Chapter 1

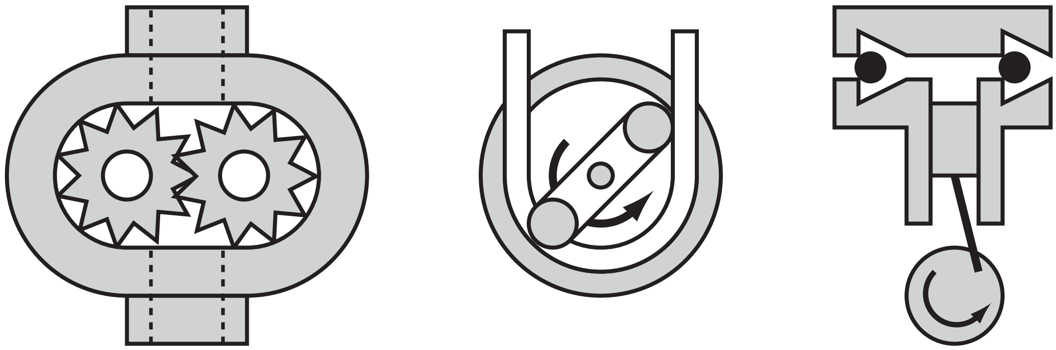
Introduction

The process of fluid transport plays a critical role in fulfilling two fundamental requirements for sustaining life: obtaining food and disposing of waste. Depending on environment and scale, there are two fundamental approaches that can be used to accomplish these tasks: move the body through the fluid, such as in swimming and flying; and move the fluid through the body, such as in digestion, breathing, and heat transport.

To move fluid we need pumps, be it our own beating hearts or our intestines, or other solutions nature has devised such as wings, jellyfish jets, gopher burrows, and flagella [33]. With all the diversity and complexity that nature has evolved in its pump designs, certain features, though not without exception, remain simple: flexible membranes, lack of blades, and lack of valves. These features eliminate mechanical complexity that is prone to failure. Even the human heart establishes unidirectional circulation prior to the formation of valves.

1.1 Pumping Mechanisms

Pumps in bioengineering can be divided into two broad categories: man made pumps used for biological research and biomedical applications, and naturally occurring pumps in biological systems. In most cases, these will overlap. The impedance pump is no exception. Biological systems can provide insight into the development of artificial pumps, and artificial pumps can prove to be models for naturally occurring



(a) Gear pump (b) Peristaltic pump (c) Piston pump

Figure 1.1: Example positive displacement pumps

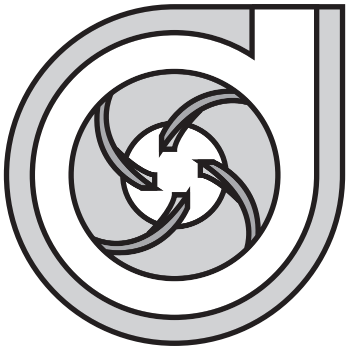
systems. Some of the more prominent fluid transport mechanisms include positive displacement pumps and dynamic pumps.

1.1.1 Positive Displacement Pumps

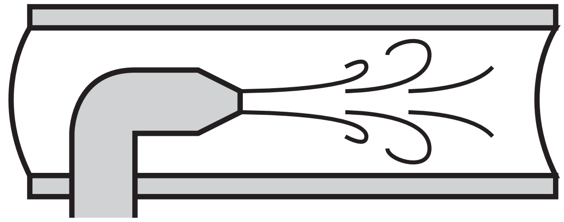
Positive displacement pumps function by filling a chamber with fluid and displacing the volume. Among the more common positive displacement pumps are peristaltic and reciprocating pumps. These type of pumps are not dependent on the pressure head or viscosity. The stroke to volume ratio is constant. That means that they have a linear response to the driving frequency, be it a motor or a piston. They typically produce low flow rates at high pressures.

A peristaltic pump consists of a tube or channel that is first compressed at one location, and then the compression is moved along the length of the channel, displacing the fluid that was in front of it. It is primarily used for moving highly viscous fluids that are either corrosive, or cannot be contaminated. The intestines are an example of such a pumping mechanism.

A reciprocating pump has two one-way valves, and a chamber that is filled and displaced between the two valves by a piston or membrane moving in a reciprocating motion. Other variations of positive displacement pumps include a gear pump, peristaltic pump and piston pump (figure 1.1).



(a) Centrifugal pump



(b) Jet pump

Figure 1.2: Example kinetic pumps

1.1.2 Dynamic Pumps

Dynamic pumps function by transferring kinetic energy to the fluid in such a way as to create a pressure head. For example, a centrifugal pump consists of a set of rotating vanes that impart kinetic energy into the fluid. The vanes or blades rely on the Bernoulli effect to create a pressure across them (figure 1.2(a)). It is the most common pump used in engineering applications though it is not found in this form in nature. A jet pump is a classic example of a kinetic pump that does not use vanes or blades. A jet of fluid is directed into a pipe that transfers its kinetic energy into the fluid, causing it to flow (figure 1.2(b)).

1.1.3 Impedance Pump

Impedance is defined as the resistance of a medium to the transmission of a wave, and is dependent on the frequency components of the wave being transmitted. Whenever two mediums connect that have different impedances, a wave passing through that intersection will partially reflect in an amount based on the relative values of those impedances. This is true for electrical signals crossing different wires, for pressure waves moving into different densities, and for mechanical waves in a string.

An impedance pump can then be defined as a fluid-filled pliant tube, open and connected at the ends to tubing of a different impedance such that when a wave travels along the surface of the pliant section there will be at least partial reflection of the wave at the impedance mismatched interface. When this pliant section is periodically compressed off-center from the interfaces to the different tubing, a net flow can occur. The impedance pump functions by imparting the kinetic energy by the action of compression and transmitting that energy via surface waves into the fluid to build a pressure head, thus making it another example of a kinetic pump that does not require vanes (figure 1.3).

It has recently been shown that the impedance pump may serve as a model of heart function in the early embryonic stages of vertebrae before valve or chamber development [5] as opposed to peristaltic pumping as was once thought [4]. In vivo observations and analysis show a number of non-peristaltic characteristics found in the impedance pump. These include pulsatile flow, retrograde flow, a non-linear response of the net flow rate to the frequency of pinching, wave reflection, and wave dissipation.

The hypothesis can be further extended to the aortic vessels of an adult. Many studies have been done on the passive elastic properties of these vessels [6, 11, 12, 25, 27, 28, 34–39] and how these properties may help reduce the power required for circulation. In the case of a diseased individual who may have hardening of the vessels, they may lose the benefit of this pumping and perhaps even have a reverse effect [7]. The impedance pump may both provide insight into the passive properties and become a medical device used in the treatment of the arterial diseases [24].

Additional research is being conducted to develop a micro-scaled version [30] with applications in medicine, heat transfer, lab-on-chip technology, and micro-mixing.

1.2 Prior Work

In 1954, Gerhart Liebau demonstrated valveless pumping (figure 1.4) [18–20] by periodically compressing and elastic tube and showed that it was able to pump fluid from a lower to a higher pressure head. Liebau suggested that elasticity, viscosity, and inertia affected the performance of the device. But he was not able to explain

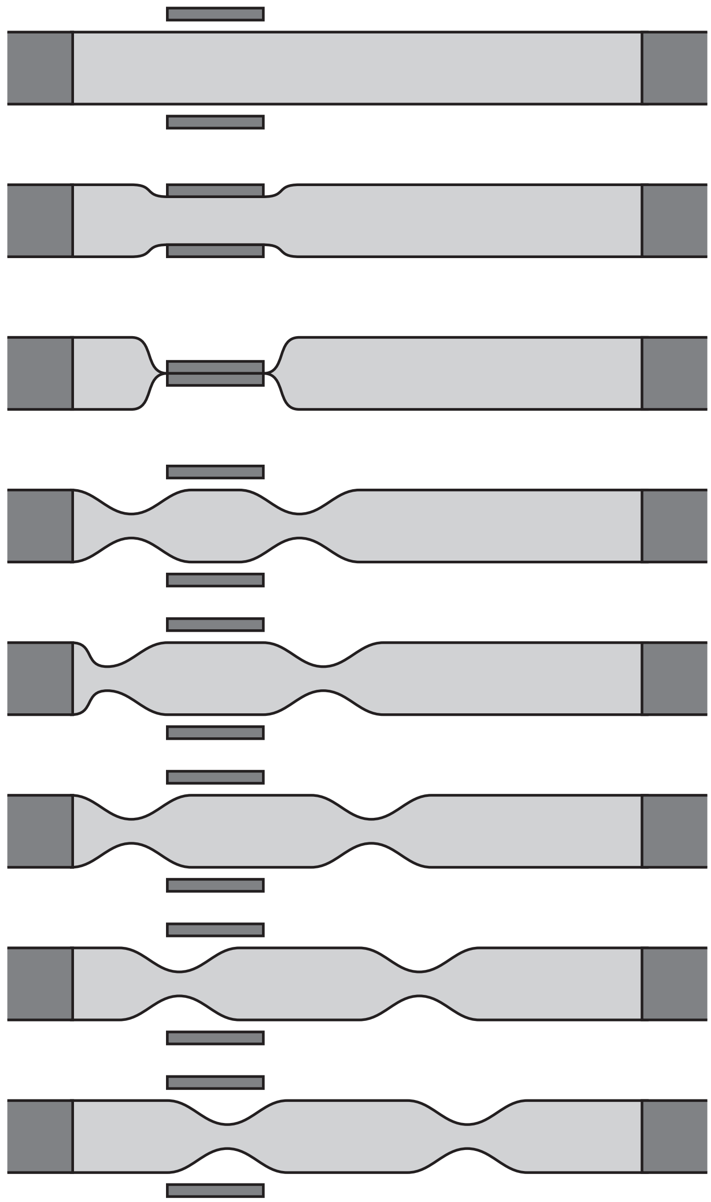


Figure 1.3: Impedance pump diagram

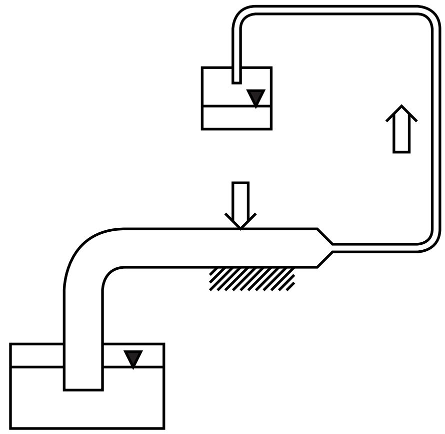


Figure 1.4: Liebau's model of the impedance pump

how these parameters contributed to the pumping [18, 23].

Since his work, there has been a large collection of analytical [1, 16, 17, 23, 26, 29, 32, 40] and computational [2, 13–15] studies that attempt to describe the phenomena. However, there have been very few experimental studies [18, 22, 26], most of which were limited to validating one or two cases to complement their analytical and computational work.

By 1978, Hans Thomann had developed a mathematical model of the pumping mechanism with simplifying assumptions [32]. The model was of a torus that can be cut open and treated as a periodic entity (figure 1.5). His model is for one-dimensional, periodic, inviscid, and incompressible flow. He assumed the volume displaced for each compression is divided equally to either side of the compression. He further assumed a fixed relationship between the pressure within the tube, p, and the cross-sectional area, A with constants c_1, c_2 and n.

$$p = c_1 + c_2 A^n$$

These assumptions were used to simplify the Navier-Stokes equations and continuity equation. He further simplified the governing equations by linearizing them, and solving them using the method of characteristics. In order to impose boundary con-

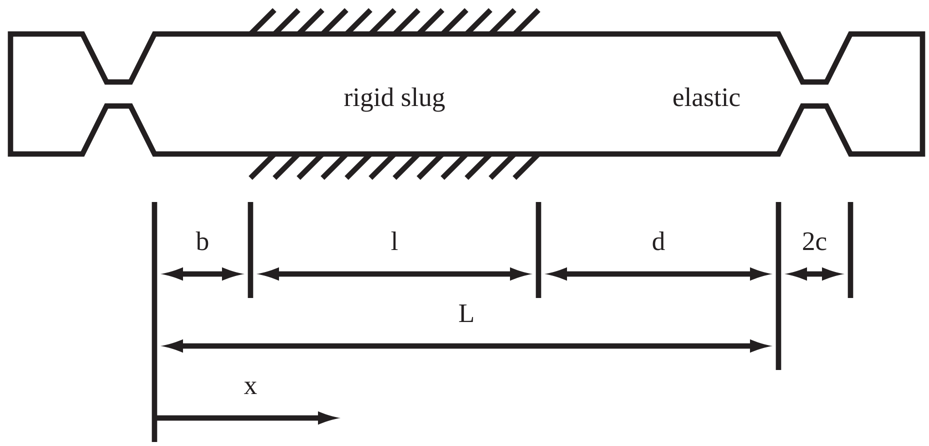


Figure 1.5: Thomann's model of the impedance pump

ditions, Thomann assumed a rigid tube connected the ends of the pump forces the flow and pressure to match at the ends of the pump.

Thomann's model shows that a net flow can be induced. His assumptions, however, greatly limit the usefulness of his results. His model required the inertial force of the fluid in the rigid connecting loop to oscillate and therefore create a net flow. Also, by linearizing the equations, he got results that are only valid for small deformations of the elastic surface. This effectively means his solutions are only valid for elastic wall deformations with long wavelengths.

Another model of the impedance pump was presented by Maximilian Moser in 1998 [23]. He suggested that the impedance pump need not be a tube, but rather two distensible reservoirs connected with rigid tubing of different diameters. He built an analogy of the pump to an electrical circuit, as diagrammed in figure 1.6. Using this analogy, he was able to make a prediction of the net flow rate as a function of the compression frequency. This electrical analogy is only applicable to the modifications that Moser made in defining the impedance pump and is not extendible to the single tube pump. His system required a closed loop system and, once again, the results were not compared with any experimental data.

The physical model that Moser used to create his theory once again requires a closed loop. If there was not a second distensible chamber, but rather two open ends,

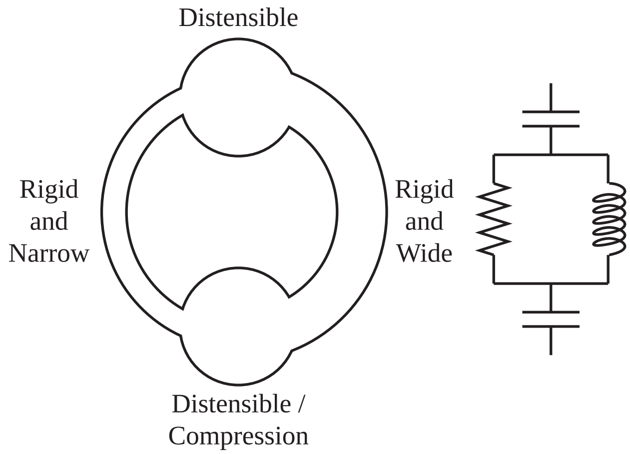


Figure 1.6: Moser's model of the impedance pump

his electrical circuit analogy would fail to predict a net flow. In addition, his plot of expected net flow at varying frequencies does not contain any distinct peaks or valleys that are characteristic of the pump's behavior as will be shown later.

Eunok Jung, in 1999, published her thesis on numerical simulations of a valveless pump using the immersed boundary method [13–15]. Her work consisted of a two-dimensional, computational model with a straight elastic section and a curved rigid section connecting the ends of the elastic pump (figure 1.7). The tube is filled with an incompressible, viscous fluid of constant density. It is compressed on the elastic section, off-center from the interfaces to the rigid section, in an oscillatory motion. Her results demonstrated that the direction and amplitude of the flow were dependent not only on the location of the compression but also on the frequency. Unfortunately, she made no physical model to describe the mechanism of the pump in her thesis.

One-dimensional simulations were carried out for a closed torus system [26] by Ottesen and an open system with two chambers at the end [2] by Borzi et al. The numerical models proposed by Borzi and Propst showed that an open loop system can create a net pressure head. Ottesen has been the only author to present quantitative experimental results. These results are limited to three data points, the net flow for one frequency at three pincher locations. Ottesen also presented qualitative results stating that the direction and mean flow is dependent on frequency and compression

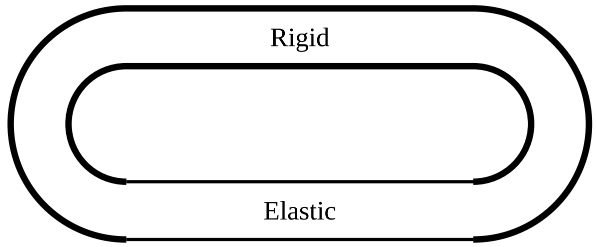


Figure 1.7: Jung's model of the impedance pump

motion. Increased elasticity generally increased net flow. Also, as the position of the pinchers approaches the symmetric position, the net flow decreases.

1.3 The Impedance Pump Problem

Each of the previous works took a different approach to understanding the impedance pump. Gerhart Liebau demonstrated valveless pumping experimentally, showing that a single tube pumped rhythmically, can pump against a pressure head in an open loop. Subsequent papers focused on computational and analytical models to describe the phenomena. The lack of experimental data has been a weak point in the development of a model for impedance pumping. It has prompted theoretical and computational researchers to speculate on the parameters that are dominant in the function of the impedance pump. Our prior efforts [8] and those outlined in this thesis hopefully fill that void.

We can revisit the larger task of identifying the underlying physics that drives the impedance pump by answering a series of key questions through experimental observation.

- What features are necessary and sufficient to create an impedance pump?
- What parameters dominate the response characteristics of the pump?
- What effect do these parameters have?
- What features are inherent versus auxiliary to the pump's response?

- What is the mechanism that induces a net flow?

The answers to these questions will hopefully lead to the broader knowledge of how we can predict the behavior of an impedance pump and how we can design such a pump.