Wave Propagation

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Group: 3

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ABSTRACT

Students were tasked with designing and conducting an original experiment. The team chose to validate a pump control system that models pulsatile fluid flow to replicate anatomical flow rates through a human artery. The system consisted of a reservoir, tap water, tubing, and a pump controlled by an arduino microcontroller setup. Data acquisition was performed by a second arduino microcontroller and two pressure transducers. Static and total pressure measurements were taken via the two pressure transducers and a pitot tube. Prior to the experiment, the transducers were calibrated using a sphygmomanometer. Pressure measurements were used to determine fluid flow rate through the system. The resulting flow rate calculations were compared against the programmed waveform of the pump controller to validate the pump and pulsatile flow control program. The increasing and decreasing slopes of the experimental data have a 107% and 52.8% difference from the anatomical data. For the programming of the pump it was suggested to use a sinusoidal waveform but given the anatomical data there is a 42% difference in the increasing and decreasing slopes and a 27% difference from the experimental data. This difference, although not close, is considered a success because the waveform is not symmetrical as a sinusoidal wave would be. Considering the uncertainty of the voltage data, the collected data has a ±5 mmhg error and the project data has a 43% correlation to the anatomical data. The main cause for this deviation is the areas where the project data does not see a zero flow region, if the system had zero flow at the desired locations the curve correlation could be as high as 75% if the collected data continued the same slope to zero flow.

INTRODUCTION

The purpose of this experimental design was to verify the waveform and fluid flow rate produced by a pump in order to validate the pump and pulsatile flow control program. Water was pumped through a horizontal pipe in the experimental apparatus. The team measured static pressure, and total pressure of the fluid flow produced by the pump using two pressure transducers and a pitot tube. These measurements were used in Bernoulli's equation to determine velocity along a streamline. Velocity was then used to calculate volumetric flow rate through the system. Bernoulli's equation assumes steady, frictionless, incompressible flow along a central streamline. This equation is given by:

$$P_1 + (\rho V_1)^2 + \rho g h_1 = P_2 + (\rho V_2)^2 + \rho g h_2 \tag{1}$$

where P is static pressure, V is fluid velocity, ρ is fluid density, g is gravity and h is elevation. Point 1 is measured at a point along a streamline, and point 2 is measured at the stagnation point along the same streamline at the tip of the pitot tube. Since fluid velocity at the stagnation point is zero and there is no elevation change between points 1 and 2, the equation becomes:

$$P_1 + (\rho V_1)^2 = P_2 \tag{2}$$

or

$$Ps + Pd = Pt \tag{3}$$

where Ps is static pressure, Pd is dynamic pressure, and Pt is total pressure. The equation can be rearranged and solved for velocity giving:

$$V_1 = \sqrt{(2Pt - Ps)/\rho} \tag{4}$$

Volumetric flow rate can then be calculated using:

$$Q = V_1 A \tag{5}$$

where Q is volumetric flow rate and A is the cross sectional area of the pipe.

METHOD

Several preliminary tasks were completed prior to conducting the experiment. The program for the pulsatile pump control was written and uploaded to the control system. Next, an 18 point calibration of each pressure transducer was conducted. The pressure transducers were calibrated to an analog sphygmomanometer over a range of 0-120mmHg. This range was selected for a nominal blood pressure range of 120/80 and zero for moments of no flow. A linear curve fit was used for values from 10 to 120 mmhg and from 0-10 mmhg an exponential fit was used. The program uses a piecewise function to calculate the pressure values. This overall curve fit is shown below in figure 1. The orange and blue curves represent the exponential and linear portions of the curve, respectively.

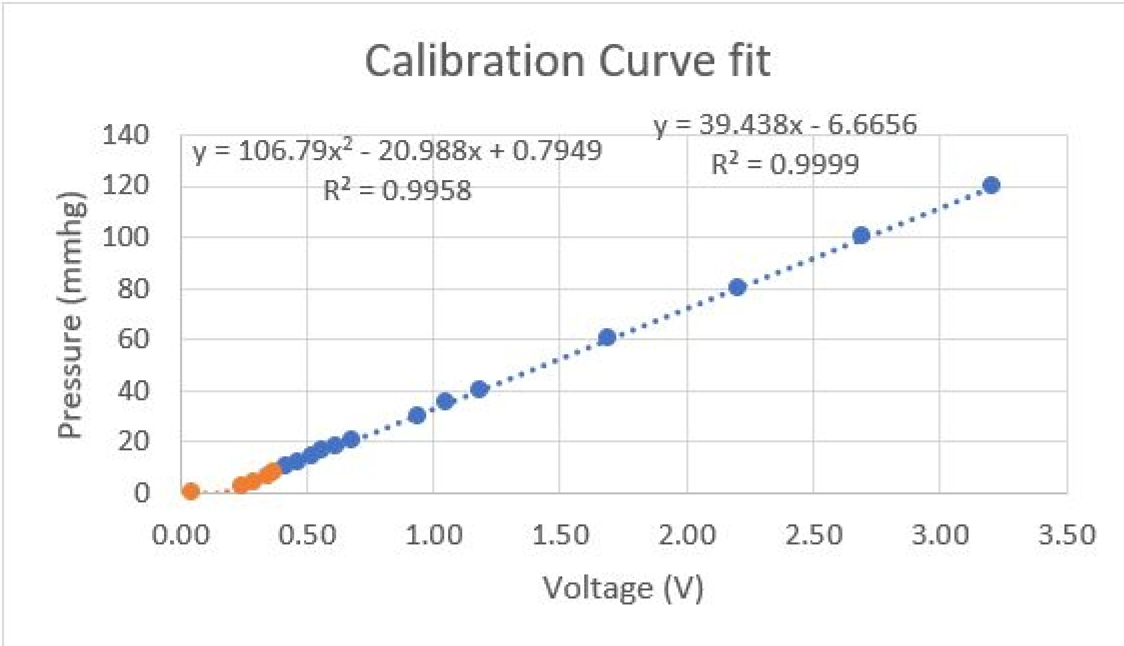

Figure 1: Calibration curve

The experimental apparatus was composed of water as a working fluid, a fluid reservoir, conduit, and a submersible pump. Additional components include sensory, control, and data acquisition systems. The fluid reservoir, pump, and conduit are connected in line. Modified barb fittings and valves are placed in line with the conduit at several points. The upstream T-fitting was modified to permit placement of a pressure transducer. The upstream pressure transducer was used for static pressure measurements. A second T-fitting was placed a distance downstream of the static pressure transducer. The downstream T-fitting was modified to allow positioning of a pitot tube and second pressure transducer. The downstream pressure transducer and pitot tube were used for gathering total pressure data. A ball valve was placed further downstream to facilitate priming of the system. After the ball valve a return line refills the fluid reservoir.

The sensory, control, and data acquisition systems utilized an Arduino microcontroller. An Arduino microcontroller and pump driver were programmed to activate the pump to produce pulsatile flow. The Arduino board was connected to calibrated pressure transducers and strain gauges. The original design used two Arduino boards (figure 2). The internal clocks of the Arduinos ran at differing times resulting in unsynced data. The experimental set up was revised to utilize a single microcontroller seen in figure 3. Pressure readings taken by the Arduino were output as serial data for export to Excel.

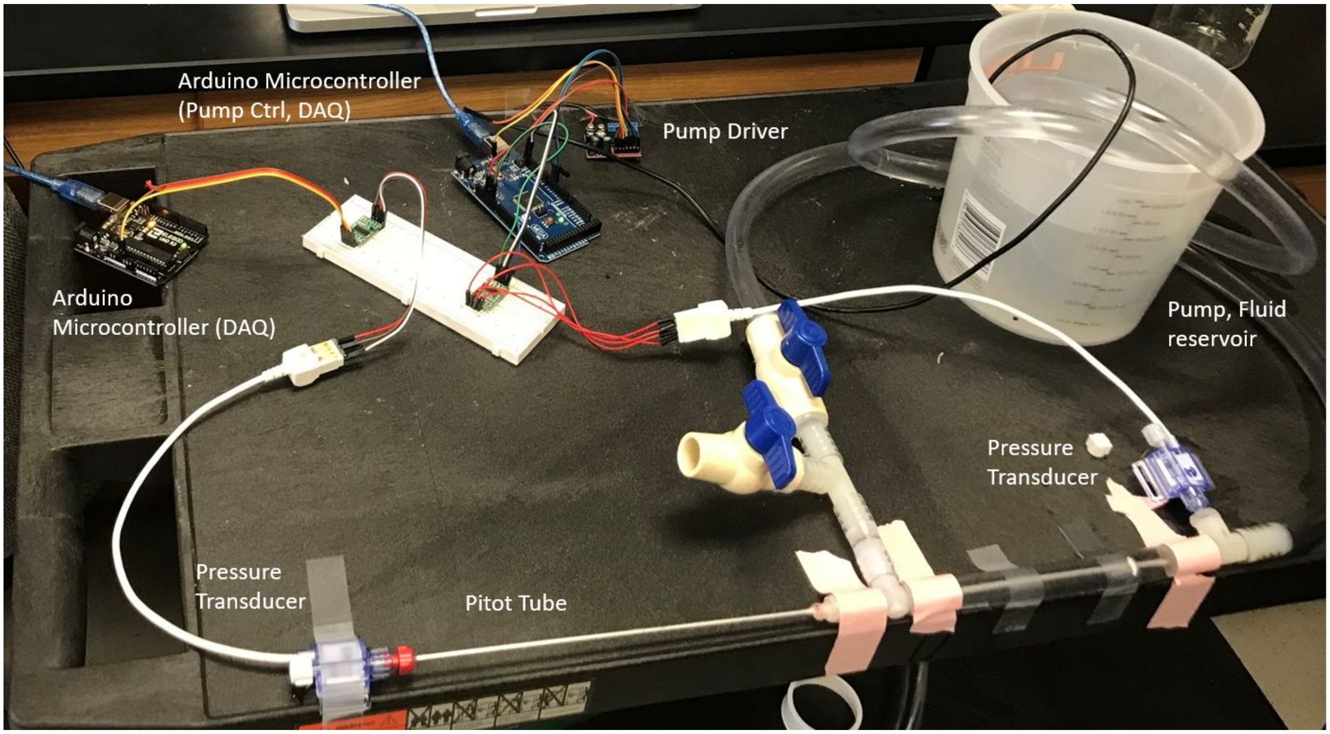

Figure 2: The experimental setup

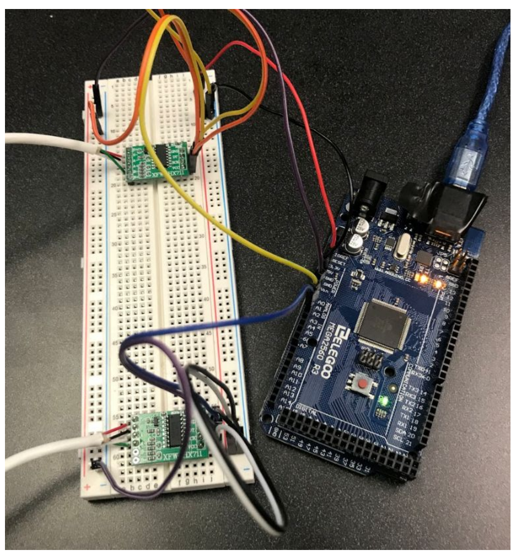

Figure 3: Control, sensor, and DAQ wiring with single Arduino

Prior to data collection the pump was run in continuous flow mode to prime the system. After purging the system of air, the pump was set to pulsatile mode at 60 beats per minute (BPM). Average volumetric flow was measured using a bucket-timer method. Next, data acquisition was enabled to collect pressure measurements from the calibrated transducers. A total of 240 pressure data points were collected and exported to Excel for analysis. These data points were used in equation (4) to calculate velocities. Resulting velocities were then used in equation (5) to determine volumetric flow rates. Flow rates were plotted as a function of time and compared to the anatomical waveform programmed to control the pump.

Measurement uncertainty exists within the experimental procedure. Sources of measurement uncertainty include systematic errors such as device resolution. Measurement devices in the experiment include: analog sphygmomanometer, pressure transducer, digital timer, 500 ml beaker, Arduino, and human blunders. The HX711 wheatstone amplifiers have an uncertainty of 20 mV. This was used to determine error bounds for the collected data.

RESULTS & DISCUSSION

<u>Results</u>

Two-hundred forty static and stagnation points were collected to analyze. The raw Data was graphed before shutting down the experiment to visualize the data (figure 4). The graph reveals that the system experienced back flow. This can be seen where the stagnation pressure is less than that of the static pressure. The stagnation pressure is less due to the pitot tube being directional and when flow reversed a vacuum pulls fluid from the pitot tube. It was recognized that the back flow was occurring in specific intervals during the test. This was believed to be due to inertial effects of the fluid building up and once these effects became high enough to overcome the pump the back flow would occur.

Figure 4: Static and stagnation pressures

The raw data was used to calculate dynamic pressure, velocity and flow rate. This calculations assume continuity effects will hold for a point in time. Table 2 is an example of the data and calculations taken, it should be noted that for points 8 and 7 for the static and stagnation pressures, respectively, their max values do not occur at the same time. This is possibly due to the length of the pitot tube. Inertial effects of the fluid would not reach the pitot transducer at the same time as the static transducer. Since the raw data does not show a consistent pressure gradient for each pulse, an average of the pulses was collected to be compared with the anatomical data.

Table 2: Calculated data example.

point	Static	Stagnation	Dynamic	Velocity	Flow Rate (Q)
	mmhg			m/s	ml/s
1	16.6295	22.0124	5.3829	1.1992	76.2928
2	16.7105	22.6795	5.969	1.2628	80.3390
3	18.066	23.1941	5.1281	1.1705	74.4653
4	18.8329	23.5116	4.6787	1.1181	71.1276
5	19.3269	23.8329	4.506	1.0972	69.8025
6	19.6313	24.3608	4.7295	1.1241	71.5127
7	21.3469	37.204	15.8571	2.0583	130.9445
8	37.8812	52.9015	15.0203	2.0033	127.4427
9	40.4107	32.9833	7.4274	1.4087	89.6177
10	19.8583	22.2384	2.3801	0.7974	50.7310

Discussion

The calculated flow rate was graphed over the anatomical data. The calculated data's uncertainty of ± 5 *mmhg* is also seen in Figure 5. When analysing the increasing and decreasing slopes of the graph, the experimental data sees a 107 % and 52.8% difference in slope respectively. The program was initially suggested to use a sine function to create reciprocating flow. This was not desired because the slope of the curves would be symmetrical where the anatomical data sees a 42% difference in magnitude of increasing slope from decreasing slope. The collected data sees a 27% difference in magnitude of increasing slope from decreasing slope. Since the experimental data never sees a zero flow rate like the anatomical values, only 43% of the anatomical is found within the uncertainty bounds of the project data. The team believes that by eliminating back flow with a check valve and having the tubing leave and enter the reservoir horizontally that the curves would have had a higher correlation. The slopes of the data were assumed to continue to the x-axis and the curve correlation reached 75%.

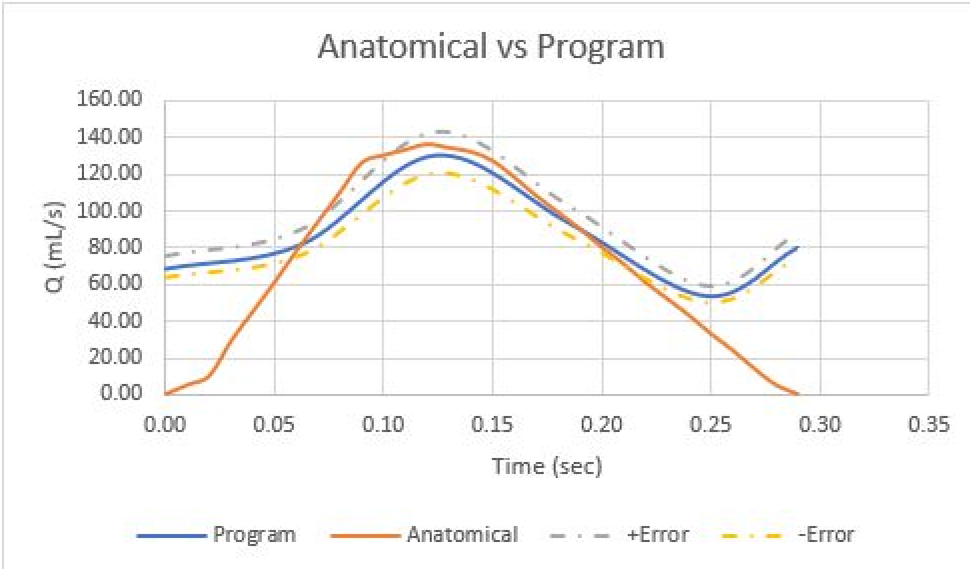

Figure 5: programmed vs experimentally measured flow rate curves

CONCLUSIONS

This experiment was used to determine the pulse wave propagation of a pump that is programmed to simulate the natural pulsatile flow of a human heart. The experiment needed further iterating to fully determine the correlation of the anatomical data. The error in the instrumentation resulted in a 43% correlation to the anatomical data. Though this difference is large, it is believed that it could be fixed with a check valve and completely horizontal piping. The difference in slopes of the beginning and end of each wave is what separates it from a sinusoidal wave. The collected data has a 27% difference between each slope where the anatomical has a 43% difference. The results of this data show that the waves do not match exactly, but their similarities validate that the program is producing flow that closely resembles anatomical flow, and with additional system modification the pump will be able to simulate an anatomical heart beat.

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