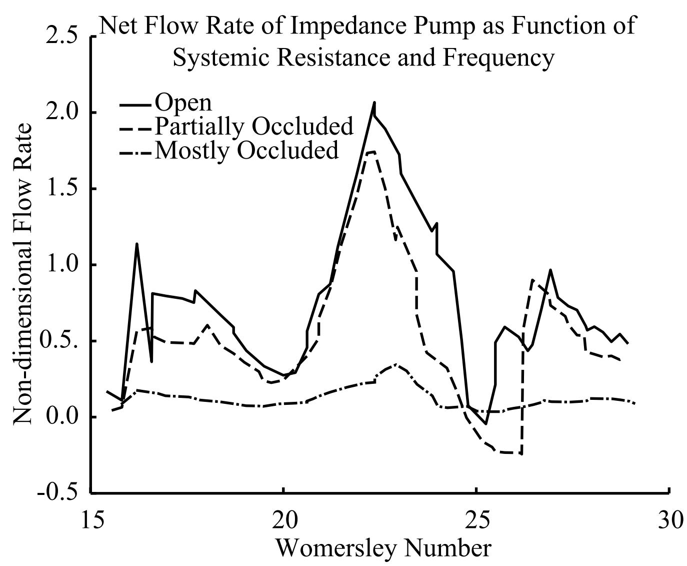


(b) Non-dimensional

Figure 3.19: The net flow rate of the impedance pump as a function of compression width represented as a fraction of the total length of the elastic section and frequency.

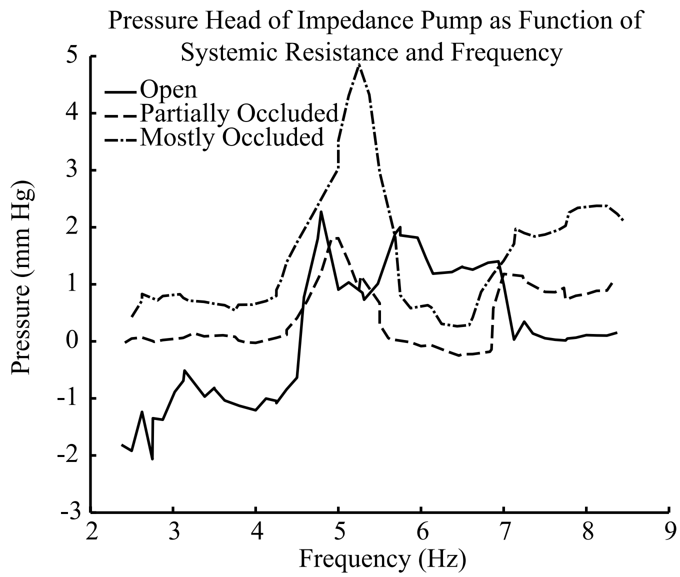


(a) Dimensional

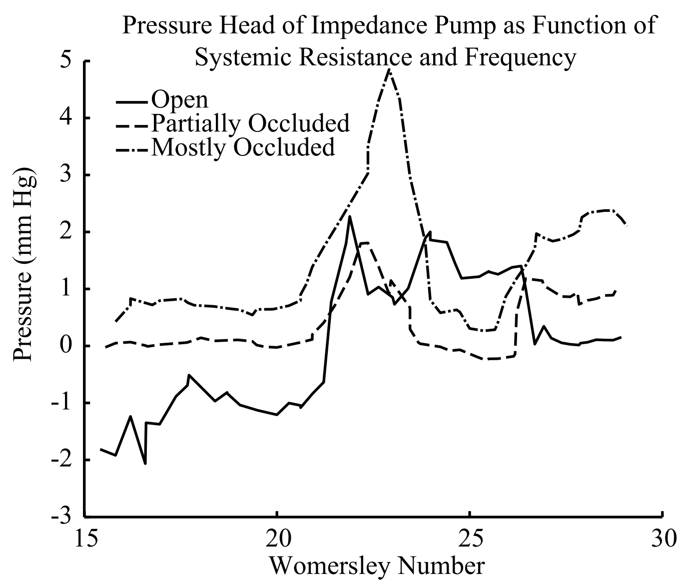


(b) Non-dimensional

Figure 3.20: The net flow rate of the impedance pump as a function of systemic resistance and compression frequency.

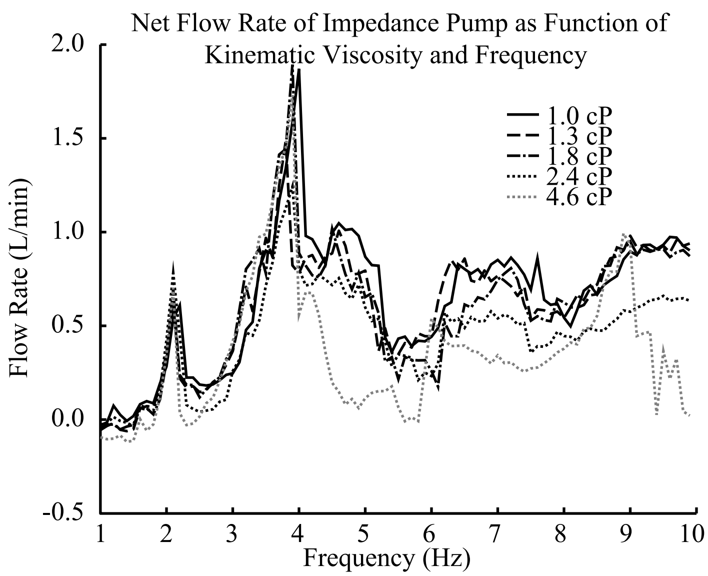


(a) Dimensional

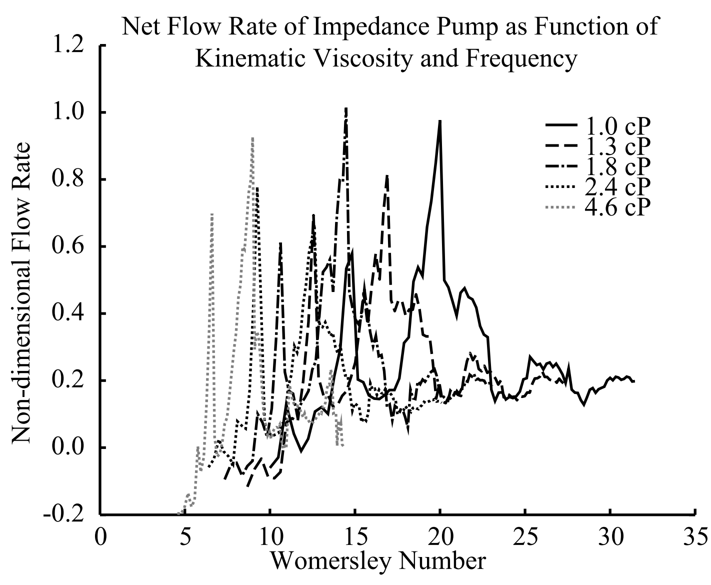


(b) Non-dimensional

Figure 3.21: The net pressure head of the impedance pump as a function of systemic resistance and compression frequency.



(a) Dimensional



(b) Non-dimensional

Figure 3.22: The net flow rate of the impedance pump as a function of kinematic viscosity and compression frequency.

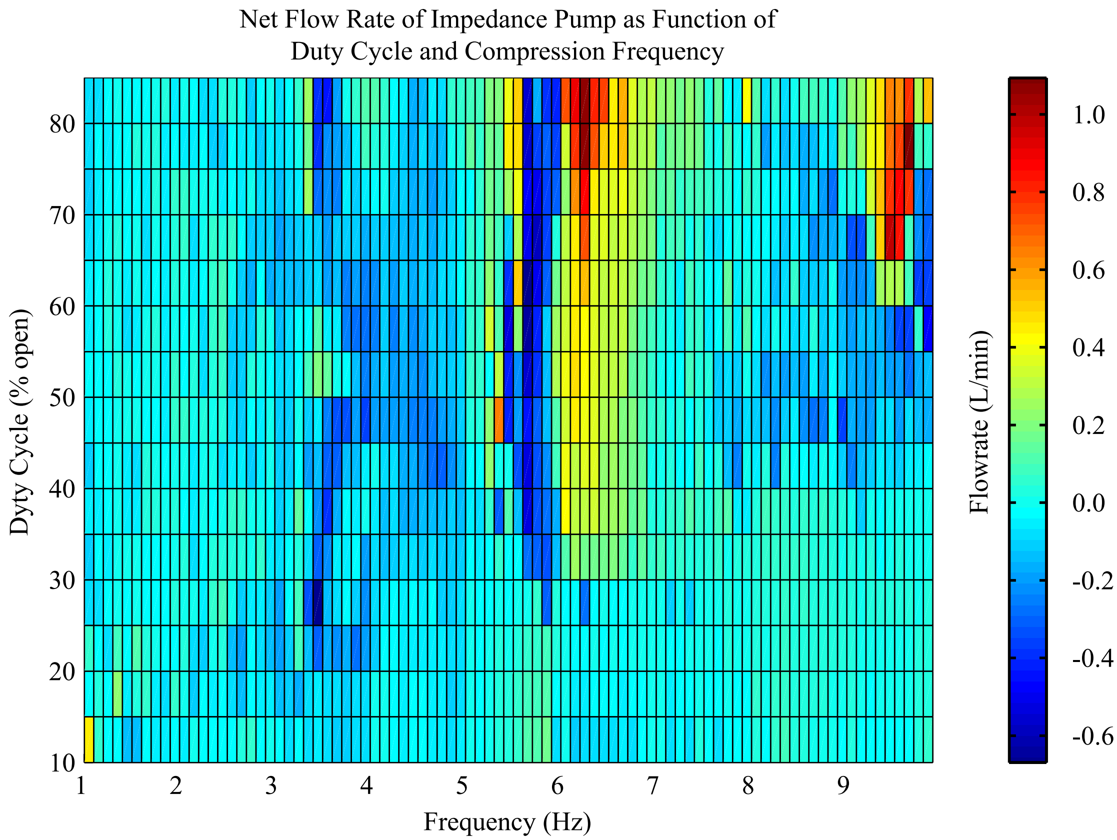


Figure 3.23: The net flow rate of the impedance pump as a function of duty cycle and compression frequency.

physically obstructed for different amounts of time and the pressure wave interaction on the tube is modified because the pressure waves can reflect off of the compression site for different amounts of time. For this configuration, the duty cycle only affects the magnitude of the net flow but not the direction or frequency response. This is caused by the obstruction to flow. In another configuration with less attenuation, the duty cycle may have more effect because the amplitude of the pressure wave will be greater when it returns to the pincher location.

3.3.7 Bulk Flow Efficiency

The efficiency of the impedance pump system may be separated into three parts: the electromechanical efficiency of the compression mechanism, the efficiency in the conversion of mechanical to fluidic power and, finally, the pulsatile nature of the flow which requires us to determine the efficiency associated with the net flow versus pulsatile flow.

The electromechanical efficiency is dependent on the design of the compression mechanism. This loss is not a fundamental part of the pump's behavior and is therefore not addressed in this thesis. The mechanical to fluidic power can sustain a loss only in the form of heat if a restoring force is incorporated into the compression mechanism. This suggests that with proper design, this loss can be minimized relative to the pulsatile flow loss. The final loss between the pulsatile flow to net flow can be calculated in the following way:

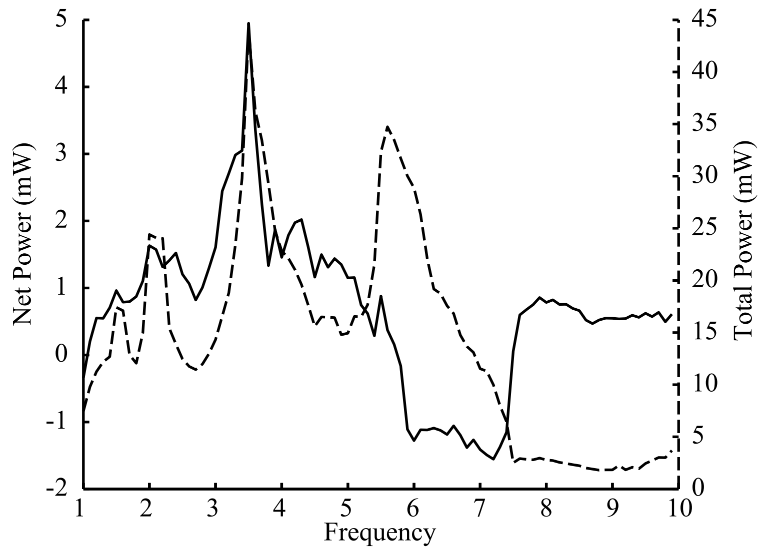
Property	Symbol
Period of compression	T
Time	t
Pressure difference across length of pump	$\Delta P(t)$
Volumetric flow rate	$Q(t)$

Table 3.1: Variables used in calculating efficiency

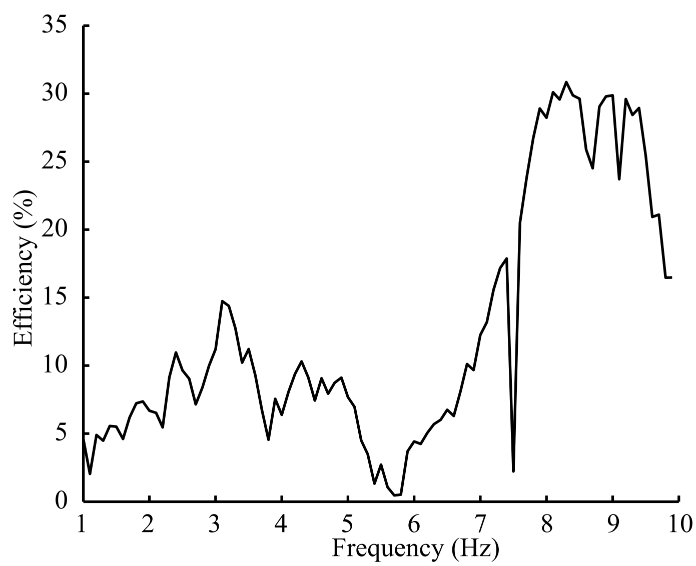
$$\text{Net Power} = \frac{1}{T}\int_{t=0}^{T} \Delta P(t)dt \cdot \frac{1}{T}\int_{t=0}^{T} Q(t)dt$$
$$\text{Total Power} = \frac{1}{T}\int_{t=0}^{T} \Delta P(t) \cdot Q(t)dt$$

We consider the data set used for analyzing the transient and resonant responses of the impedance system whose bulk flow behavior is illustrated in figure 3.6. An efficiency of 15% is seen at the point of maximum net forward flow.

A typical centrifugal pump with comparable flow rates to the impedance pump tested will have an efficiency between 40% and 65% at its optimal operating point [9]. This is significantly higher than the 15% of the impedance pump. However, the advantages of a simply actuated tube over a pump requiring seals and blades may overcome this difference. In addition, for some applications, such as for mixing, a pulsatile flow is preferred over a simple flow. For those cases, the efficiency calculated



(a) The total and net fluidic power as a function of compression frequency



(b) The efficiency of power as a function of compression frequency

Figure 3.24: The power efficiency of the impedance pump based on the net forward and total power of the fluid as derived from the data set shown in figure 3.6

in the loss due to the pulsatile nature does not apply.