Using a Negative Impedance Converter to Dampen Motion in Test Masses*

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Damping the motion of mirrors in a suspension systems has already been achieved at the University of Glasgow using eddy current damping. However, to improve the effectiveness of this system a circuit based off a negative impedance converter was tested in the 10m prototype lab at the Albert Einstein Institute. This was done to compensate for the resistance of the wire in copper coils thus increasing the current flow allowing for a greater force to oppose the motion of the mirror. The results suggest that this method is highly effective and works well to dampen motion quickly.

I. INTRODUCTION

A. Gravitational Wave Detection

Gravitational waves are ripples in spacetime that are produced by masses that are accelerating non spherically or cylindrically[5]. They carry energy as gravitational radiation and were described by Albert Einstein in his Theory of General Relativity in 1916. They are detected using laser interferometry. In a Michelson interferometer a laser beam is split and travels down the arms of the interferometer. It then hits a mirror and travels back where it is recombined and reaches a photo diode. If a gravitational wave passes through the interferometer the arms are stretched or squeezed so that the light does not travel the same distance[4]. This means that when the split beams are recombined an interference pattern is evident. Since the first detection of gravitational waves in September 2015 there have been a great many advancements in the technology used to detect gravitational waves and the analysis of the data itself. There have been many more detections, several from binary black hole mergers and one from a binary neutron star merger in August 2017. Improving the technology used can also bring about observations of different kinds which may lead to a broader understanding of gravitational waves and the events that produce them. The 10 meter prototype at the Albert Einstein Institute will test advanced techniques to be used for future gravitational wave detectors. The main focus of the 10m prototype is to enhance the technical performance of the gravitational wave detectors and to also address questions in quantum mechanics.[1]

B. The 10m Prototype

The 10 meter prototype at the Albert Einstein Institute in Hanover, Germany is interested in improving gravitational wave detectors and investigating those questions in quantum mechanics which cannot be address in the detectors. The prototype includes a 100m3 ultra high vacuum system which supplies an area for experiments. There are three tanks connected in an L-shape by 1.5m diameter tubes. This system can be entered for easier installation and maintenance of experiments. In addition to this there are seismically isolated tables with vibration isolation systems which can attenuate seismic noise in six degrees of freedom. There is also a suspension platform interferometer, control and data systems, and arm cavity suspensions. One of the main goals of

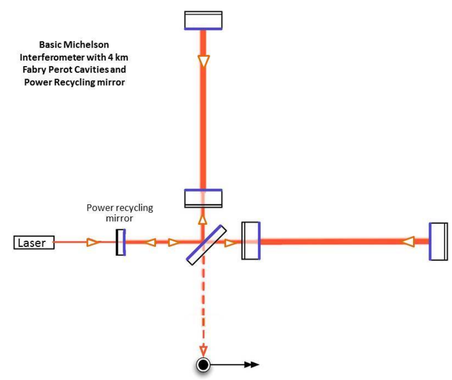

FIG. 1. a basic Michelson interferometer

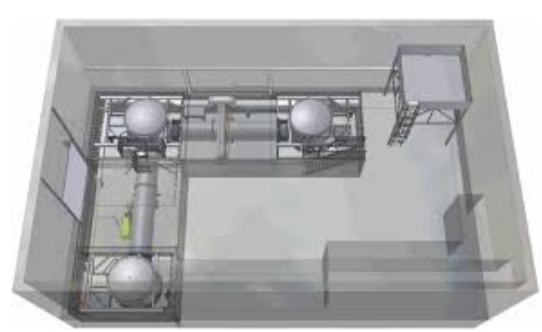

FIG. 2. an overhead view of the 10m AEI prototype

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the prototype is for it to be an apparatus that is capable of reaching the standard quantum limit. To make this possible, classical noise need to be greatly reduced. The seismically isolated tables provide a low noise platform. However, in order to perform quantum experiments a much higher level of isolation is needed. Mirrors are put into multiple stage suspension systems that act as pendulums attenuating noise above their resonant frequencies[2] Slow actuation and local damping are also used to further decrease noise.

C. Eddy Currents and Motion

In order to perform experiments limited by quantum radiation pressure noise low mass suspensions with high-Q pendulum stages are needed.[2] To attenuate seismic and thermal noise a multiple stage pendulum, vertical blade springs and other materials are used. However, this is still not enough to perform these experiments and additional local damping is required. The damping system needs to dampen motion in multiple degrees of freedom in order for the experiment to be possible. Eddy current damping has been regularly used in gravitational wave detectors and prototype experiments. This system however, is still being improved upon. An eddy current damping system was tested at the University of Glasgow in conjunction with a suspension system to further reduce motion.[2] When the mirror moves magnets that are attached to the corners move in and out of copper coils that are held in place on the suspension. The ends of the coils are connected to create a current loop. The changing magnetic field leads to a change in flux inducing the eddy currents that oppose the motion of the mirror. The voltage generated by the magnet moving in the coil can be represented by Faraday's law.

$$Emf = -N\frac{\Delta\psi}{\Delta t}$$

This voltage can run through a coil and power an eddy current amplifier increasing the effectiveness of the damping. The opposing force produced by the eddy currents is relative to the velocity of the motion of the magnet. So as the magnet slows the force applied decreases. This means that for weaker oscillations of the magnet weaker eddy currents will be produced. Ideally this would mean that as the test mass comes to a stop the eddy current damping will also stop however, this system was made switchable at the University of Glasgow so as not to excite motion via the electronic and thermal noise of the damping system.
The effectiveness of the damping system is limited by the resistance of the wires of the copper coils. Only a limited amount of current can pass through the wire due to its natural resistance so compensating for this resistance can in theory lead to an increase in the amount of current that can flow and therefore the level of damping achieved. To accomplish this a variant of a negative impedance circuit was built to increase the eddy current damping.

D. Negative Impedance Circuit

A negative impedance converter can be used to input energy into a circuit by creating a negative load with an op-amp. Normally, as current travels through a resistor there is a positive voltage drop and the circuits behavior can be described using Ohms Law,

$$V = IR$$

However, for a negative impedance converter the current flows in the opposite direction or if the current is not inverted the voltage drop is negative,

$$V = -IR$$

The op-amp attempts to keep its inverting and non-inverting inputs at the same or nearly the same voltage. In this case this would mean that the impedance being converted, the Z resistor, behaves as if it were connected to the input signal The resistor connected to the converted resistance draws current from the op amp output in order to achieve this. If there is a positive input into the circuit current will actually flow in the opposite direction into the input.

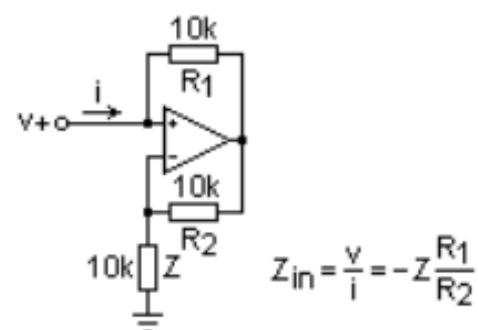

FIG. 3. Negative Impedance Converter from THE Art of Electronics

As one might expect, using this device resulted in a complete inversion of current which might actually excite motion if this were connected to a suspension system and not reduce it. This is because the currents amplitude does not change but it moves in the opposite direction. Current flowing in a loop in a reverse direction would result in a magnetic field that is also in the opposite direction. The resulting eddy currents would then cause the magnets to move in and out of the coil. Not only does this excite motion but as long as the op-amps were powered it would keep the mirror swinging continuously. To address this problem we had to redesign the circuit so that the resistance of the copper wires was compensated for without completely inverting the current flowing into the device. The circuit was then altered so that the compensating resistor was connected to the coil and the non inverting input of the op amp. The other two resistors were then connected to the inverting terminal of the op amp.

This was done so that the final resistance of the circuit was about -2.95ohm when using a 295Ω, 100Ω and 10kΩ.

$$Z_{in} = -Z\frac{R_1}{R_2}$$

The resistance of the small test coil was measured to be about 3Ω as measured by an LCR bridge. For the coils used in the suspension a a 560Ω, 100Ω and 10kΩ were used resulting in a negative resistance of about 5.6Ω.

The circuit can be broken up into two components a negative feedback loop and a voltage divider. When the output of an operational amplifier is connected to its negative input this is called negative feedback. The output is fed back to the input in order to reach some equilibrium. A voltage divider connected to the output of an op amp will only allow a fraction of the output voltage to be fed back to the input. This results in the output voltage of the op amp being some multiple of the input voltage. This was also observed in when measuring voltages across the circuit.

II. PROCEDURE

This circuit was built to accomplish the task of compensating for the resistance of the copper coils.

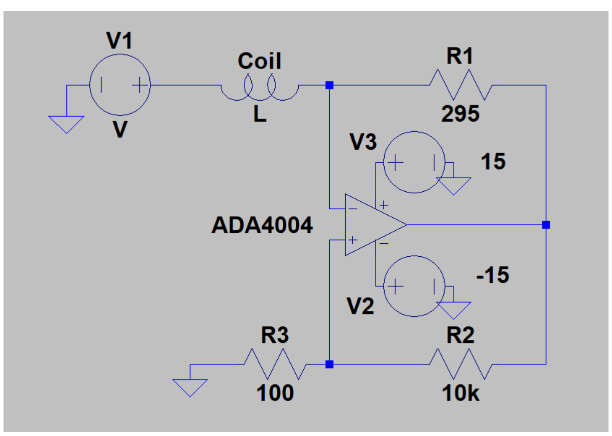

FIG. 4. Negative Impedance Circuit designed on LT SPICE

The circuit was built into a printed circuit board with pins in place were the resistors would go. This allowed for easy replacement of resistors so different values could be tested to optimize damping. After testing, four of these circuits were built into a 15 x 8 3/10mm metal box for easier mobility and electronic shielding. The circuit box has four BNC connections allowing cables to be connected to an oscilloscope to measure the output voltage of the op amps. An input for a power supply was connected to voltage regulators which powered the op amps with +/- 15 volts. At the front of the box is a DSUB9 socket which connects to a DSUB9 plug onto which the copper coils are soldered.

A. Preliminary Test

After working with the circuit for some time we wanted to make sure we could see the signal from induced EMF on an oscilloscope. In order to observe this we used a small S-03-06-N magnet, as used on the penultimate masses on the AEI 10m prototype main suspension, attached to a thin metal ruler and a small copper coil with 80 rounds of 0.15mm diameter copper wiring. The coil was wound around hollow plastic tubing with dimensions 4x5mm. The magnet was attached to the ruler which was then clamped in place above the coil. It was then tapped causing the magnet to oscillate in and out of the coil. The ends of the coil were connected to our original circuit which was simply a negative impedance converter. The output of the op-amp was connected to an oscilloscope via a Stanford SR560 preamplifier set to low-pass filter the output above 1kHz and provide gain of $2x10^3$

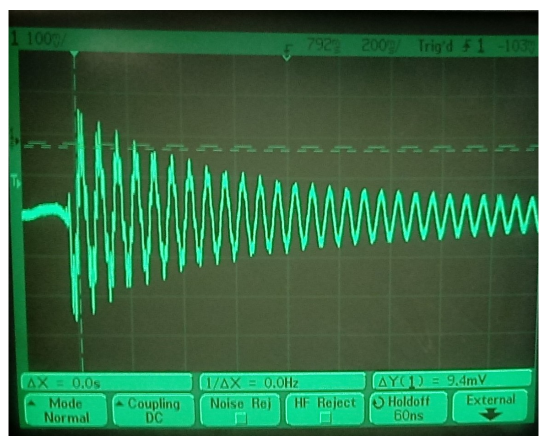

FIG. 5. Signal from oscillating magnet on a wire

A video was also taken of the oscillating magnet in order to estimate the amplitude of its motion. Looking at the video frame by frame we were able to determine the displacement at which the magnet reached by counting pixels and using the ruler in the video as a reference to determine the physical size represented by each pixel Every 100 pixels was about 1mm and the peak amplitude was found to be about 0.5mm. The oscilloscope measured 500mV peak to peak with amplification of the Stanford preamplifier. With 500mV/ 500um there is 1V/mm so if the amplitude was found to be 500nm this would give a voltage of $2.5\mu V$ with a 15Hz frequency of oscillation. The diagram below shows the circuit that was connected to the coil in order to produce a negative impedance in the coil. Initially a transformer with a 230:15 coil turn ratio was used in the circuit. This was done in an attempt to simulate the charging and discharging of current that would occur with a swinging mirror, due to the concern that a simple signal generator would not have low enough output impedance to sufficiently charge the coil. The circuit was tested in LT SPICE, a circuit simulation tool, and was then built and tested using several combinations of resistors.The impedance of the coil was measured to be $400\mu H$. However this did not provide the desired results. The current completely inverted as previously described and so the circuit was had to be redesigned.

This circuit design successfully dampened the motion of the magnet.

To test it the same magnet from before was attached to a steel wire with a high Q that was clamped to a desk. The magnet was placed above the same coil which was connected to the circuit.

The ends of the wire were stripped of their copper enamel, one end was connected to ground and the other to the inverting input of the op amp.

The op-amp was powered using a +/- 19 volts DC source that ran through voltage regulators. This allowed 15 volts to power the op-amp. An oscilloscope was connected to the output of the op-amp and ground. Again the steel wire was tapped causing the magnet to oscillate into the copper coil.

The oscilloscope was used to save the traces of the voltage at the output of the op-amp.

Now that the circuit was working four new coils were made using the dimensions of the coils from the suspension system.

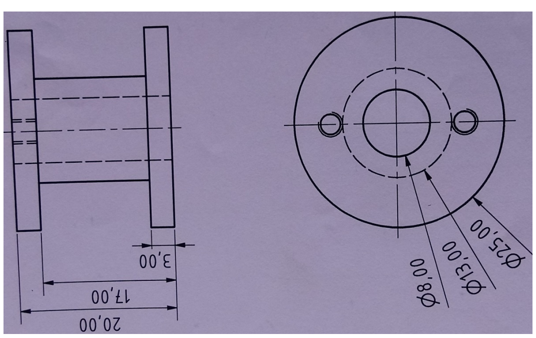

FIG. 6. Design and dimensions of coil holders for suspension system

0.2mm diameter copper wire was coiled onto plastic coil holders 200 times and these coils were then individually tested with the circuit. The final circuit was made with a 100 ohm, 10k ohm, and 560 ohm resistor with an ADA4004 SMD op-amp chosen because of its low voltage noise. Four of these circuit were then built into a metal box with a DSUB9 socket and 4 BNC connectors to send the op amp feedback signal to an oscilloscope. The coils were soldered to the DSUB9 connector which was then attached to the circuit box. The schematics for this circuit box were drawn up by Andreas Weidner. Three different scenarios were compared: the magnet oscillating in the coil with its ends connected to ground, with an amplified eddy current damping circuit and with the negative impedance circuit we designed. It was clear from the signals that the circuit we built dampened motion much quicker than the other two situations.

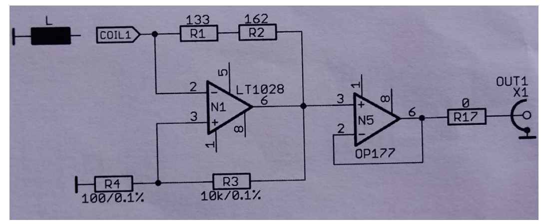

FIG. 7. Circuit box schematic as drawn by Andreas Weidner

The damping of the motion of the magnet was compared to the damping of an amplified eddy current system using the same coils.

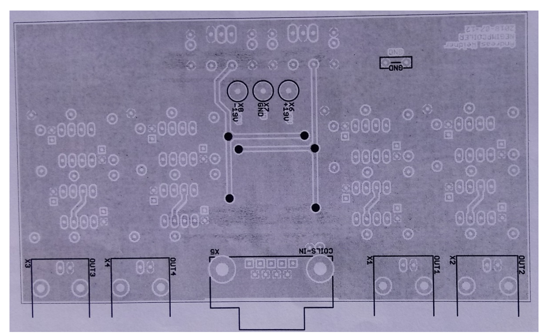

FIG. 8. Top view of circuit box with connectors, test points and wired components visible

Each circuit was connected to buffers and then to BNC outputs. This was done so that the input impedance of the oscilloscope did not affect the feedback to the coils. Instead of all the current going to the coils some could go to the oscilloscope if the input impedance was low enough. The buffers consist of op amps in a unity gain configuration which allows for the output voltage to be the same as the input[3]. The measurement circuit is then separated from the negative impedance circuit. The resulting input impedance ends up being very high so that there is little to no current drawn to the oscilloscope but it goes to the coils.

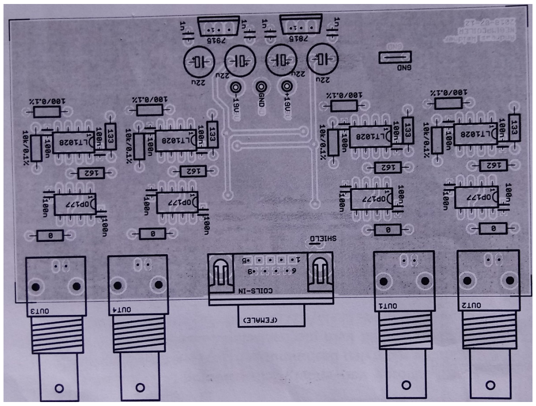

FIG. 9. Top view of the board with all components including resistors, voltage regulators, buffers, inputs and outputs

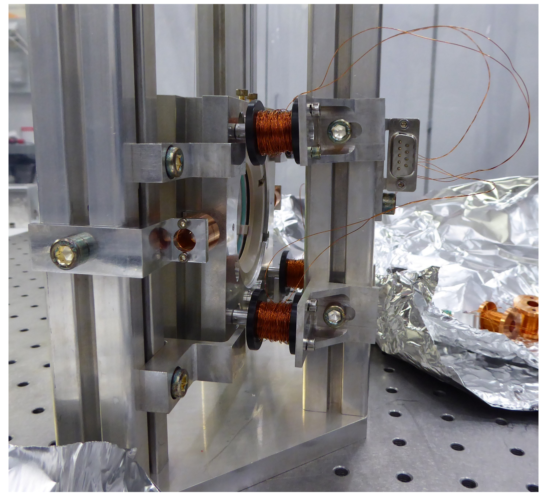

FIG. 10. The suspension system with copper coil damping system

B. Lab Testing

Testing in the electronics workshop suggested that the NIC device does dampen motion quicker than the amplified eddy current system so the device was then tested in the lab. A suspension system used in the 10m prototype was used as a final test to determine the effectiveness of the circuit. A mirror hung from the suspension system and the four coils were connected. These were held in place directly behind four magnets and connected to the circuit box.
Video was taken of the swinging mirror with shorted coil ends, with the coils disconnected from the circuit box and with them connected to the circuit box. To obtain better measurements the oscilloscope was connected and each coil was measured independently. The mirror would receive a force and begin to move and the resulting signal was recorded on the oscilloscope. The traces were then plotted and fitted to an exponential curve and compared.

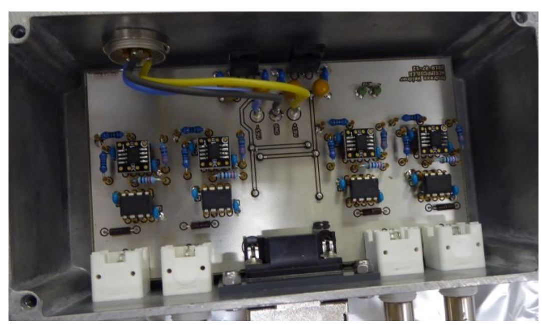

FIG. 11. Negative impedance converter circuit box

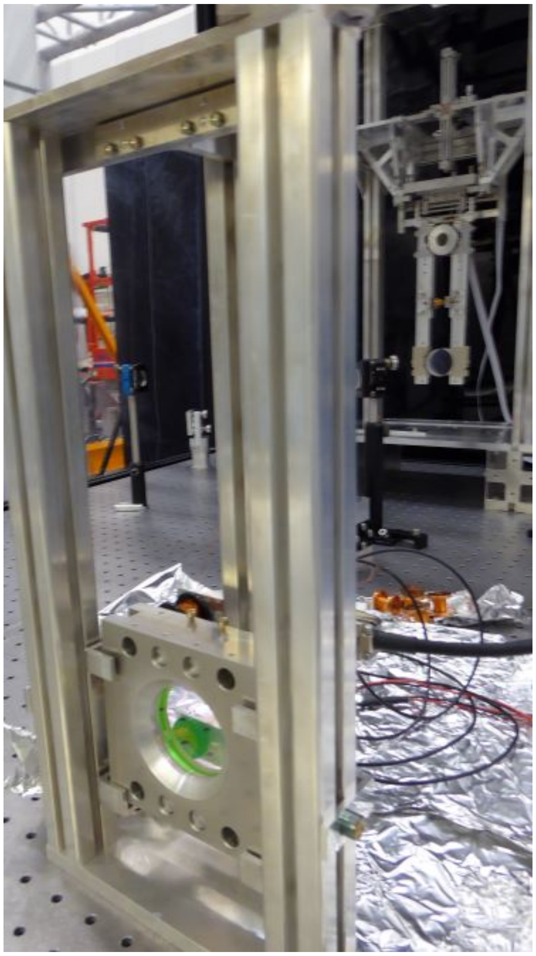

FIG. 12. Close up of mirror in suspension system

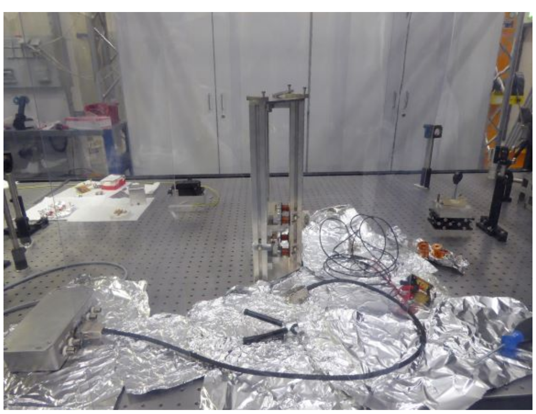

FIG. 13. lab set up

III. RESULTS

Looking at the video alone it is evident that the eddy current damping with the negative impedance like device is much better than regular eddy current damping systems. The free swinging mirror with the coils disconnected continues swinging for about six minutes. The eddy current damping system with the ends shorted swings for about three minutes and the damping system connected to the circuit box dampens in 7 or 8 seconds. They were fit with exponential curves which were used to estimate the time constant of the decay rate.
The signal plots clearly show that the damping with the circuit box is much more effective. The plots from the different channels have varying amplitudes because when the mirror was tapped the force did not consistently reach all four coils. The different degrees of freedom that the mirror rotated in resulted in some beat frequencies in the signal plots. The plots were also fit with an exponential curve in order to estimate the time constants of their decay.

The time constants were estimated and listed in the table below.

no damping	ECD	NIC
115s	50s	0.64s

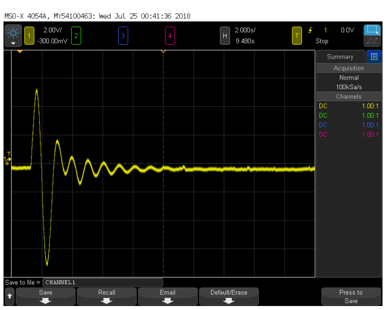

FIG. 14. signal from channel 1 coil

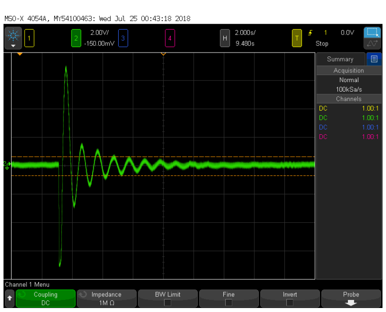

FIG. 15. signal from channel 2 coil

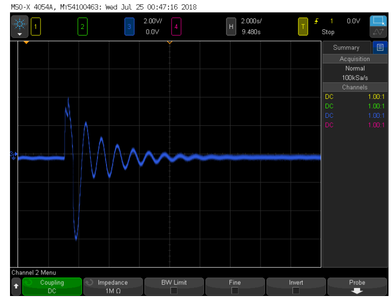

FIG. 16. signal from channel 3 coil

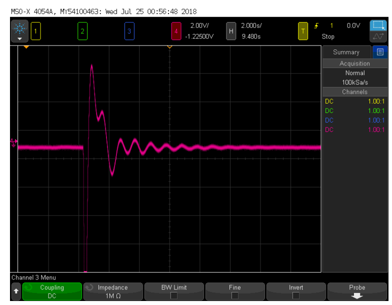

FIG. 17. signal from channel 4 coil

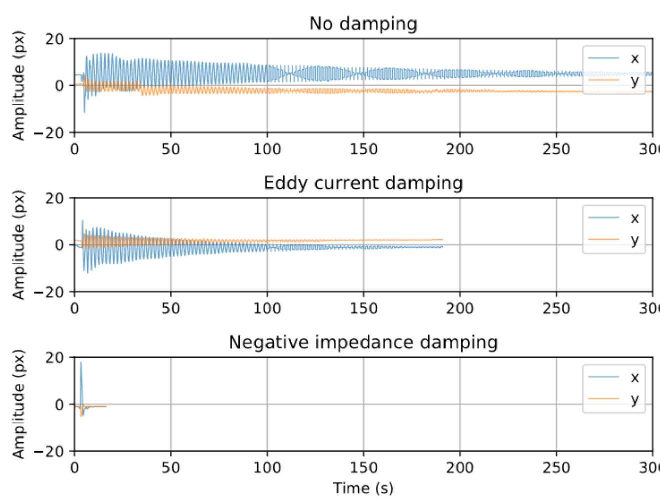

FIG. 18. the amplitude of the signals from the three scenarios

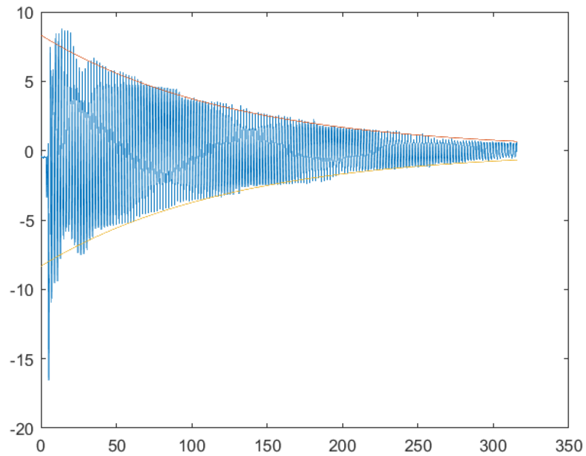

FIG. 19. the amplitude of the signals from the undamped case

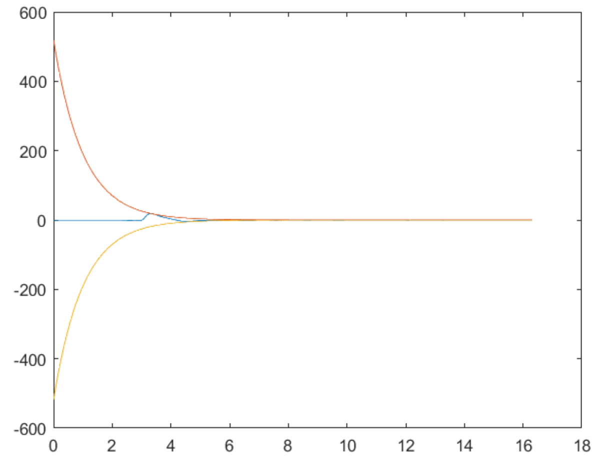

FIG. 21. the amplitude of the signal when the coils were connected to the circuit box

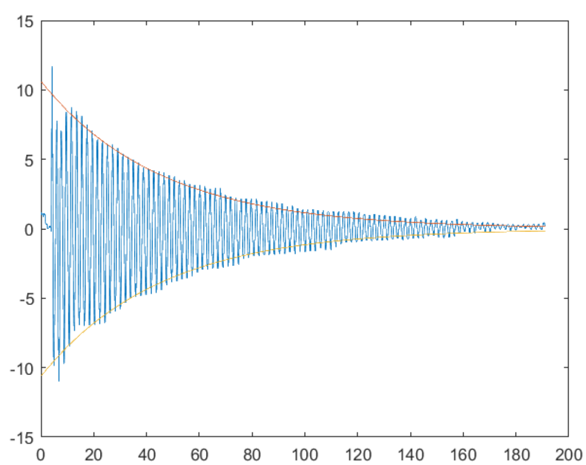

FIG. 20. the amplitude of the signal from the eddy current damping case

IV. CONCLUSION

Mirror stability in laser interferometry is crucial for clear reliable data. This circuit provides a way to better stabilize mirrors based on the amount of motion they are producing. Not only does this provide a way to obtain more reliable measurements but it helps the mirrors reach the stability they need in order for quantum experiments to be performed. To perform these experiments limited by quantum noise the mirrors would need a quick an efficient damping system. It would also be important to investigate the effects of electronic noise that may be fed back to the coils. There may or may not be a significant effect on the mirrors motion. This device may not be well suited to low noise operations. The ADA4004 op amp was decided on because of its low noise but this may not be enough for the circuit to be used in low noise interferometric operations, such as with gravitational wave detectors. There are other sources of noise within the circuit. The device can actually be connected to the coils and sit outside the vacuum. This would make it easier to replace parts if need be. It also allows it to be easily disabled or replaced during low noise operations and can be used in conjunction with BOSEMs and other damping methods.

V. ACKNOWLEDGEMENTS

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