ROMER

Center for Robotics and Artificial Intelligence

Metal-Wire Position Detection for Catheters using Inductance Responsive Circuits

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Introduction

A catheter is a thin, flexible tube inserted into the body to allow the passage of fluids or to access certain areas for medical treatment or diagnosis. They can be made from materials such as silicone, latex, or teflon, and come in various shapes and sizes depending on their medical use.

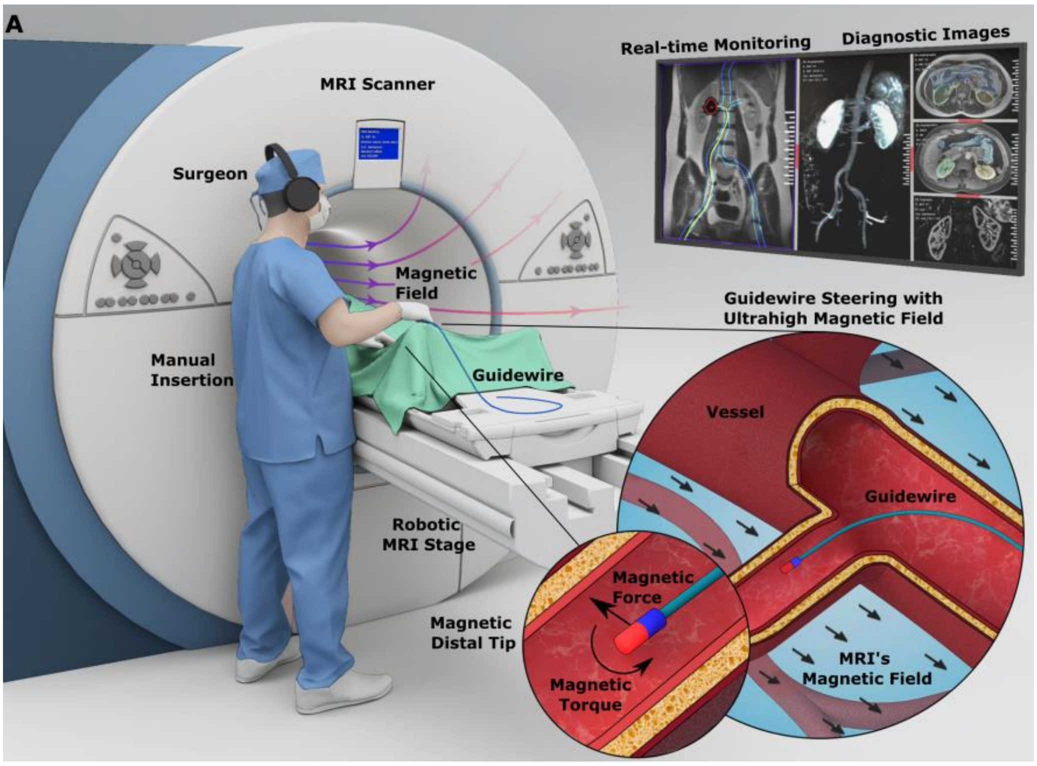

Figure 1.1 Catheter [1].

The catheter in our project is controlled by moving the metal wire inside the teflon tube. However, to move the catheter in the desired direction we need to know the distance between the tip of the catheter and the metal wire.

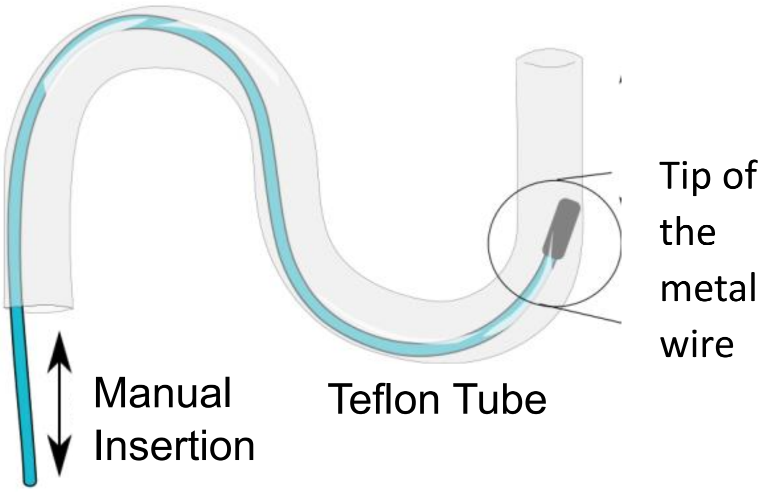

Figure 1.2 Teflon Tube and Metal Wire [2].

The idea we will use to solve this problem is winding a solenoid around the tip of the Teflon tube and running a current through it. As we manually insert the metal wire, the permeability inside the solenoid will increase due to the core changing from air to metal. Hence, the inductance of the solenoid will increase (Equation 1). The change in the inductance will lead to a phase and gain difference in the circuit, if we use an inductance-responsive circuit. Then, we will be able to measure the change in gain/phase by using Analog Devices' Gain/Phase Detector (Figure 1.3). After that, we will map the output voltage to the distance and achieve the goal.

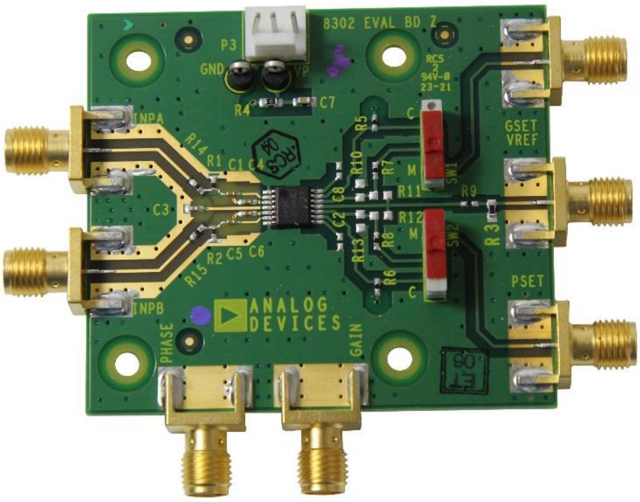

Figure 1.3 AD8302-EVALZ ANALOG DEVICES

Theoretical

Inductance of a solenoid is calculated with the following equation,

$$L = \mu \frac{N^2 I}{l}$$

$$L = Inductance$$

$$\mu = \mu_0 \mu_r \ (Absolute\ permeability)$$

$$N = Number\ of\ turns$$

$$I = Current\ magnitude$$

$$l = length\ of\ the\ solenoid$$

Equation 1

As we mentioned before, inserting the metal wire into the solenoid increases the core's permeability, as the metal's permeability is higher than the permeability of air. However, the metal wire does not fill the Teflon tube completely. Hence, air is not fully replaced from the core, and we have a mixture of air and metal core. Because we aim to change the inductance as much as possible when we insert the metal wire, it is optimal to use a metal wire that is as thick as possible.

Another optimization idea is increasing the number of turns and keeping the length of the solenoid equal to the maximum distance. If the metal wire stays inside the solenoid through its motion, it will have a larger effect on the permeability of the core. Therefore, it would be better to keep it long. Yet, we want the inductance to be high to obtain a larger change in the inductance with the exact percent change in the permeability (Equation 1). Hence, we should keep the length of the solenoid low and the number of turns high. Because we need to keep the solenoid's length longer than the maximum distance, but at the same time as low as possible, it is best to keep it the same length as the maximum distance.

Circuit Design

Setting up the inductor's proper length and turn values is not enough to achieve our goal. We also need a circuit that is responsive to the changes in the inductance. There is no specific choice for this purpose; any design that can approach 90° phase change or $30\ dB$ gain change (the widest range the AD8302 can detect) would be sufficient.

We have worked on the simple RL circuit both in low-pass and high-pass filter configurations, but that design could not approach the desired gain/phase change values. Therefore, we tested the behaviour of a third-order Butterworth filter (Figure 2.1). It is important to note that although the positions of the components are the same as those of a third-order Butterworth filter, component values are not set according to the setup of a Butterworth filter.

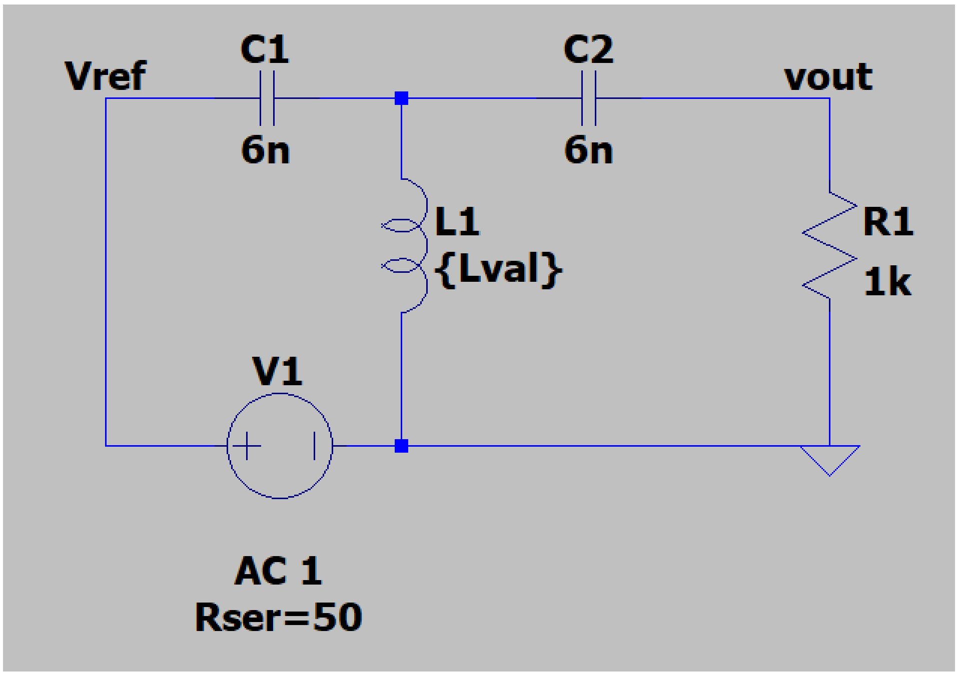

Figure 2.1 Third-Order Butterworth Filter Design

We used MATLAB code to find the component values that gave us the desired behaviour for the circuit. MATLAB code simply checks the phase and gain change between two different inductance values (metal wire not inserted and fully inserted) for many different capacitance, resistance, and frequency values. The output gives the best combination for the maximum phase/gain change. Details about how to set up the variables are explained in the code.

Following figures shows the behaviour of the circuit and optimal component values for different inductance ranges.

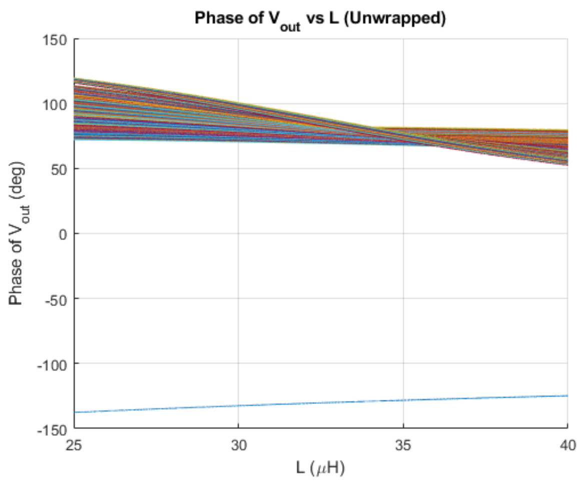

Figure 2.2 Phase Output for $30\mu H - 34\mu H$

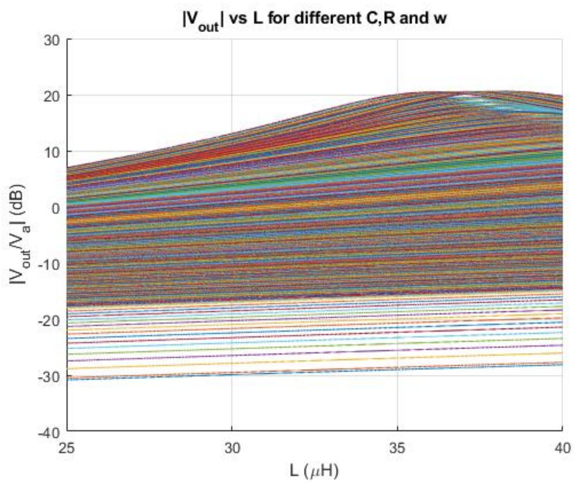

Figure 2.3 Gain Output for $30\mu H - 34\mu H$

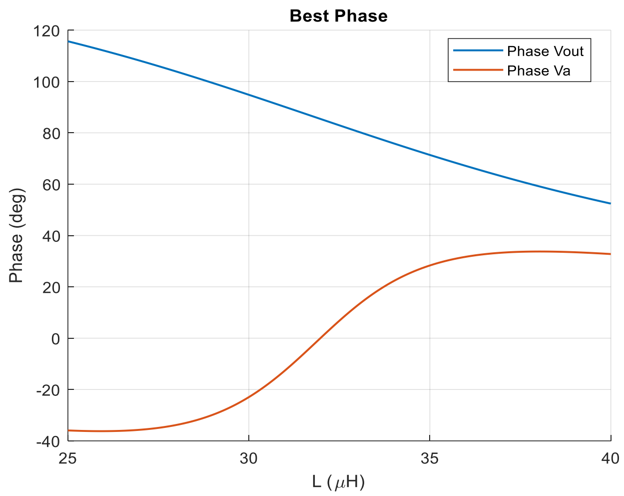

Figure 2.4 Best Phase Output for $30\mu H - 34\mu H$

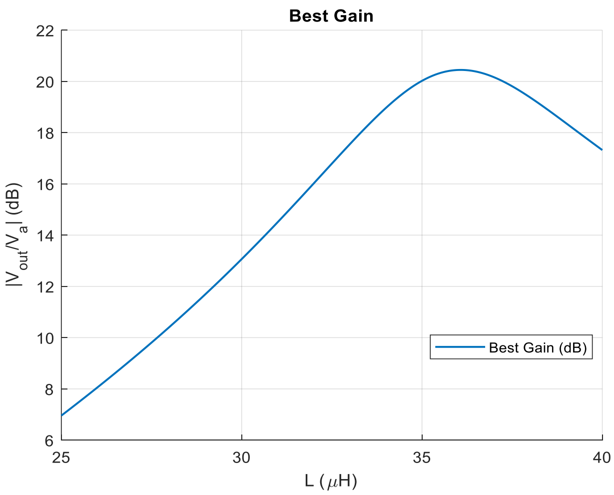

Figure 2.5 Best Gain Output for $30\mu H - 34\mu H$

```
Maximum phase change: 64.13 deg (unwrapped)
Best Phase Params:
  C1 = 9.12e-10 F
  C2 = 9.12e-10 F
  Rout = 10000 Ohm
  f = 933267 Hz
Maximum gain change: 5.90 dB
Best Gain Params:
  C1 = 9.12e-10 F
  C2 = 9.12e-10 F
  Rout = 10000 Ohm
  f = 880962 Hz
```

Figure 2.6 Optimal Component Values for $30\mu H - 34\mu H$

Figure 2.6 shows us that maximum phase change for inductance values between $30\mu H$ and $34\mu H$ is around 64 degrees, and maximum gain change is around 6 dB. AD8302 responds to every 1° change with 10 mV change in the output, and responds every 1 dB change with 30 mV in the output. Hence, if we measure the output voltage from the PHASE pin (Figure 1.3) we would be operating in a 640 mV range, but if we measure the output voltage from GAIN pin we would be operating in a 180 mV range. In conclusion, for this setup, PHASE output is more suitable for our goals, which is obtaining a larger response for the same amount of change in the distance.

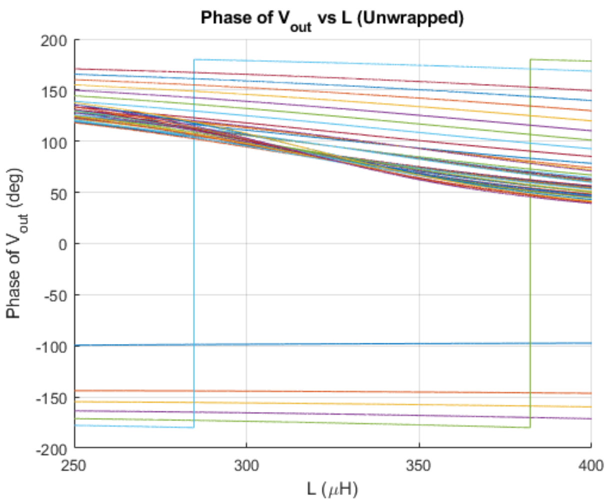

Figure 2.7 Phase Output for $300\mu H - 340\mu H$

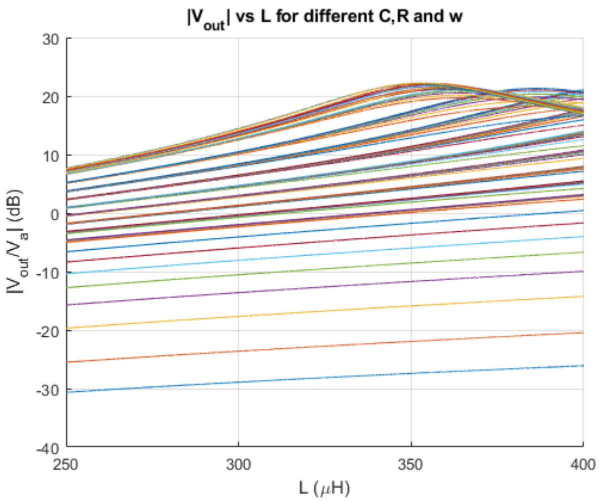

Figure 2.8 Gain Output for $300\mu H - 340\mu H$

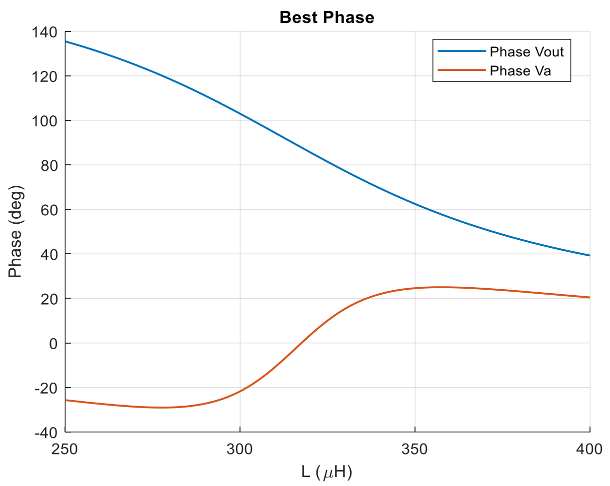

Figure 2.9 Best Phase Output for $300\mu H - 340\mu H$

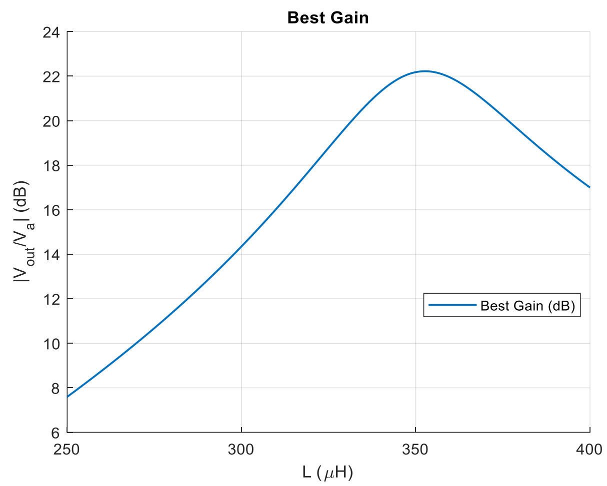

Figure 2.10 Best Gain Output for $300\mu H - 340\mu H$

```
Maximum phase change: 77.23 deg (unwrapped)
Best Phase Params:
  C1 = 2.13e-09 F
  C2 = 2.13e-09 F
  Rout = 10000 Ohm
  f = 193788 Hz
Maximum gain change: 6.97 dB
Best Gain Params:
  C1 = 2.54e-09 F
  C2 = 2.54e-09 F
  Rout = 10000 Ohm
  f = 168537 Hz
```

Figure 2.11 Optimal Component Values for $300\mu H - 340\mu H$

Figure 2.11 shows that, as we increase the inductance values and the inductance range, both maximum phase and gain changes increase. Yet, PHASE output is still more suitable to use than the GAIN output, because PHASE output gives us 770 mV operating range while GAIN output gives us 210 mV operating range.

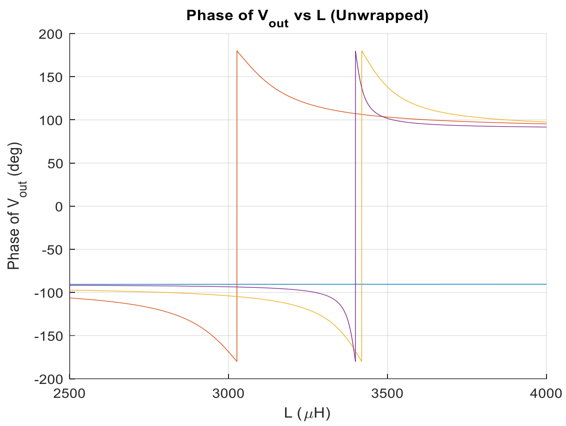

Figure 2.12 Phase Output for $3mH - 3.4mH$

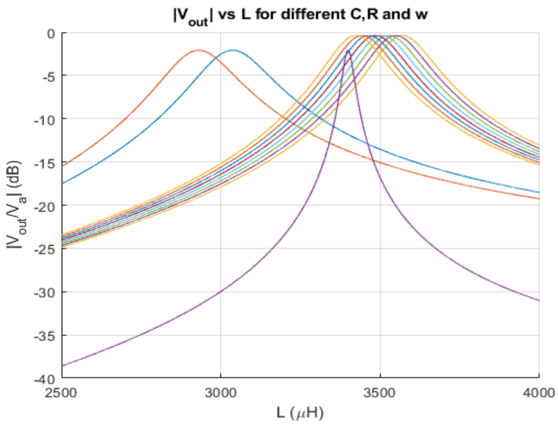

Figure 2.13 Gain Output for $3mH - 3.4mH$

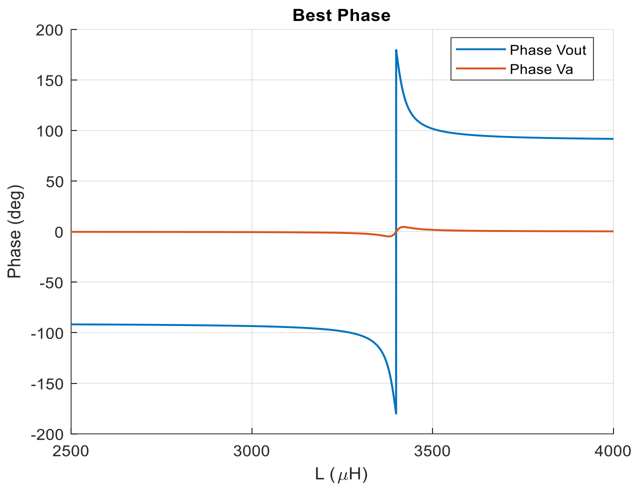

Figure 2.14 Best Phase Output for $3mH - 3.4mH$

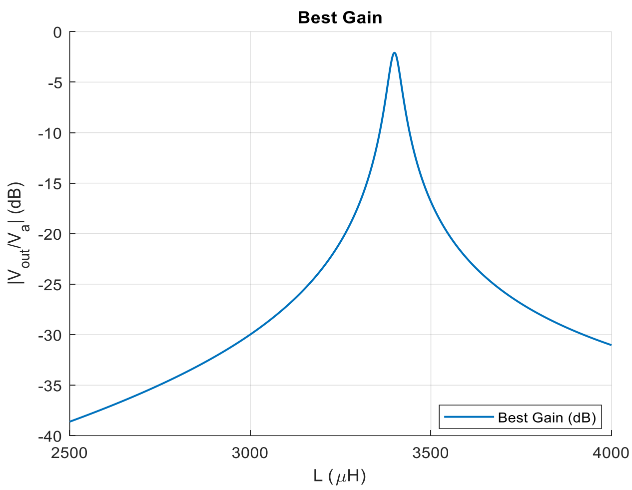

Figure 2.15 Best Gain Output for $3mH - 3.4mH$

```
Maximum phase change: 83.82 deg (unwrapped)
Best Phase Params:
  C1 = 1.00e-11 F
  C2 = 1.00e-11 F
  Rout = 220 Ohm
  f = 610421 Hz
Maximum gain change: 27.88 dB
Best Gain Params:
  C1 = 1.00e-11 F
  C2 = 1.00e-11 F
  Rout = 220 Ohm
  f = 610421 Hz
```

Figure 2.16 Optimal Component Values for $3mH - 3.4mH$

Figure 2.16 shows that increasing the inductance value even further gives us a wider range of output. We also see that both phase and gain outputs give us about $840\ mV$ operating range. This result supports our idea of increasing inductance as much as we can so that same percentage of change in inductance will give us a wider operating range. However, it is important to notice that these results are theoretical, and as we increase the inductance we might need to use capacitors with too low capacitance values. For example, in $3mH - 3.4mH$ configuration optimal capacitance value was $10\ pF$ in $10\ pF - 20\ nF$ range. Such low capacitance values might cause unexpected fluctuations in the measurement. Hence, before deciding to use a very high inductance value, it is best to check the optimal component values of the configuration. Capacitance values should not go under $100\ pF$, and resistance values should not go under 500Ω. These numbers are not obtained from any theoretical calculations, but from experiments done with many different resistance and capacitance values. Experiments performed with components smaller then those values resulted in unparallel outputs with the theoretical results.

Experimental

First step is to measure the inductance of the solenoid. If a LCR meter is not accessible, we can use a simple RL circuit (Figure 3.1).

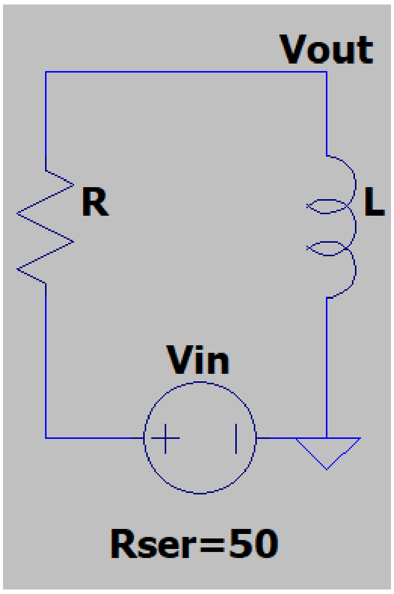

Figure 3.1 RL Circuit

After setting up the circuit in Figure 3.1 we read the voltage across the inductor (Vread) with a oscilloscope. Then, we calculate the inductance using the following formula,

$$L = \frac{V_{out}R}{\omega\sqrt{V_{in}^2 - V_{out}^2}}$$

Equation 2

There is no need to do these calculations manually, **calculator_inductor.py** file gives the inductance value as output when we insert the resistance, frequency and voltage values.

Oscilloscopes may not be able to measure low voltages precisely, hence it is better to keep the V_{in} higher then 2 volts. Also, set the frequency to a value where you read the $V_{out} \approx \frac{V_{in}}{\sqrt{2}}$. This will help us to do our measurements around the cutoff frequency. Again, purpose of this is to avoid the low voltage precision errors. However, while setting up the frequency do not exceed $500\ KHz$. At high frequencies effects of the things we ignore, such as parallel capacitance of the inductor, increases. If you can not obtain "$V_{out} \approx \frac{V_{in}}{\sqrt{2}}$" under $500\ KHz$, use a lower resistance so that cutoff frequency decreases, and you can achieve the desired output voltage at a lower frequency.

After measuring the inductance values for both conditions (metal wire not inserted – fully inserted), enter those values to the matlab code and run it to find the optimal component values. Then setup your circuit according to it. Give 5 volts to the **VP** pin of the AD8302 and connect **GND** pin to a common ground. Connect $\boldsymbol{V_{ref}}$ (Figure 2.1) to the **INPB** pin and connect $\boldsymbol{V_{out}}$ to the **INPA** pin. After those connections you can read the phase difference from **PHASE** pin.

Example Setup

I have measured my inductance values as $30\ \mu H$ and $37\ \mu H$. I did not have many choices for capacitor values, so I used $6.875\ nF$ capacitors. MATLAB code showed that optimal resistance value was $1\ K\Omega$ (in the $500\Omega - 1K\Omega$ range) and optimal freqeuncy value was $310\ KHz$ (in the $10\ KHz - 1\ MHz$ range).

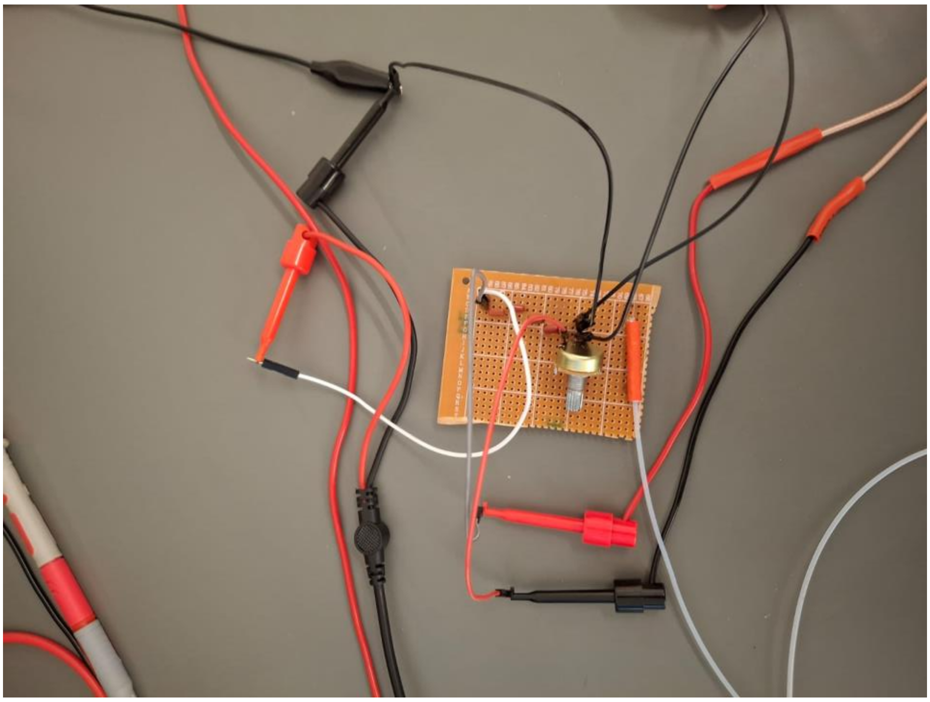

Figure 4.1 Example Circuit

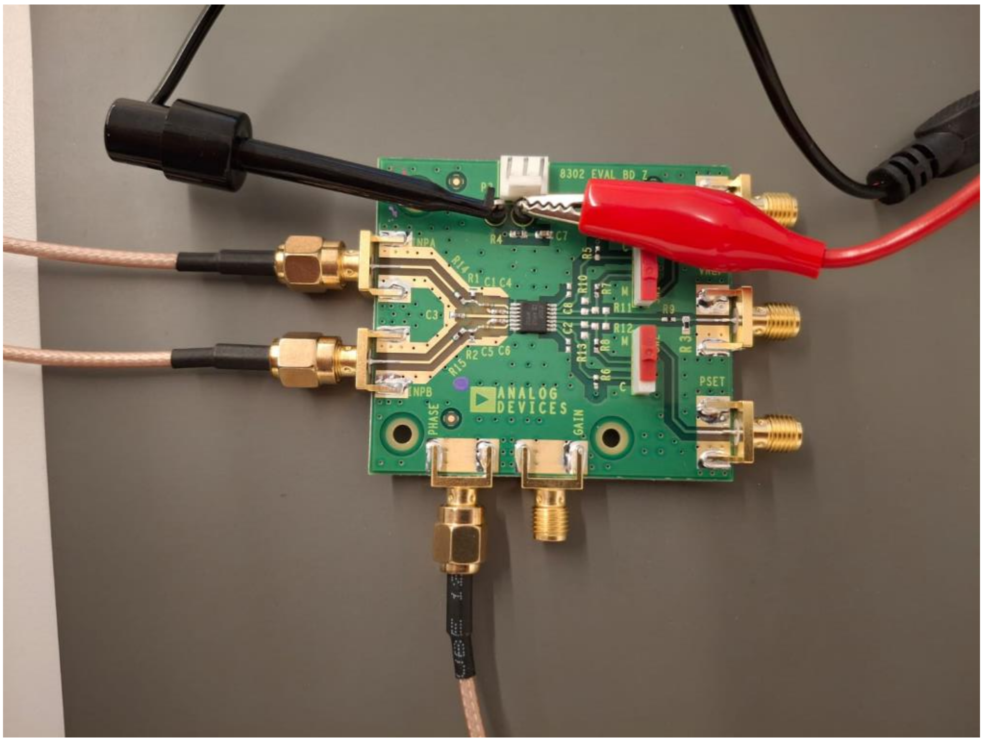

Figure 4.2 Example Connections for AD8302

In the following video, we show how the setup works. As the metal wire move towards the solenoid, output voltage increases. And when the metal wire moves in the opposite direction output voltage decreases.

Figure 4.3 Video for Illustration
https://youtu.be/72hIl8qrljw

As we can see in the video, that setup gave us an $230\ mV$ operation range. We should also note that, when we used a metal wire doubled in thickness operation range became $350\ mV$.

Further Studies

Although we obtained a design to monitor the movement of the metal wire as variations in the voltage, we did not map those voltage values to the distance. For that purpose, we need to find a stable measurement method that can send the voltage values to the computer. For that, we tried using Arduino Mega, but the voltage readings were unstable. They were oscillating. There might exist a way to avoid those oscillations, it needs to be searched. Otherwise, we should use another board that can take stable measurements.

Moreover, we should also find a way to increase the inductance change when the metal wire is fully inserted. One obvious method would be to use a metal wire with a higher permeability. But different methods should also be searched.

Conclusion

In conclusion, the idea of winding a solenoid to the tip of the teflon tube and measuring the distance by using the changes in the phase or gain is working. However, there are some critical points that we need to be aware of while applying this idea. First of all we need a inductance responsive circuit design, and any circuit that can create 90° phase change or $30\ dB$ gain change between two specific inductance values would work. For that, we have used a setup similar to that of a third-order Butterworth filter. Also, we have mentioned that for the most optimal configuration, we should keep the length of the solenoid equal to the maximum distance and the number of turns as high as possible. Yet, there exists a limitation in the experimental side, and while increasing the inductance, which is simply increasing the number of turns, we have to check the optimal component values for the inductance range we obtained. Increasing inductance too much might require us to use capacitance values lower than $10\ pF$. We should avoid operating at such inductance ranges. Moreover, for some inductance ranges, MATLAB code might indicate that using a resistance as low as possible gives the best result. However, using resistance values such as 2Ω would give results different then expected (due to the ignored resistance of the wires and serial resistance of the capacitors). Hence, we advised using resistance values higher than 500Ω to obtain similar outputs to the theoretical results. Finally, despite all those efforts to approach theoretical results, we might not be operating at the optimal values due to what we ignore in our calculations. The best and easiest method to check if we are at the optimal operating values is to try other frequency values close to the one suggested by the MATLAB code. With minor changes in the frequency, we might obtain a broader range for the output voltage.

All in all, this project can be successfully accomplished by considering the points we have mentioned and finding a way to map the voltage values to the distance.