4. Evaluation

The prototype of the electromagnetic blood flow meter underwent several tests. Most of the tests were performed on the meter's individual subsystems. Each test evaluated the specific system's functionality and performance to ascertain whether it met the project's design constraints. The details and results of these tests are outlined in this document.

4.1 Test Specification

--------Test Specification introduction paragraph including technical design constraints table---------

4.1.1 Simulation

Before manually testing the AD524 precision instrumentation amplifier, the amplifier's performance was simulated in Orcad Capture CIS. The simulations tested the amplifier's capability to yield a gain of 1, 10, 100, and 1,000 given positive and negative input voltages and a reference.

The AD524 part is not found in Orcad's libraries. For this reason, the internal circuit of the amplifier was constructed based on the amplifier's functional block diagram. The Orcad circuit was constructed with 741 op-amps and resistors. The functional block diagram of the AD524 amplifier is shown in Figure 4.1.1.1 and the Orcad schematic of the amplifier is shown in Figure 4.1.1.2

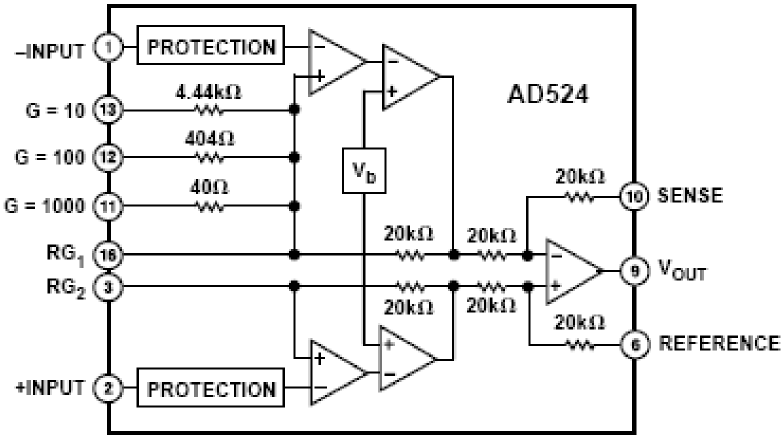

Figure 4.1.1.1 – AD524 functional block diagram [a]

<Insert schematic here>
Figure 4.1.1.2 – AD524 Orcad circuit

Using the block diagram as a guide, six 20 kΩ resistors and five 741 op-amps were used to construct the Orcad circuit. The gains were simulated by alternating the value of the gain resistor between 4.44 kΩ, 404 Ω, and 40 Ω. These resistor values correspond to gains of 10, 100, and 1,000, respectively. A gain of 1 was obtained by leaving out the gain resistor. The expected input voltage range for the amplifier was between ±50 µV and ±500 µV, so each gain was tested using varying input voltages within that range. Since the maximum voltage input to the PIC18F2550 is 5.5 V, only input voltages and gains yielding voltages below 5 V were simulated. Table 4.1.1.1 contains the results of the simulation.

Table 4.1.1.1 – Simulated amplifier results

Gain	Input Voltage (V1)	Input Voltage (V2)	Reference	Expected Output Voltage	Actual Output Voltage	% Error
1	-50 µV	50 µV		100 µV		
1	-225 µV	225 µV		450 µV		
1	-500 µV	500 µV		1 mV		
1	-50 mV	50 mV		100 mV		
1	-225 mV	225 mV		450 mV		
1	-500 mV	500 mV		1 V		
10	-50 µV	50 µV		1 mV		
10	-225 µV	225 µV		4.5 mV		
10	-500 µV	500 µV		10 mV		
10	-50 mV	50 mV		1 V		
10	-225 mV	225 mV		4.5 V		
100	-50 µV	50 µV		10 mV		
100	-225 µV	225 µV		45 mV		
100	-500 µV	500 µV		100 mV		
1,000	-50 µV	50 µV		100 mV		
1,000	-225 µV	225 µV		450 mV		
1,000	-500 µV	500 µV		1 V		

In addition to simulating the instrumentation amplifier, the passive low-pass filter following the amplifier was also simulated. The filter was tested independent from the amplifier. The filter is a simple RC filter. Since the microcontroller samples the waveform from the probe at 500 Hz, the cutoff frequency is around also 500 Hz. A resistance of 3 kΩ and a capacitance of 0.1 µF provide a cutoff frequency around 500 Hz. Using the values of the expected output voltages from the instrumentation amplifier as inputs, several tests were conducted on the simulated filter to verify its operation. Figure 4.1.1.3 and Figure 4.1.1.4 show the schematic and simulated output for a test in which the input to the filter was 100 mV. Table 4.1.1.2 contains the results of all conducted tests on the simulated filter.

<Insert figure here>
Figure 4.1.1.3 – Low-pass filter

<Insert figure here>
Figure 4.1.1.4 – Simulated output

Table 4.1.1.2 – Simulated filter results

Input Voltage (V1)	Expected Output Voltage	Actual Output Voltage	% Error
100 μV			
450 μV			
1 mV			
100 mV			
450 mV			
1 V			
1 mV			
4.5 mV			
10 mV			
1 V			
4.5 V			
10 mV			
45 mV			
100 mV			
100 mV			
450 mV			
1 V			

A final simulation was performed in which the output from the instrumentation amplifier circuit was connected to the input of the low-pass filter circuit. Table 4.1.1.3 contains the results of the final simulation.

Table 4.1.1.3 – Final simulation results

Gain (amplifier)	V1 Input (amplifier)	V2 Input (amplifier)	Expected Filter Output	Actual Filter Output	% Error
1	-50 μV	50 μV			
1	-225 μV	225 μV			
1	-500 μV	500 μV			
1	-50 mV	50 mV			
1	-225 mV	225 mV			
1	-500 mV	500 mV			
10	-50 μV	50 μV			
10	-225 μV	225 μV			
10	-500 μV	500 μV			
10	-50 mV	50 mV			
10	-225 mV	225 mV			
100	-50 μV	50 μV			
100	-225 μV	225 μV			
100	-500 μV	500 μV			
1,000	-50 μV	50 μV			
1,000	-225 μV	225 μV			
1,000	-500 μV	500 μV			

4.1.2 Hardware Subsystem Certification

-----Hardware subsystem certification introduction paragraph-----

4.1.2.1 Probe

Since the electronics portion of this project was not in a state capable of testing the probe and to give a reference while performing the system tests, measurements were carried out using the Zepeda Instruments Model SW-7 flow meter. Even though the flow meter adds inaccuracy in addition to the probe's contribution, the flow meter was assumed to introduce no error in the flow rate measurements. Also, the SW-7 flow meter only has one decimal point of precision and limits the ability to accurately determine the probe's performance, but only low flow rates are significantly affected. For testing purposes, the probe was set up using the previously described test apparatus with acrylic tubing. The actual flow rate was calculated for comparison to the measured flow rate by collecting exactly 20 L of fluid pumped through the test apparatus in a reservoir and timing each run. The flow rate was calculated by dividing 20 L by the amount of time taken to fill the reservoir. The flow meter was calibrated by zeroing it while the acrylic tubing of the test apparatus was completely filled with the saline solution under no flow conditions. The zeroing was done by adjusting the measured flow rate until zero flow was observed. Then, fluid was pumped through the test apparatus, and the actual flow rate was determined as previously described. Next, fluid was pumped through the test apparatus at the same flow rate, and the flow meter's gain was adjusted until the correct flow rate was displayed. After this procedure was performed, the flow meter was theoretically calibrated for any other flow rate since the output voltage of the probe increases linearly, along with the gain, with the flow rate.

Table 4.1.2.1.1 lists the data and percent error for several different flow rates using a 0.9% saline solution, and Figure 4.1.2.1.1 shows a plot of the actual versus measured flow rates. As expected, the accuracy of the probe decreased as the flow rate decreased. However, the results do not fully represent the probe's performance. The one decimal point of precision of the SW-7 flow meter prohibits the lower flow rates from being accurately measured by the flow meter itself, which means the probe is probably measuring the induced voltage more accurately than shown by the results. Figure 4.1.2.1.1 illustrates how accurate the measured flow rate is compared to the actual flow rate. Since the plotted line is linear, the measured and actual flow rates closely correspond to one another.

Table 4.1.2.1.1. Flow rate measurements using 0.9% saline

Actual flow rate (L/min)	Measured flow rate (L/min)	Percent error (%)
0.59	0.5	-15.25
1.09	0.9	-17.43
1.86	1.7	-8.60
2.89	2.7	-6.57
5.80	5.7	-1.72
7.64	7.4	-3.14
10.32	10.1	-2.13
16.80	16.6	-1.19
20.37	20.2	-0.83
25.00	25.0	0.00

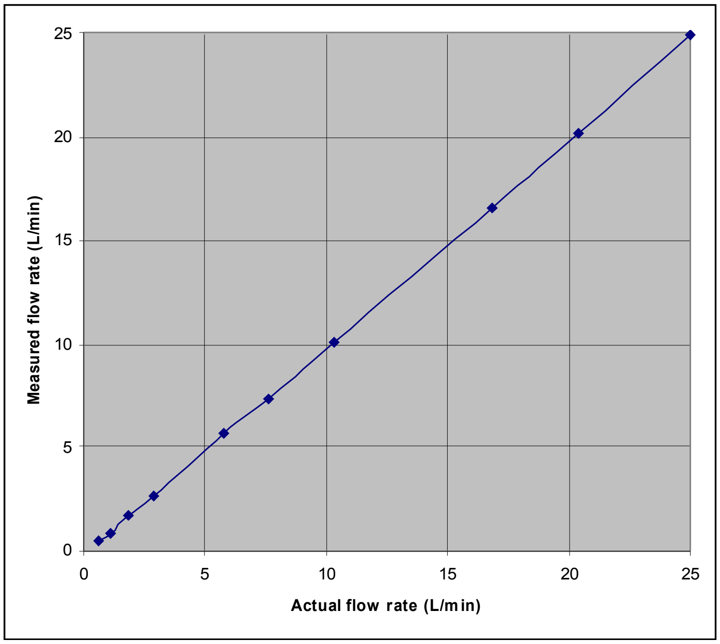

Figure 4.1.2.1.1. Plot of the Actual vs. Measured Flow Rates

Since the inner diameter of the acrylic pipe is known to be 3/4 in., the flow rates can be converted into fluid velocities to verify the probe is capable of measuring fluid velocities from 0.1-1 m/s within 1 cm/s of the actual value. The flow rate is converted into fluid velocity by using Equation 4.1.2.1.1. The converted values, along with the difference in fluid velocity, are shown in Table 4.1.2.1.2. The range of fluid velocities used exceeds the 0.1-1 m/s range and are still approximately within 1 cm/s of the actual value. Therefore, the probe meets this constraint and is capable of measuring fluid velocities well above the 1 m/s maximum fluid velocity constraint while also retaining the targeted accuracy at as low as 3.45 cm/s.

$$FluidVelocity = \frac{4 * FlowRate}{\pi * (PipeDiameter)^2} \tag{4.1.2.1.1}$$

Table 4.1.2.1.1. Fluid Velocity using 0.9% saline

Actual fluid velocity (cm/s)	Measured fluid velocity (cm/s)	Difference (cm/s)
3.45	2.92	-0.53
6.37	5.26	-1.11
10.88	9.94	-0.94
16.90	15.79	-1.11
33.92	33.33	-0.59
44.68	43.27	-1.41
60.35	59.06	-1.29
98.24	97.07	-1.17
119.11	118.12	-0.99
146.19	146.19	0.00

In the previous probe tests, a 0.9% saline solution, which consists of 0.9 g of sodium chloride per 100 ml of water, was used because it is accepted as the standard solution to replicate blood. However, the probe was tested with fluid conductivities ranging from 0.6-0.8 S/m to ensure it can operate properly at the extreme conductivity ranges of blood. The 0.9% saline solution has a conductivity of 0.67 S/m, but the ratio of sodium chloride to water to achieve 0.6 S/m and 0.8 S/m had to be experimentally determined. This was accomplished by using a dielectric tester.

*****more to come*****

4.1.2.2 Amplifier and Filter

The testing of the physical AD524 instrumentation amplifier IC and the low-pass filter followed similar steps as the procedures outlined in the simulation section. Input voltages were applied to the instrumentation amplifier IC to test each gain. Unlike the simulations, a voltage divider was connected to the inputs to the amplifier when microvolt inputs were needed during this testing stage. The filter was tested by connecting the amplifier output to the filter input. Table 4.1.2.1 compares values obtained from the physical tests to the values obtained from the simulations.

Table 4.1.2.1 – Physical test results

Gain (amplifier)	**V1 Input (amplifier)**	**V2 Input (amplifier)**	**Actual Amplifier Output (simulated)**	**Actual Amplifier Output (physical)**	**% Error**	**Actual Filter Output (simulated)**	**Actual Filter Output (physical)**	**% Error**
1	-50 µV	50 µV						
1	-225 µV	225 µV						
1	-500 µV	500 µV						
1	-50 mV	50 mV						
1	-225 mV	225 mV						
1	-500 mV	500 mV						
10	-50 µV	50 µV						
10	-225 µV	225 µV						
10	-500 µV	500 µV						
10	-50 mV	50 mV						
10	-225 mV	225 mV						
100	-50 µV	50 µV						
100	-225 µV	225 µV						
100	-500 µV	500 µV						
1,000	-50 µV	50 µV						
1,000	-225 µV	225 µV						
1,000	-500 µV	500 µV						

4.1.3 Software Subsystem

As demonstrated by the design schematic in Figure 4.1.3.1, the PIC18F2550 microcontroller is used to perform a number of tasks. Theses tasks include driving the probe input, reading an amplified voltage from the probe output, displaying this voltage to an LED 7-segment display, and transferring the data to a PC for data acquisition. While all of these tasks are implemented eventually, only a few are currently undergoing tests.

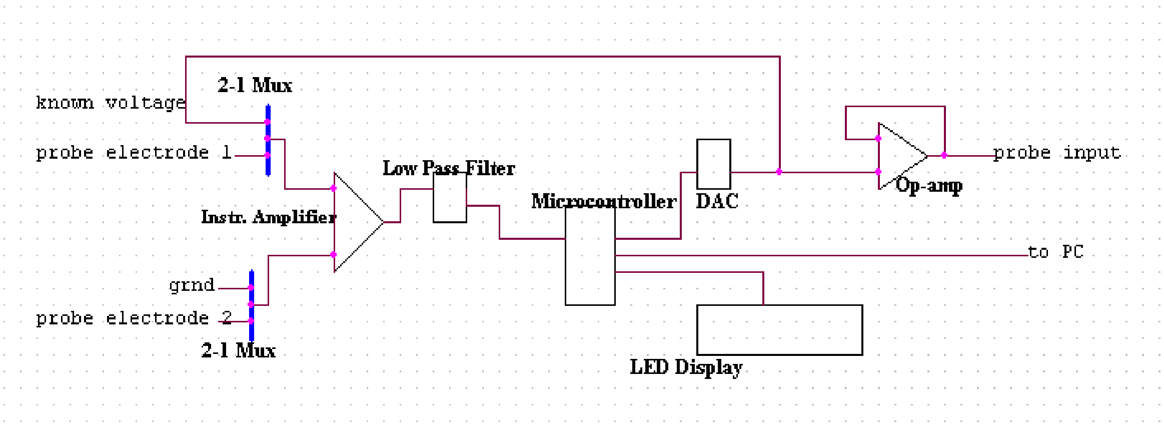

Figure 4.1.3.1 Flow Meter Design

4.1.3.1 Generating a Square Wave

Initially, the original probe was driven by a waveform generated from the SW-7 flow meter. This waveform, as shown in Figure 4.1.3.2, was best defined as a square wave with a 50% duty cycle. Although the square wave contains Gibb's ears (distortion at the edges), the range is estimated as -5.5V to 5.5V, or 11V peak-to-peak. The frequency measured with the oscilloscope is about 500Hz. To make an equivalent waveform drive the probe from the PIC18, tests were performed with varying input voltages and frequencies at one of the ADC inputs to the PIC18. This was done by using a potentiometer to change the ADC input voltage. Also, hard-coded frequencies were used to reach about 500Hz for the PIC18. Varying voltages and frequencies were used to obtain several waveforms, such as the one shown in Figure 4.1.3.3. However, the waveform that measured most closely to the original produced by the SW-7 flow meter is shown in Figure 4.1.3.4.

<insert pic here>

Figure 4.1.3.2 Square Wave Generated by the SW-7 Flow Meter

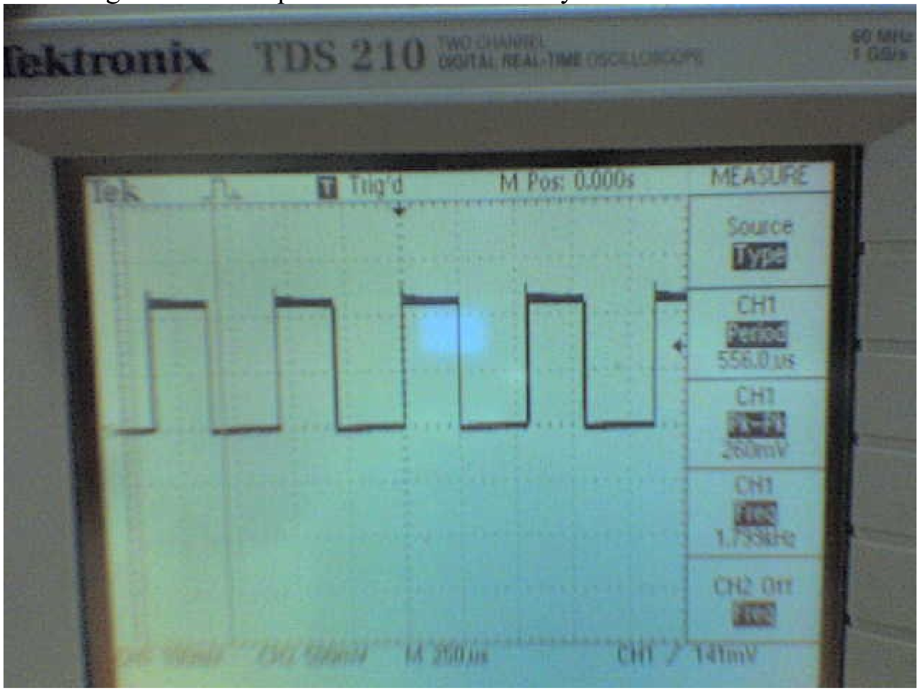

Figure 4.1.3.3 Sample Square Wave Generated by the PIC18

<insert pic here>

Figure 4.1.3.4 Best Square Wave Generated by the PIC18

4.1.3.2 Reading the Amplified Probe Output

-----Coming soon---------

4.1.3.3 Displaying Voltage

-----Coming soon---------

4.1.3.4 Data Acquisition

-----Coming soon---------

4.1.4 System Test Certification

-------------------Coming Soon!!!------------------------

References