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Low-Noise Piezoelectric Driver for External Cavity Diode Lasers

Physics 492R Capstone

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1. **Abstract:**

I built a piezoelectric amplifier for a laser system used in a matter-wave interferometer. The piezoelectric driver is an essential part of each laser feedback system that controls the lock of each laser in the matter-wave interferometer. The lasers that we are building require extremely stable laser locks, therefore the piezoelectric amplifier I built must also be very quiet. I built this piezoelectric driver to be a lot less expensive and quieter than commercial units.

2. **Introduction:**

2.1 Background-

In our research group we are building a matter-wave interferometer. The interferometer requires lasers to cool strontium atoms in a magneto optical trap, to ionize a stream of slow strontium atoms, and to provide pi and half pi pulses used in the interferometer tube to split and recombine the stream of ionized strontium. The interferometer requires a number of lasers that must be held at very specific wavelengths of light. The specific wavelengths correspond to different atomic transitions in strontium and therefore we are "locking" each laser to these wavelengths. Each laser is an extended cavity diode laser with an accompanying feedback system to provide the stable lock.

The level of sensitivity that we wish to achieve requires that each laser lock be extremely quiet. The feedback system, of which the piezoelectric driver is a part, provides very precise control of the frequency of the laser light. It utilizes a temperature controller, a current driver, and a diffraction grating to reduce mode hopping as well as noise in the laser.

2.2 Motivation-

The piezoelectric amplifier that I built controls the angle of a diffraction grating that is placed outside the lasers cavity. The diffraction grating extends the cavity of the laser by reflecting the first order fringe back into the cavity. This first order reflection will aid with mode competition inside the cavity in order for the desired mode to be selected. Adjusting the angle of the diffraction grating allows control of the specific mode that is reflected back into the laser and thus controls the laser's mode.

The angle of the diffraction grating is adjusted by applying high voltages to piezoelectric actuators on which the diffraction gratings are mounted. Piezoelectric actuators use a special crystal that deforms when a voltage is applied to it. A high enough voltage will induce a lengthening of the piezoelectric crystal. By controlling the voltage applied to the crystal, we can precisely control the length of the crystal and thus the angle of the diffraction grating mounted to it. However, the voltages needed to affect the desired changes in angle of the diffraction grating are as high as 100 volts. For this reason, I built a piezoelectric amplifier to drive the high voltage that the crystals require to lengthen.

The piezoelectric driver that we have designed is based on an inexpensive high voltage operational amplifier (op-amp) that we found. The discovery of an inexpensive high-voltage op-amp is what made the construction of the piezoelectric driver possible. The high-voltage op-amp is a series PA240 by APEX Mircotechnology. We use surface mount components along with the TO-220 staggered leads PA240[1] to construct the piezoelectric driver on a PCB board.

Our piezoelectric driver will save us money compared to buying expensive commercial drivers. However, our design must be better than commercial piezoelectric drivers with regards to noise performance. I analyzed the noise of our design and compared it to commonly used commercial piezoelectric drivers with the goal of making our version quieter than commercial versions.

2.3 Context-

Typically piezoelectric drivers are simply bought commercially, but they are very expensive. By building our own, we will be familiar with its design, able to fix it if necessary, and save a lot of money. The design I relied on was generated by James Archibald and Christopher Erickson.

3. <u>Methods:</u>

3.1 Construction-

3.1.1 Design-

The piezoelectric driver is designed to deliver between 0 and about 120 volts to the piezoelectric stacks. The piezoelectric driver is composed of two key stages built around an op-amp and the PA240 high-voltage op-amp. The design is simple and can be constructed quickly. The circuit layout is given below:

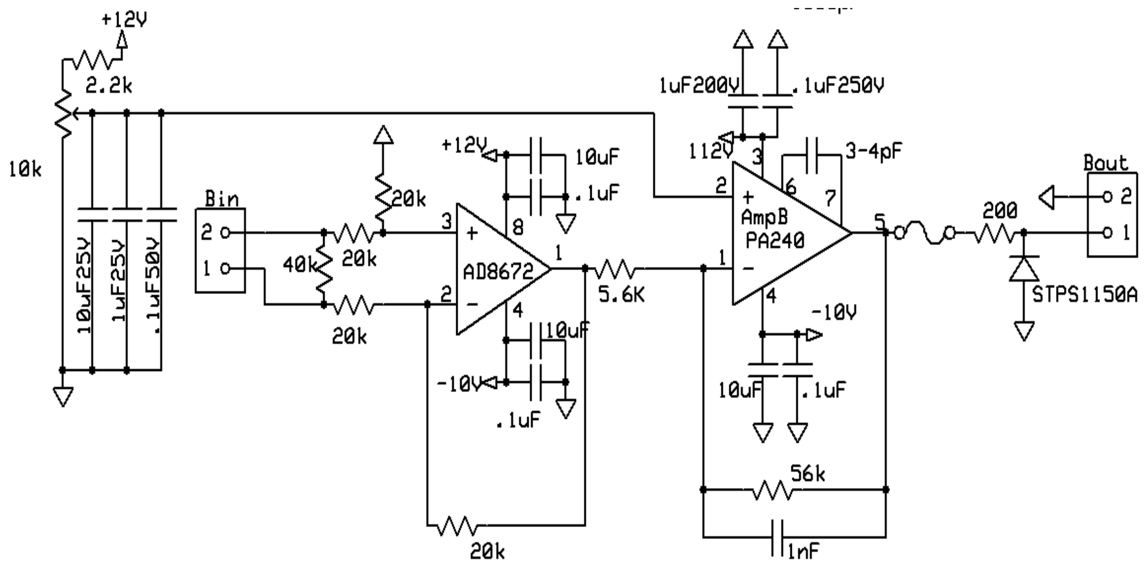

Fig. 1- Piezoelectric driver circuit diagram

3.1.1.1 First Op-amp stage-

The piezoelectric driver utilizes two operational amplifiers to deliver the correct voltage to the piezoelectric stacks. The first op-amp serves as an inverting differential amplifier. A PID controller sends a signal to the piezoelectric driver that is received at Bin. The first op-amp references the ground of the signal from the PID controller to the ground of the piezoelectric driver.

3.1.1.2 High-voltage PA240 Stage-

The second stage is where the PA240 high-voltage op-amp lies at the center of figure 1. The PA240 is connected as a inverting amplifier with a gain of ten. The non-inverting pin of the PA240 is connected to a potentiometer that can sweep from zero to ten volts. The inverted signal from the first op-amp is received at the inverting input of the PA240. The voltage that the PA240 will output is given by the equation:

$$V_{OUT} \approx V_{ADJ} - (V_{IN} - V_{ADJ}) R_2/R_1 \quad (1)$$

Where Vadj is the adjustable voltage from the potentiometer, Vin is the voltage signal from the first op-amp, and ratio of the resistors R_1 and R_2 gives circuit's gain. We chose R_1 to be 5.6 KΩ and R_2 to be 56 KΩ to give a gain of ten.

3.1.1.3 Circuit protection stage-

Following the PA240, we have a fuse connected in series with a 200 Ω resistor followed by a diode connected to ground. The purpose of the resistor is to regulate the current from the PA240 because it is not able to handle high current. Therefore, the resistor serves to keep the current low. However, we discovered that a big resistor combined with the capacitance inherent in the piezoelectric actuators produced a time constant that was too long for the response needed in the piezoelectric actuators. So we needed to chose a resistor big enough to protect the PA240 from high current, but small enough to maintain a small time constant. We settled on a 200 Ω resistor to perform the task. In case the resistor was inadequate in protecting the PA240, we added a fuse as a failsafe.

Lastly, we added a diode connected to ground to protect the piezoelectric actuators. The special properties of piezoelectric crystals are very sensitive to negative voltages. Negative voltages can reverse the polarization of the crystals that gives them their piezoelectric properties. Therefore, to protect against applying negative voltages to the piezoelectric stacks we have a diode connected to ground for the negative voltage to pull current from ground and avoid destroying the piezoelectric actuators.

3.1.2 Materials-

The piezoelectric driver is constructed using surface mount components. Surface mount components have many advantages:

1. Inexpensive
2. More models to choose from
3. Lower parasitics
4. Sit close to board to reduce noise pick-up
5. Quick and easy to find
6. Quick and easy to assemble
7. Compact
8. Simple to fix

Each of these advantages lead to the design of the piezoelectric driver on a PCB board using surface mount components. They do, however, have few disadvantages:

1. Much harder to prototype with
2. Require learning new techniques to work

We designed the circuitry on PCB boards, a skill that requires a fair amount of knowledge and practice.

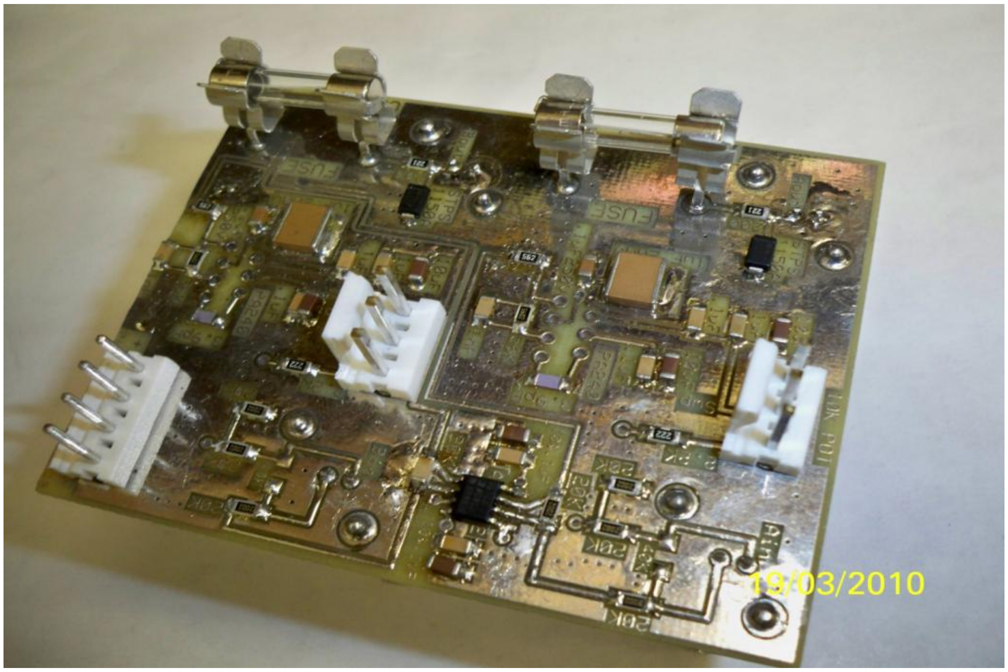

Fig. 2- Photograph of the piezoelectric driver using surface mount components

3.1.3 Power Supply-

To provide the 120 volts that the driver needs we are using a high-voltage power supply. We originally had designed a power supply specifically for the piezoelectric driver, but it gave us too many problems. The power supply's circuit was providing the correct voltages needed to power the piezoelectric driver, but the circuit was picking up noise from a number of sources including the fan used to cool the voltage regulators within it. For this reason we decided to abandon the design we made for the power supply of the piezoelectric driver. We are now used a commercial high-voltage power supply.

3.2 Testing-

The main goal of constructing this piezoelectric driver is to make it quieter than commercial units. I analyzed the noise spectrum of the piezoelectric driver and compared it to the noise spectrum of a Thorlabs commercial piezoelectric driver.

3.2.1 Set-up-

To measure the noise of the piezoelectric driver I need to measure how big a voltage signal it generates at all frequencies with no input. This was then compared to the voltage noise generated by the set-up itself.

3.2.1.1 Pre-Amplifier-

To measure the noise we hooked the piezoelectric driver to an SR 560 Pre-Amplifier to act as a low-pass filter so we can look at the noise over specific ranges. The Pre-amplifier is important to reduce aliasing that can result from high frequencies. We used BNC cables to connect the two units. On the Pre-Amplifier, I selected the low-pass filter setting and set the roll-off to be at 12 dB per octave. I swept the frequency of the Pre-Amplifier from 20 MHz down to 2 Hz and graphed the filtered signal on a Lecroy Oscilloscope.

3.2.1.2 Lecroy Oscilloscope-

The Pre-Amplifier was connected to a digital Lecroy Oscilloscope that graphed the filtered signal from the Pre-Amplifier.

3.2.1.3 Computer-

The Lecroy Oscilloscope was connected to a computer by a serial port. The voltage data on the Lecroy Oscilloscope was saved to the computer by the program Scope Explorer to be analyzed. Scope Explorer saved the voltage data as text files of voltage versus frequency.

3.2.2 Scope Explorer-

The data from the Pre-Amplifier was read and saved to a computer by Scope Explorer. We used a Lecroy Oscilloscope to gather the voltage data from the Pre-Amplifier. Scope Explorer connects the oscilloscope to a computer where the data is save as a text document. From the text document, the data could then be read by a MatLab script and analyzed.

3.3 Noise Analysis-

To measure the noise levels of the piezoelectric driver we need to see the voltage noise as function of frequency. The noise is analyzed by graphing the spectral density of the voltage data saved by Scope Explorer.

3.3.1 Spectral Density-

The data received from the Pre-Amplifier will carry the voltage noise with it at specific ranges of frequencies. To see how much noise the signal has I calculated the spectral density of the noise. The spectral density is essentially a Fourier transform of the signal. It shows the frequency components of the voltage signal at each range of frequencies.

3.3.1.1 MatLab Script-

The spectral density is calculated by a MatLab script that was written by Daylin Troxel. The MatLab script takes the voltages data saved as a text document by Scope Explorer, imports it, and computes the Fourier transform to give the spectral density of the noise. The scripts then graphs the spectral density as a function of frequency on a logarithmic scales. The units in the Spectral density are volts per square root hertz. The graph shows how much voltage noise is present at each frequency, therefore the amount of noise is given by integrating the square of the signal over a particular frequency range.

3.3.1.2 Noise Floor-

In order for the voltage noise to be correctly attributed to the piezoelectric driver we obtain the lowest amount of noise that is inherent in the set-up of our system to test the noise. The noise that is inherent in the Pre-Amplifier and the Lecroy Oscilloscope constitutes the noise floor of the set-up. The noise of the piezoelectric driver is then compared to the noise floor to see how much noise is added.

4. Results and Discussion:

4.1 Data-

The data gathered from our piezoelectric driver was analyzed using MatLab and shown on a graph with the corresponding graph of the noise floor. The two can therefore be easily compared and the extra noise added by the piezoelectric driver can be visually identified.

4.1.1 Graphs-

4.1.1.1 Our Piezoelectric Driver vs. Noise Floor-

The following graph represents the voltage data gathered from our piezoelectric driver with respect to frequency. The graph represents the noise floor of the set-up by the colored line and the voltage noise of our piezoelectric driver with a black line. The y-axis is given in volts per root hertz and the x-axis is in hertz.

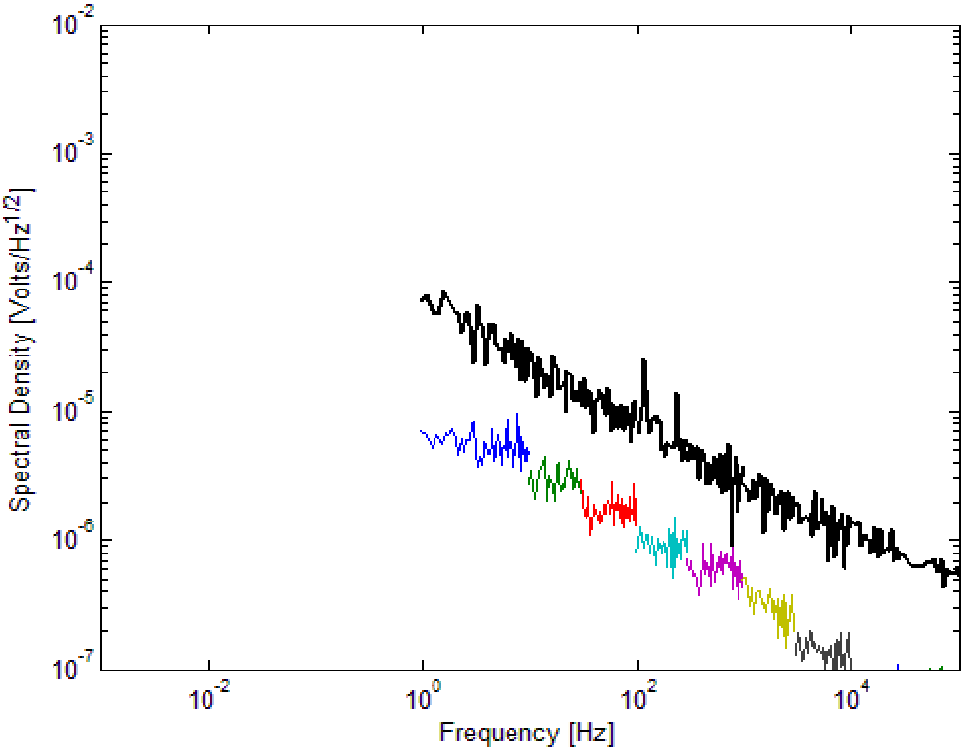

Fig. 3- Spectral density graph of our piezoelectric driver (black line) compared to the noise floor (multi-colored line)

4.1.1.2 Commercial Thorlabs Piezoelectric driver vs. Noise floor-

The following graph represents the voltage data gathered from the Thorlabs piezoelectric driver with respect to frequency. The graph represents the noise floor of the set-up by the colored line and the voltage noise of a commercial Thorlabs piezoelectric driver with a black line. The y-axis is given in volts per root hertz and the x-axis is in hertz.

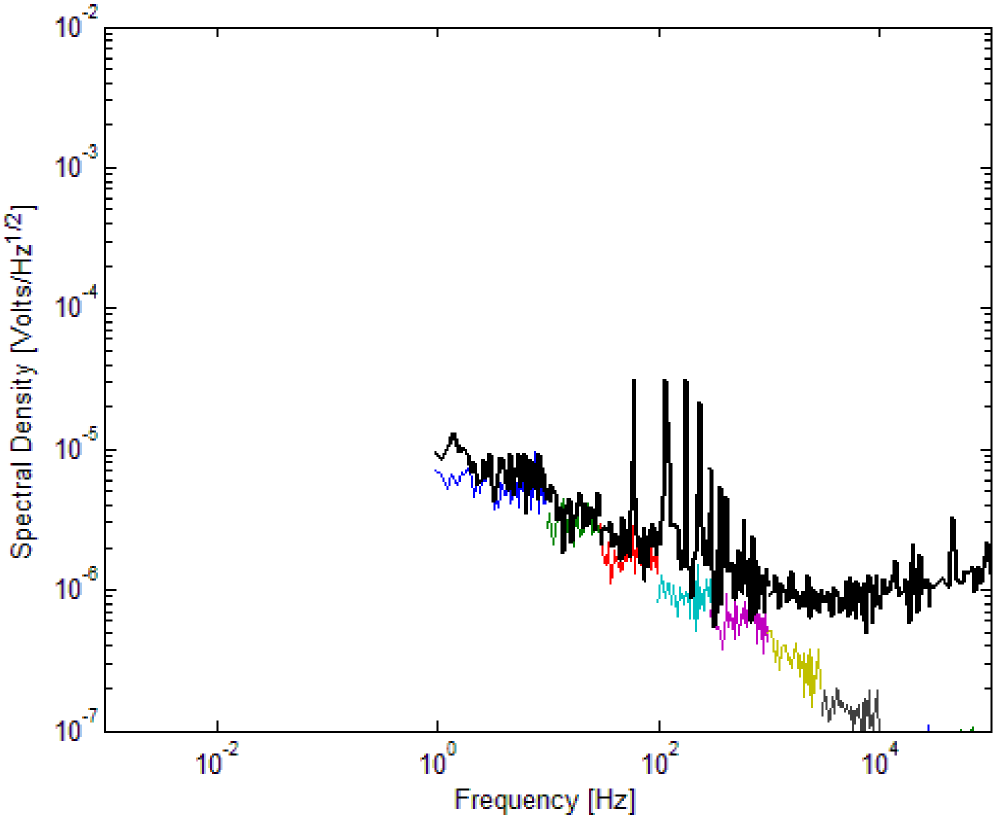

Fig. 4- Spectral density graph of Thorlabs piezoelectric driver (black line) compared to the noise floor (multi-colored line)

4.2 Our Piezoelectric driver vs. commercial Thorlabs driver-

4.2.1 Graph-

The following shows the commercial Thorlabs piezoelectric driver by the colored line and the voltage noise of our piezoelectric driver with a black line. The y-axis is given in volts per root hertz and the x-axis is in hertz.

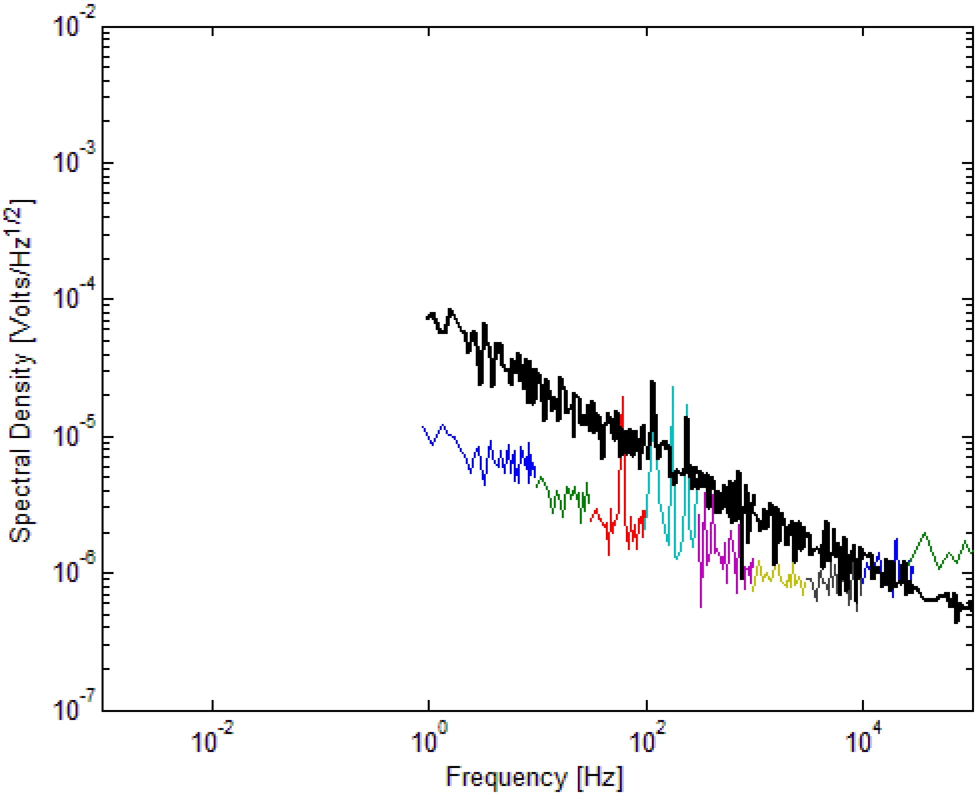

Fig. 5- Spectral density graph of our piezoelectric driver (black line) compared to the Thorlabs piezoelectric drive (multi-colored line)

4.2.2 Comparison of frequency ranges-

4.2.2.1 Zero-100 Hz-

The spectral density graph of our piezoelectric driver vs. the Thorlabs driver shows that at lower frequencies the Thorlabs driver has less noise than our driver. The graph shows the noise level of our piezoelectric driver to be about one order of magnitude higher than the Thorlabs driver over the range of zero to one-hundred hertz.

4.2.2.2 100-10^4 Hz-

The spectral density graph of our piezoelectric driver vs. the Thorlabs driver shows the noise levels to be about equal for most of this range of frequencies.

4.2.2.3 10^4 Hz and up-

The spectral density graph of our piezoelectric driver vs. the Thorlabs driver shows that at higher frequencies the Thorlabs driver has more noise than our driver. The graph shows the noise level of our piezoelectric driver to be about half an order of magnitude lower than the Thorlabs driver over the range of 10^4 hertz and up.

4.3 Attempts to reduce noise-

The spectral density graphs show that while the piezoelectric driver we built is good, does not outperform the commercial Thorlabs piezoelectric diver. This led me to work on how to reduce the noise that our piezoelectric driver generates.

4.3.1 Sources

4.3.1.1 Johnson Noise-

I first turned to Johnson noise in my search for the source of the voltage noise of our piezoelectric driver. Johnson noise is inherent in every circuit to a degree. Johnson noise is generated by the thermal agitation of the atoms and electrons that make-up resistors. This is calculable quantity given by the equation:

$$V_n^2 = 4\ k_B\ T\ R \tag{2}$$

The variable V_n is the voltage noise, k_B is Boltzmann's constant, T is the temperature and R is the resistance of the resistor[2]. I was able to calculate the Johnson noise for the piezoelectric driver and found that it should be on the order 10^{-7} volts per root hertz. This led me to believe that the noise source did not lie with the Johnson noise.

4.3.1.2 Search for source-

The search for the source of noise being a full order of magnitude above the noise floor continues. Further work is needed with regards to Johnson noise to completely rule it out. I have started work analyzing the noise circuit element by circuit element to see of any particular piece is having a dramatic effect. This work is ongoing, as well as the investigation into other possible sources for the noise.

4.4 Cost-

One of the key motivators in constructing our own piezoelectric driver is the amount of money we would spend to build them ourselves compare to buying commercial units. I added up the cost of all the materials needed to build an entire box of our piezoelectric driver design. The box totaled about $300 dollars to build and carries six separate piezoelectric channels. Therefore, one channel costs about $50 dollars. That is compared to piezoelectric driver cubes built by Thorlabs which house one channel and costs $595 dollars each. So, for nearly the cost of 12 channels of our piezoelectric driver, we would be able to buy one Thorlabs piezoelectric driver. This is huge amount of savings that can be generated by building our piezoelectric driver.

5. <u>Conclusions:</u>

5.1 Noise analysis-

The results of the spectral density analyzes shows that the piezoelectric driver we have designed and constructed is very quiet in the high frequency ranges, but does not perform as well at lower frequencies. As it turns outs the lower frequencies are mostly the more important ranges of our use of the piezoelectric driver.

I am continuing to look for the true source of the noise presented by the spectral density graphs of the data gathered. The Johnson noise may be a source, but calculations appear to show it is not. I am attempting to rebuild the piezoelectric driver to analysis the noise as each stage of the piezoelectric driver.

5.2 Cost-

There is a hope that this piezoelectric driver can benefit other research groups needing piezoelectric drivers by saving them money on having to buy commercial units. The Thorlabs piezoelectric driver has shown to be a quieter unit than our design, but it is still very quiet and very effective. Efforts will continue to refine the design and construction of the piezoelectric driver in order for it to become quieter than commercial units available.

6. References:

[1] High Voltage Operational Amplifier PA240 by APEX Mircotechnology data sheet- PA240U REV E OCTOBER 2006 © 2006 Apex Microtechnology Corp.

[2] Wikipedia: Johnson-Nyquist Noise- http://en.wikipedia.org/wiki/Johnson_noise

7. Acknowledgments:

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