Performance of a Nanopositioner Controller Filter Compensator

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Abstract

We describe the use of appropriate type simple resistor and capacitor (RC) compensators, which properly connected to a power amplifier, can improve the dynamic performance of MEMS (Microelectromechanical Systems) nanopositioners. Research on compensators led to the design of several simple RC compensators that may be appropriate for the NIST symmetric dual parallel lever nanopositioner. Using basic circuit theory, the RC circuits were analyzed and their transfer functions were found. The bandwidth of the RC compensator controller nanopositioner system was measured by the frequency range in which the magnitude of the response drops about 3 dB from its initial value.

Keywords: controller compensator, nanopositioner, dynamic performance

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I. Introduction

The Precision Meso/Micro Systems for Nanomanufacturing project, currently being conducted at NIST, features a MEMS micro-scale nanopositioning stage. A schematic of the stage is shown in Figure 1a. This is a high precision positioning device that may be used for scanning probe microscopy, nano-manipulation, and prototyping nano-devices [9]. It may also be an integral part of the automated assembly of micro and nano-scale components. The major goal is to decrease the cost of nano-manufacturing by reducing the size of equipment and establishing high yield, parallel nano-manufacturing. This will be accomplished by designing fully integrated nano-manufacturing workcells on a single silicon chip.

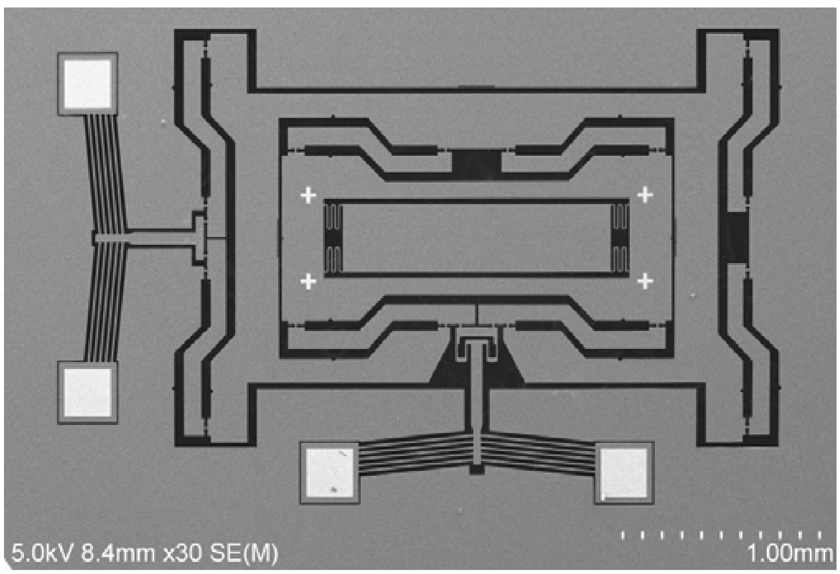


Figure 1a: Schematic of Nanopositioning Device

The center stage of the device is moved by bent-beam thermal actuators. The actuators apply forces to the flexure mechanisms which then displace the stage. The flexure mechanisms utilize parallel dual-levers to amplify motion along an axis while minimizing crosstalk and angular deviation with the other axes. To understand the actuator bandwidth and determine the effects of resonance on the device's motion, the frequency response of the stage is measured using the swept sine method and a laser reflectance microscope. The resulting Bode plot is shown in Figure 1b. This data is critical to the mechanism's performance in nano-manipulation because it determines the fastest rate at which the manipulator can move without exciting resonant oscillations.

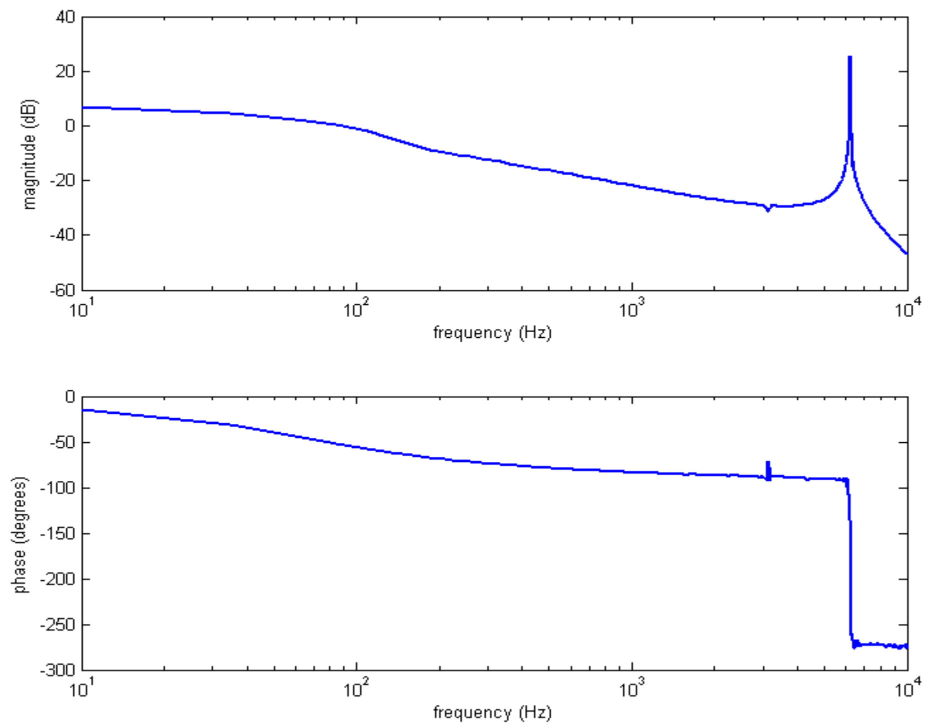


Figure 1b: Bode Plot of Nanopositioning Stage with Current Amplifier

The purpose of this project is to increase the bandwidth of the nanopostioning stage to 100 Hz and improve its frequency response. This report documents the complete process in which RC (resistor-capacitor) compensators were designed and tested to determine the most beneficial compensator. First, several circuit concepts that were considered for the project are explained. Then, a full description of the testing procedures is given and the data results are presented. The data are analyzed, and then a conclusion is drawn on which final circuit is the most successful in improving the performance of the nanopositioning device.

II. Objective

The objective of this project is to increase the working bandwidth of the system while still maintaining nano-scale position resolution. One method of doing this is to apply a compensator to the system. During this project, research will be conducted on simple RC compensators and how they may be used to improve the frequency response of a system. The designed compensator will be added to the current controller and then tested to evaluate its effectiveness.

III. Concept Generation

Research on simple controller compensators led to the design of several simple RC compensators that may be appropriate for this project [Lurie 2000]. A general RC compensator circuit with two resistors R_1, R_2, and two capacitors C_1, C_2, shown in Figure 3.3a, was chosen as the master design. Combinations of this circuit with fewer elements were then studied. Due to time limitations only two of these simpler circuit designs and the master circuit design were studied and are described here. Future studies will expand this work with a greater variety of circuit designs. Using basic circuit theory, the circuits were analyzed and their transfer functions were found. Since the functions are in the Laplace domain, their Bode plots can be added when placed in series. The bandwidth of a system is measured by the frequency range in which the magnitude of the response drops about 3 dB (70.7 %) from its initial value [Bandwidth 2008]. Figure 3, an enlarged view of the uncompensated Bode plot, depicts the bandwidth to be about 41 Hz. A larger bandwidth generates a faster rise time, so the objective of this project is to increase this bandwidth. Thus, it is desirable for the compensated response to have a less negative slope and, as a result, a wider bandwidth. In order for a compensator to have this affect, its transfer function should have a positive slope. To see the response of each compensator circuit, their transfer functions were graphed (see Fig. 3.1b). The graph was then used to apply different values of resistors and capacitors, changing the constants, in order to find the combinations that would yield the desired function. Only resistors and capacitors available at local electronic component supply stores were considered. The best compensator designs were selected to be built, and the necessary components were purchased. A review of the concepts considered during brainstorming and their analyses are given in the following sections.

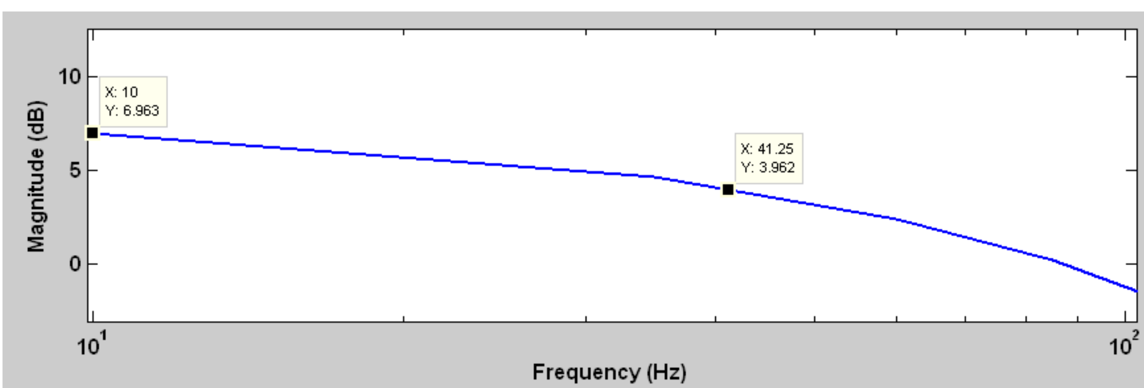


Figure 3: Enlarged View of Magnitude Plot in Figure 1b

3.1 Concept #1

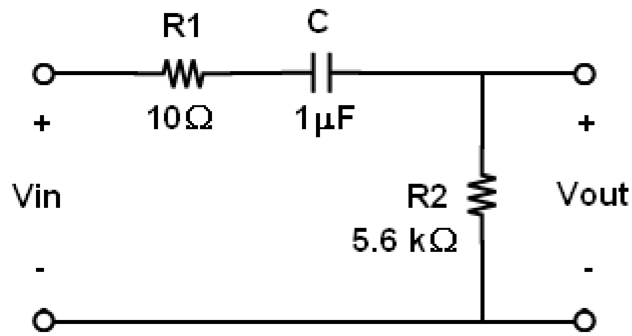


Figure 3.1a: Circuit Diagram for Concept #1

In the first compensator concept, there is a 1 µF capacitor in series with a 10 Ω resistor. The output voltage is taken across a 5.6 kΩ resistor. Figure 3.1a shows the circuit diagram. Analysis of this circuit yields a transfer function of:

$$H(s) = \frac{R_2 C s}{(R_1 + R_2) C s + 1}$$

where s is the input frequency in radians per second in the Laplace domain. The graph of this function, is shown in Figure 3.1b. The function has a positive slope, increasing about 0.5 dB in magnitude across a frequency range of 100 Hz.

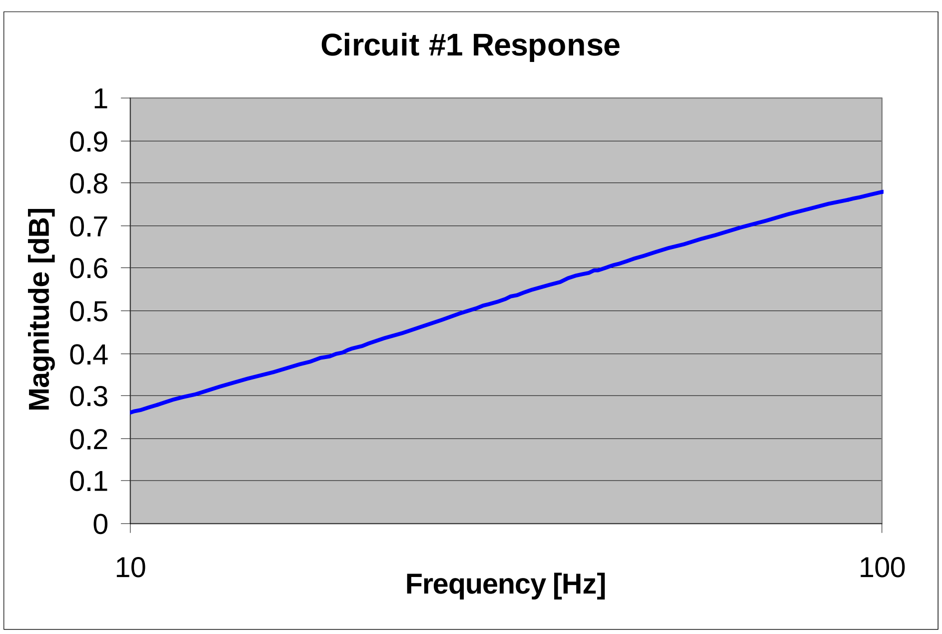


Figure 3.1b: Calculated Frequency Response of Circuit #1

3.2 Concept #2

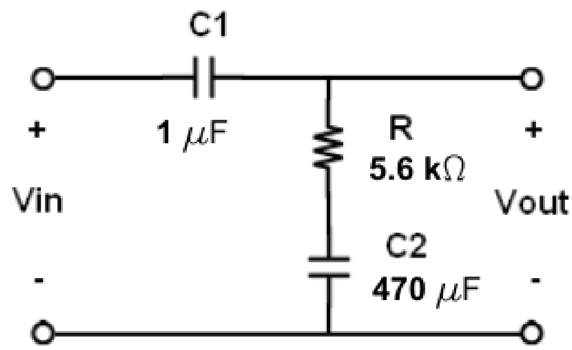


Figure 3.2a: Circuit Diagram for Concept #2

Figure 3.2a is the circuit diagram of the second compensator concept. There is a 1 μF capacitor in series, a 5.6 kΩ resistor and a 470 μF capacitor in parallel. The output voltage is taken across the 5.6 kΩ resistor and the 470 μF capacitor. Analysis of this circuit yields the transfer function to be:

$$H(s)= \frac{RC_1C_2s + C_1}{RC_1C_2s + C_1 + C_2}$$

The plot of this function, shown in Figure 3.2b, reveals that it is similar to the first concept because it has a positive slope as well.

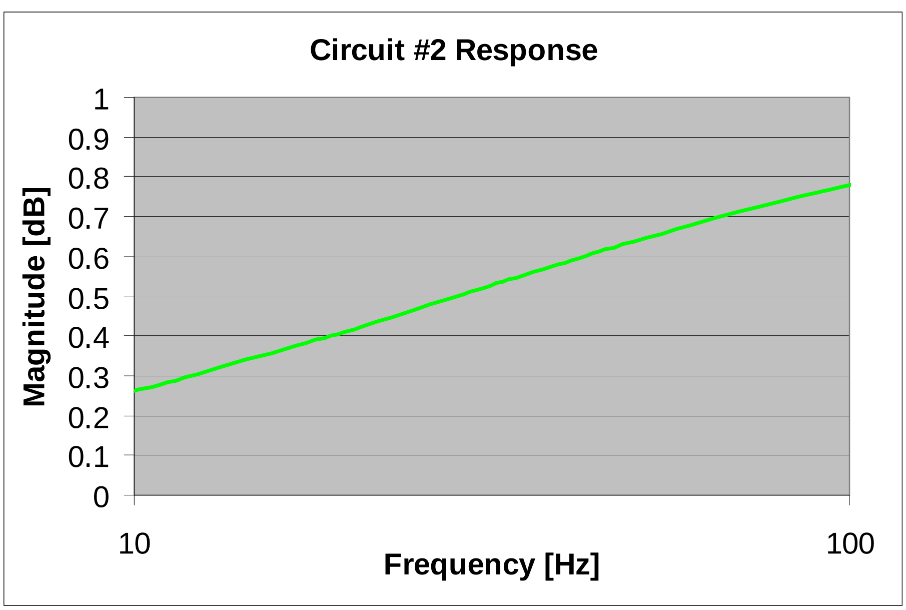


Figure 3.2b: Calculated Frequency Response of Circuit #2

3.3 Concept #3

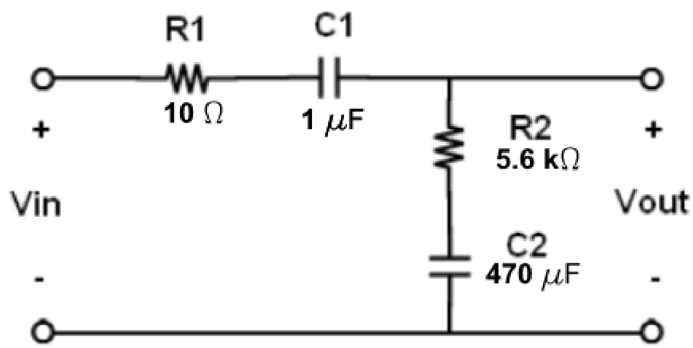


Figure 3.3a: Circuit Diagram for Circuit #3

Finally, in the third compensator, there is a 10 Ω resistor, a 1 μF capacitor, a 5.6 kΩ resistor, and a 470 μF capacitor. The output voltage is taken across the 5.6 kΩ resistor and the 470 μF capacitor. The circuit diagram is shown in Figure 3.3a. Analysis of this circuit yields the transfer function to be:

$$H(s) = \frac{R_2 C_1 C_2 s + C_1}{(R_1 + R_2) C_1 C_2 s + C_1 + C_2}$$

Figure 3.3b shows that this circuit is very similar to the previous two circuits because the magnitude increases as the frequency increases. These circuits ultimately change the ratio of voltage input to output and make the amplitude of the system frequency dependent. As seen from these calculations, all three concepts are very similar and expected to increase the current bandwidth. Tests will be conducted on the three concepts to see which will produce the best results in reality.

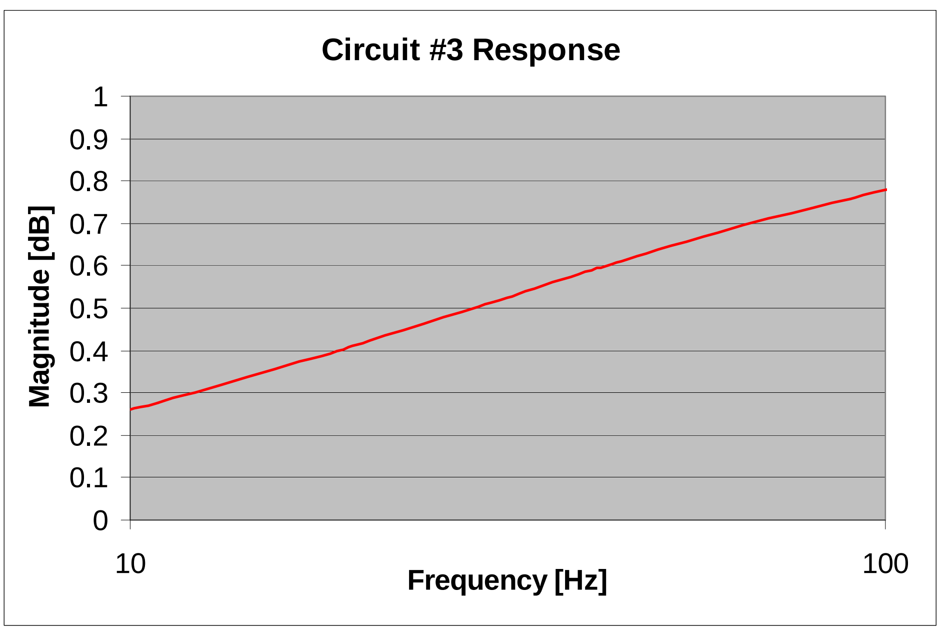


Figure 3.3b: Calculated Frequency Response of Circuit #3

IV. Test Setup and Procedures

Materials

- Compensator
  - Resistors: 10 Ω, 1.2 kΩ, 5.6 kΩ
  - Capacitors: 1 μF, 10 μF, 470 μF
  - Wire
  - Breadboard
- Amplifier Controller
- Nanopositioning Stage
- Function Generator
- Oscilloscope
- Microscope
- Laser Reflectance Microscope
- Dynamic Signal Analyzer

First, the three circuits selected during concept generation were fabricated on a breadboard. One at a time, the output of each circuit was connected to the controller amplifier which was then connected to the nanopositioning stage. The circuit diagram of the amplifier controller circuit is shown in Figure 4a. The figure has a box indicating where the compensator circuits were connected. The gain of the amplifier without the compensator is about 1.454. Figure 4b gives the specifications for the test setup.

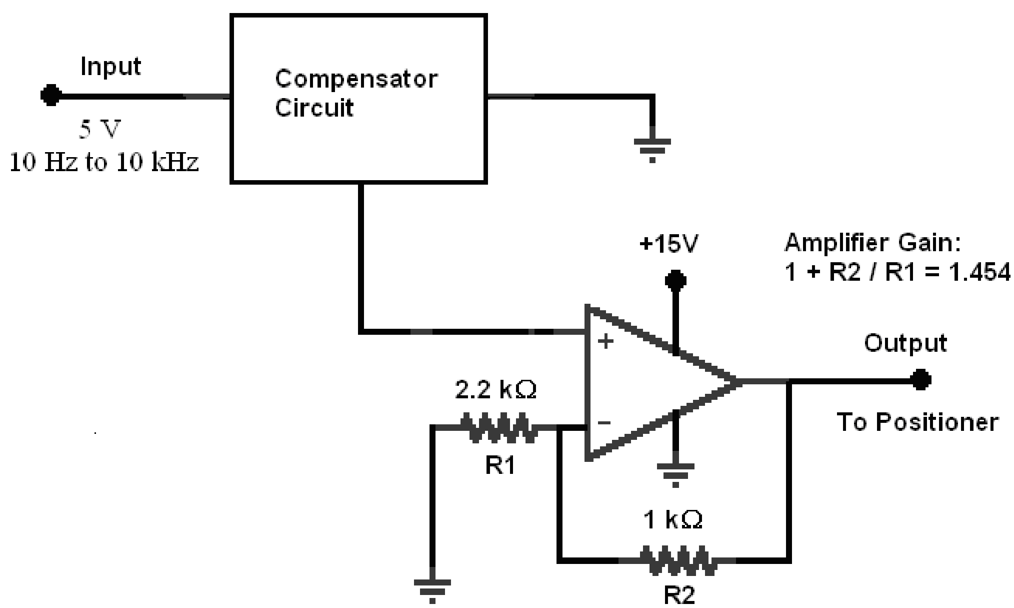


Figure 4a: Amplifier Controller Circuit Diagram

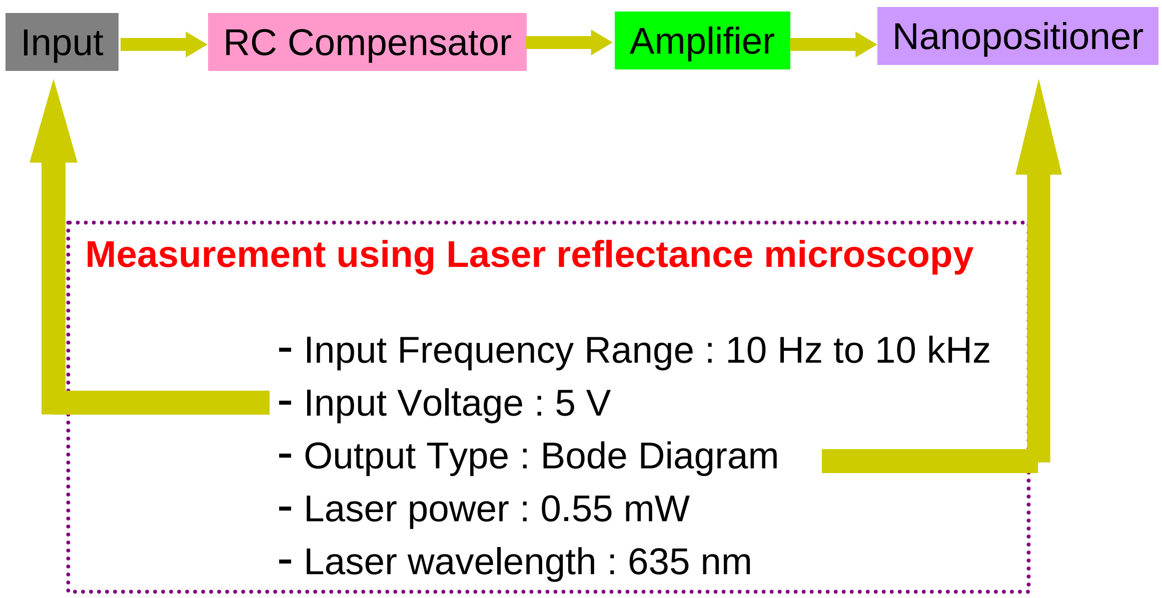


Figure 4b: Test Specifications

A function generator was used to supply the voltage and frequency signal to the input of the circuit, for a range of 10 Hz to 10 kHz. Finally, the frequency responses of each compensator-amplifier controller were measured using the laser reflectance microscope (fixed wavelength of 635 nm and 0.55 mW power) and the dynamic signal analyzer. Figure 4c shows the setup. The stage was placed under the microscope and connected to the test circuit and amplifier for testing. Figure 4d is an image of an oscilloscope and the dynamic signal analyzer. The oscilloscope aided in positioning the laser so that it accurately detected the stage's displacement. The dynamic signal analyzer plotted the frequency response.

Figure 4c: Laser Reflectance Microscope Test Setup

Figure 4d: Oscilloscope and Dynamic Signal Analyzer Measuring Frequency Response

Initial test results revealed that the Concept #2 compensator produced a more uniform response than the other two concepts, for the selected resistor and capacitor values. The other two concepts were abandoned and testing was continued with Concept #2. To improve this circuit further, the values of resistors and capacitors were manipulated, and their effects on the frequency response were evaluated. The RC combinations which produced the best results were then selected for further analysis. All results from the preliminary tests are presented in Appendix C. The two chosen RC combinations for the Concept #2 circuit are shown on the following page.

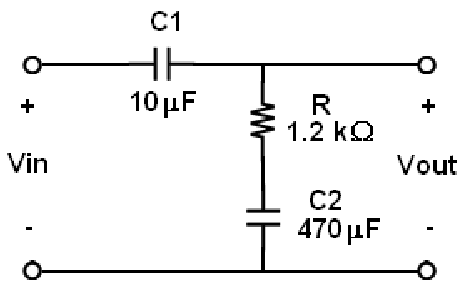


Figure 4e: Circuit Diagram for Final Circuit #1

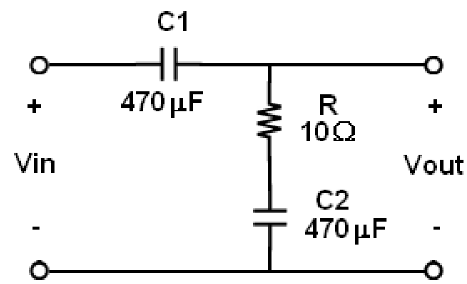


Figure 4f: Circuit Diagram for Final Circuit #2

The first circuit that produced very favorable results is depicted in Figure 4e. This circuit has a 10 µF capacitor at the input and then a 1.2 kΩ resistor and a 470 µF capacitor at the output. With these RC values, the transfer function of the circuit is shown below. Its gain, shown in the plot in Figure 4g, increases about 0.45 dB between 10 Hz and 100 Hz.

$$H(s)= \frac{(5.64\ E\ {-6})\ s + (1\ E\ {-5})}{(5.64\ E\ {-6})\ s + (4.8\ E\ {-4})}$$

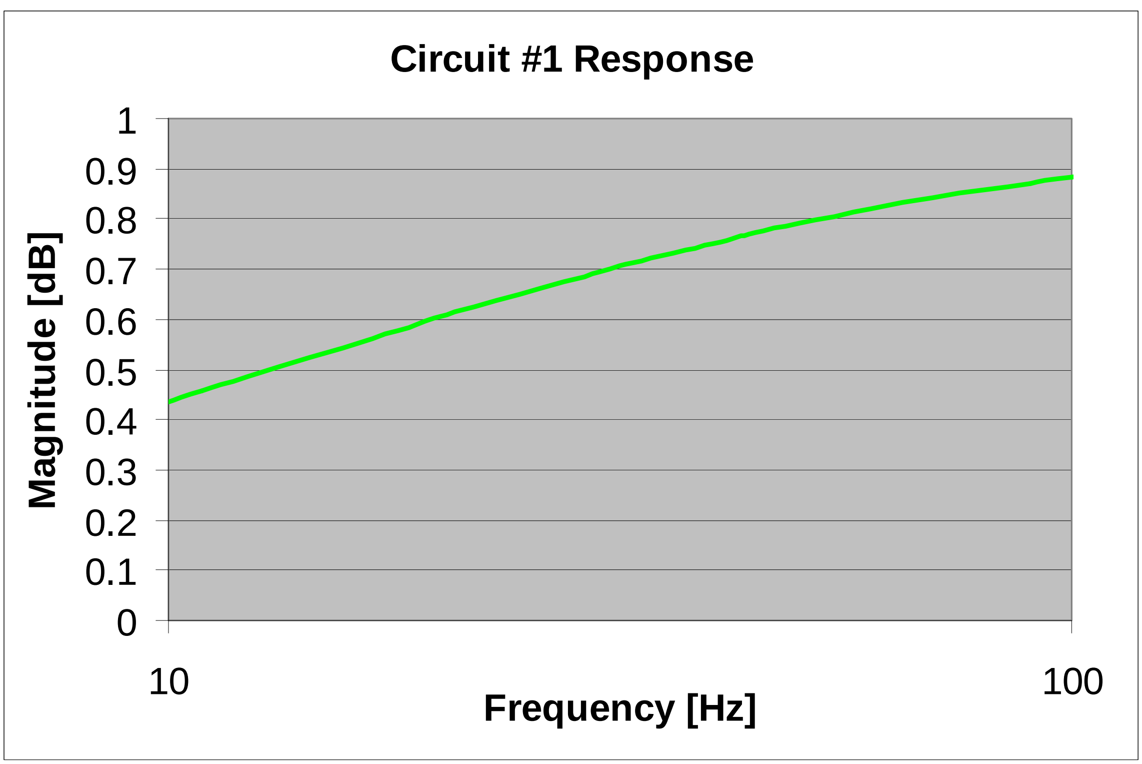


Figure 4g: Transfer Function of Circuit #1 Graphed

The second set of favorable results came from the circuit shown in Figure 4f. After several tests, the capacitor in this circuit at the input was increased to 470 µF and the resistor in the shunt was reduced to 10 Ω. The shunt capacitor remained at 470 µF. Similarly, the transfer function of this circuit is shown below. Its plot, shown in Figure 4h, does not increase as rapidly as the previous; only increasing about 0.25 dB from 10 Hz to 100 Hz.

$$H(s)= \frac{(2.21\ E\ {-6})\ s + (4.7\ E\ {-4})}{(2.21\ E\ {-6})\ s + (9.4\ E\ {-4})}$$

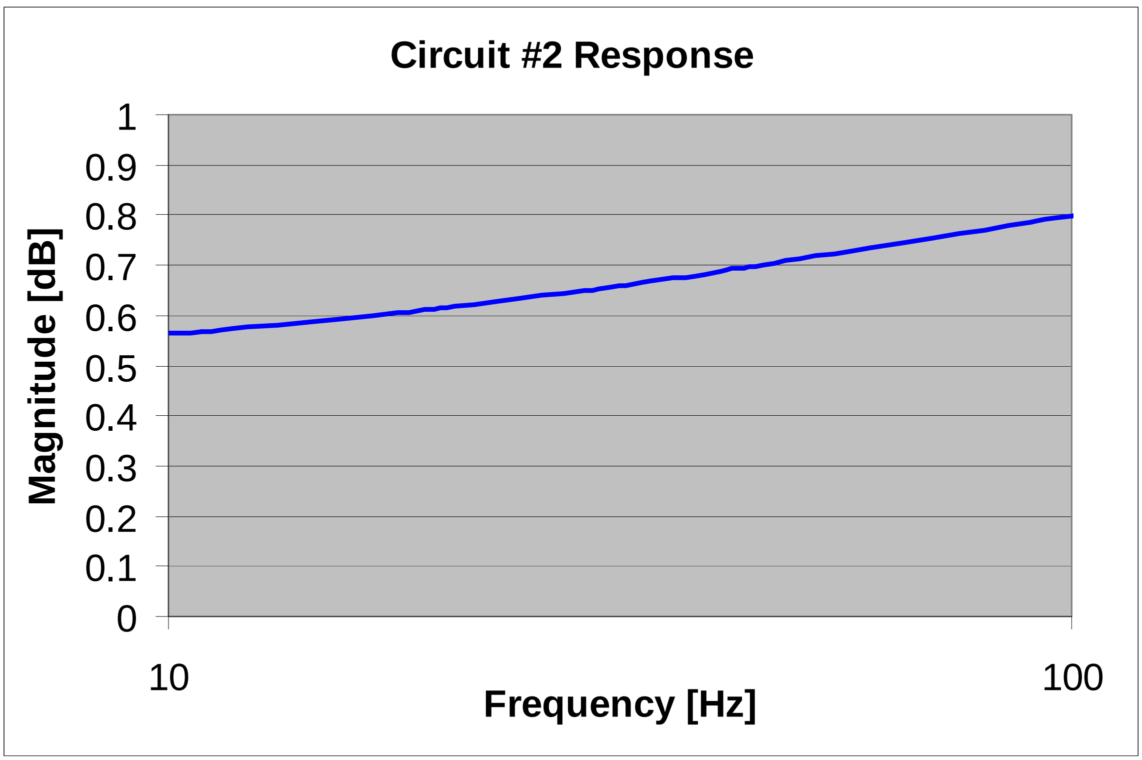


Figure 4h: Transfer Function of Circuit #2 Graphed

The frequency response of the system when compensated by these two circuits was measured again and the results are presented in the following section.

V. Data Results

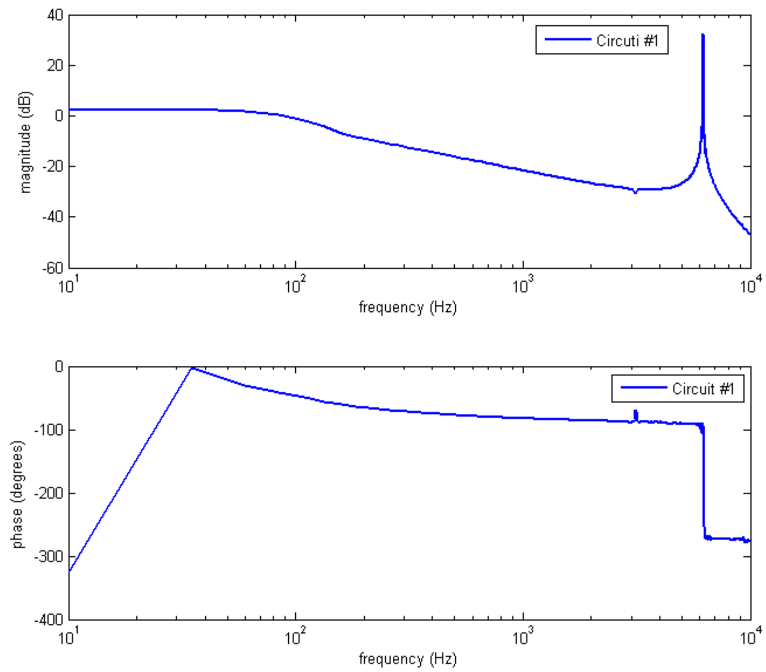


Figure 5a: Bode Plot of Controller with Circuit #1

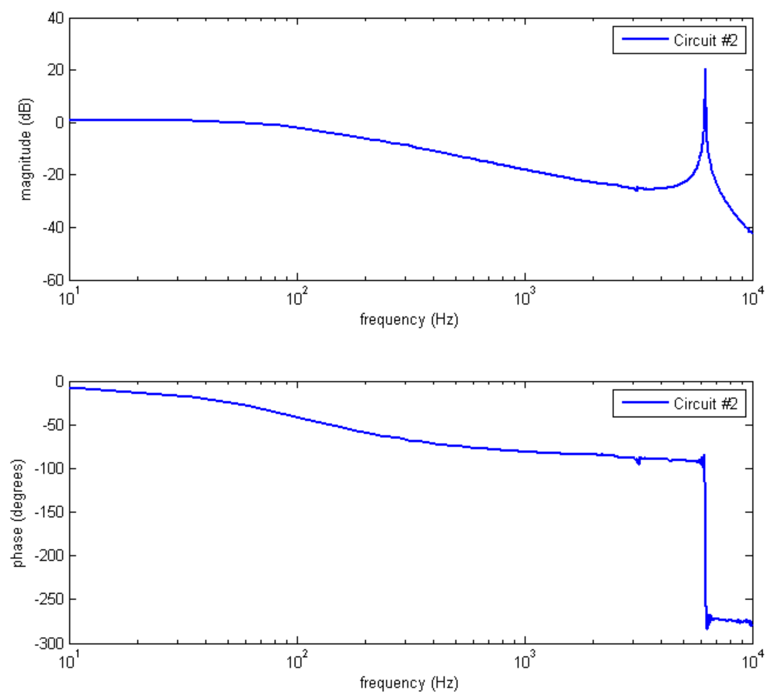


Figure 5b: Bode Plot of Controller with Circuit #2

VI. Data Analysis

The frequency response of the controller with no compensator is shown in Figure 1b. This plot serves as a baseline from which to compare the frequency response of the controller when compensated by the two test circuits. Figure 3 is an enlarged view of the magnitude plot in Figure 1b. The yellow boxes give the coordinates of the initial point and the point where the initial magnitude dropped 3 dB, or the bandwidth. Without any compensator, the actuator bandwidth is just above 41 Hz. The bandwidth is a measure of the frequency range where you can expect your system to be responsive to an input command.

The frequency response of Circuit #1 is shown in Figure 5a. The magnitude plot shows similar behavior to the uncompensated response. Since the initial magnitude has decreased, the frequency at which there is a 3 dB drop is much greater. From the enlarged view, shown in Figure 6a, it is evident that the bandwidth is almost 94 Hz. With this compensator, the bandwidth is more than doubled. This is a significant improvement. However, upon closer review, there is some odd behavior shown from the phase plot of Figure 5a. Between 10 Hz and 35 Hz, the phase angle decreases rapidly. The phase increase is a phase wrap artifact created by the graph scale. This is a large deviation from the steady curve in the uncompensated phase plot. In addition, there is a slight increase in magnitude within this frequency range whereas the uncompensated magnitude plot is constantly decreasing. This is because the DC gain of the compensator circuit is less than 1.

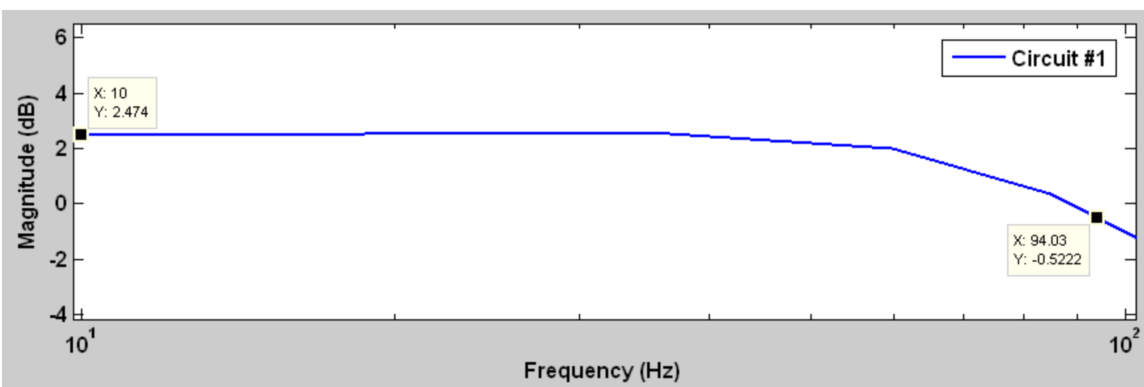


Figure 6a: Enlarged Magnitude Plot with Compensator #1

After changing the capacitor and resistor values of Circuit #1 to get Circuit #2, the frequency response was measured again and the results are shown in Figure 5b. Once again, the overall behavior is very steady and similar to the uncompensated response. However, the initial magnitude has decreased to 1.25 dB, shown in Figure 6b. The bandwidth is shown to be about 97 Hz. Looking at the phase plot in Figure 5b, the phase response is much steadier than the phase response with Circuit #1. In contrast to Circuit #1, the phase plot of Circuit #2 is very similar to that of the uncompensated plot. Also, the magnitude plot constantly decreases instead of slightly increasing as it did with

Circuit #1. Figure 6c shows all three Bode plots graphed together to make these comparisons visible.

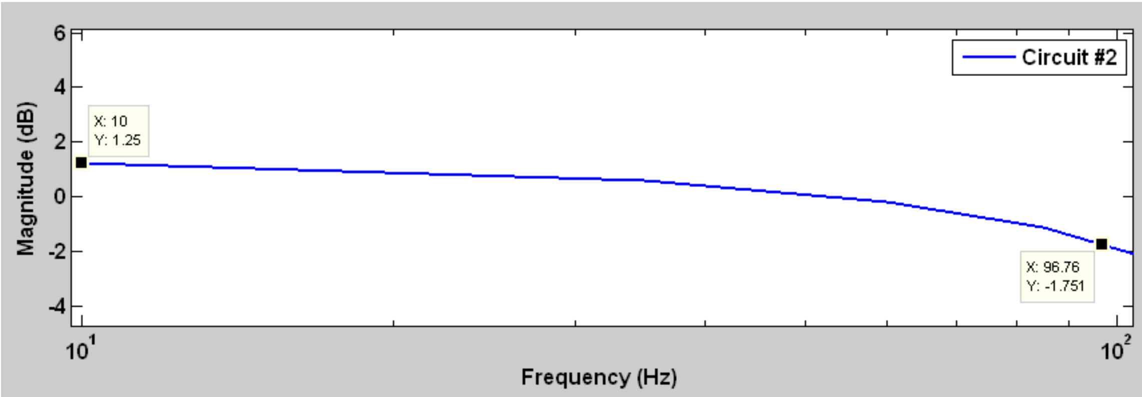


Figure 6b: Enlarged Magnitude Plot with Compensator #2

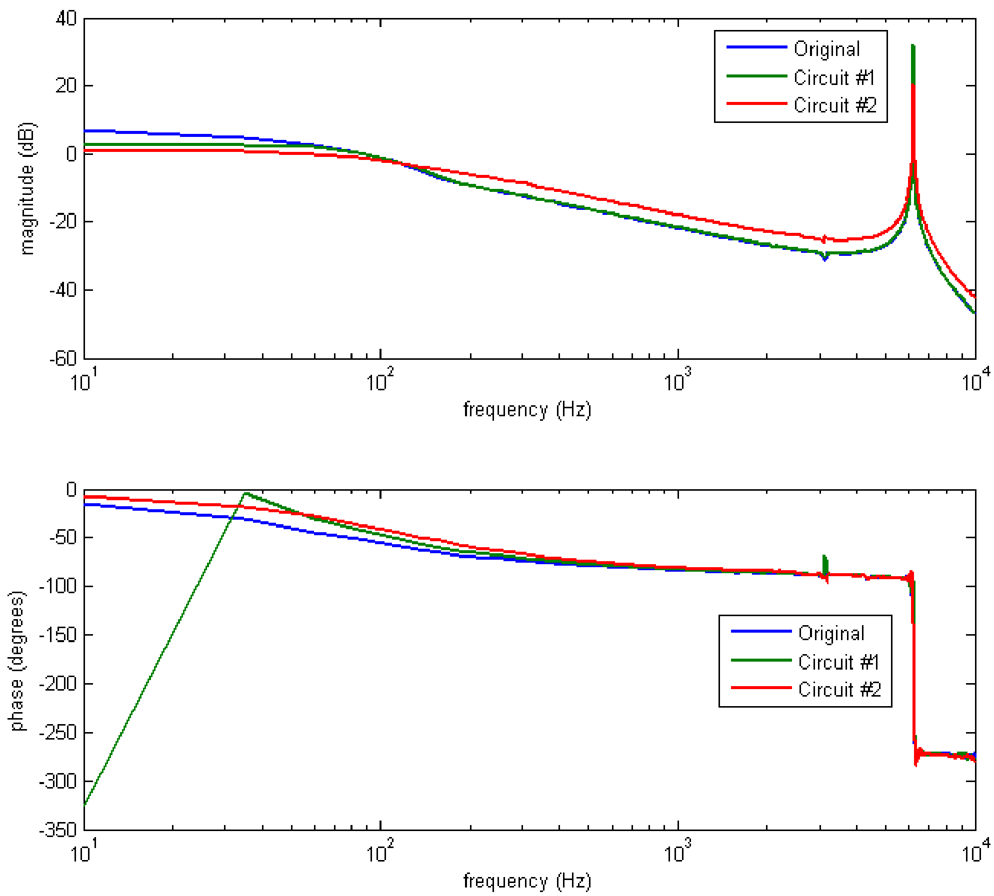


Figure 6c: Bode Plots of Original, Circuit #1, and Circuit #2 Plotted Together

VII. Final Circuit

From the test results, it is evident that Circuit #2 is the more favorable compensator circuit. The frequency response is uniform, and the bandwidth has increased from 41 Hz to about 97 Hz. The amplifier with the addition of this compensator circuit is shown in Figure 7. The red and black clips at the bottom of the image, are the input from the function generator to the circuit. The second pair of clips, on the left, supplies power to the amplifier. Finally, the green wires connect the circuit to the nanopositioning devices which are being viewed under the microscope. In the future, this circuit will be fitted into a fully functional controller.

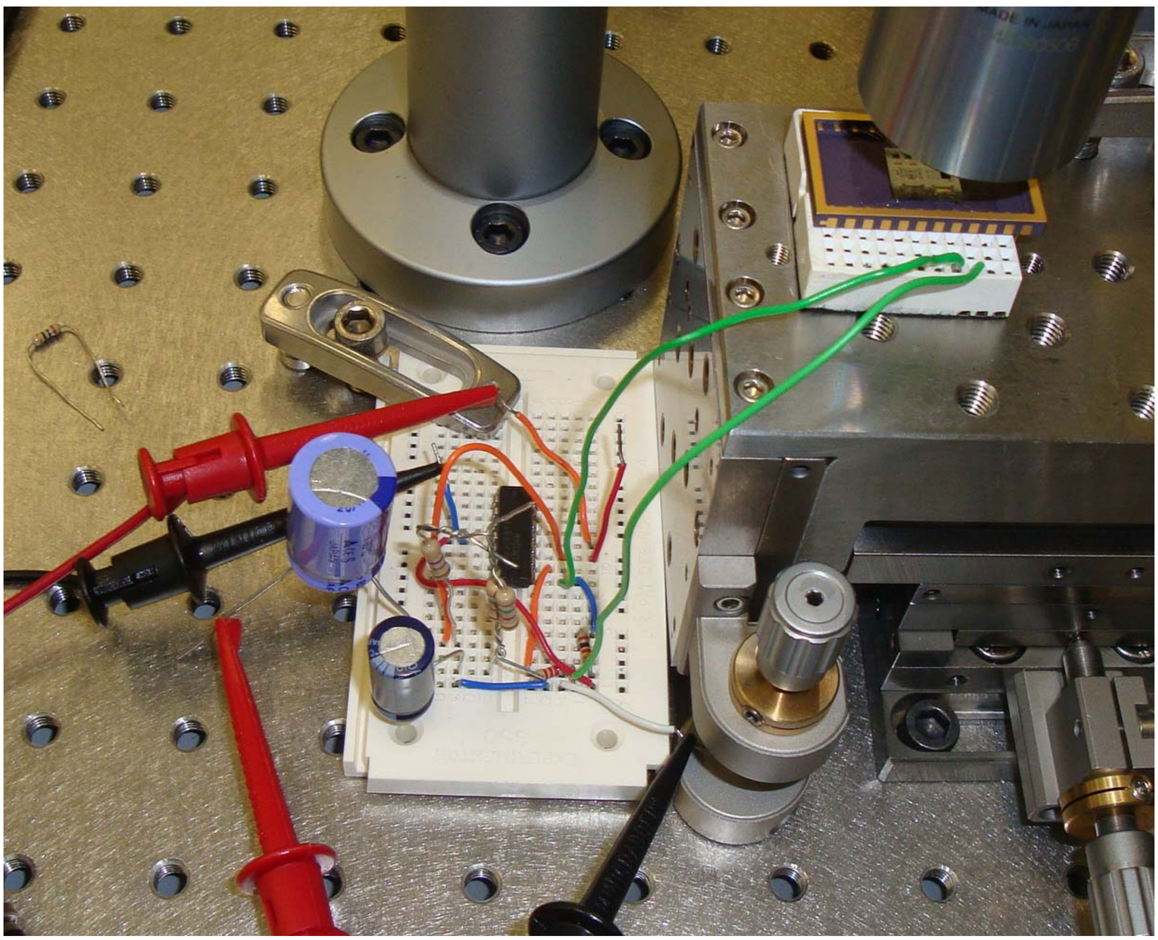


Figure 7: Amplifier with Final Compensator

VIII. Conclusions

The goal of this project was to increase the actuator bandwidth of the nanopostioning stage and ultimately improve its frequency response. This report has described the process in which RC compensators were designed and tested until a beneficial compensator was determined. First, research was conducted and utilized to generate several circuit designs. Basic circuit analysis was used to find the transfer function of each circuit and then the most favorable designs were selected to be built and tested. From the results of the preliminary tests, the best circuit configuration was found and then its RC values were manipulated until the compensator performed at its highest potential. The best results were taken and analyzed. Ultimately, it was determined that Circuit #2, shown in Figure 4f, is the configuration that produced ideal results. The addition of this compensator to the current controller increased the actuator bandwidth from 41 Hz to almost 97 Hz. Although the compensator caused the amplifier to output less voltage, the resulting response was more uniform which will make calibration for a closed loop control system much simpler. Additionally, the drop in voltage can be easily corrected by simply increasing the gain of the amplifier circuit. Thus, the compensator provides a simple tool to reshape the dynamic response of the nanopositioner, and in the future, both the compensator and the amplifier will be embedded into the die.

Appendix A: Definitions

Bandwidth: The difference between the upper and lower cutoff frequencies of, for example, a filter, and is typically measured in hertz [1].

Compensator: A component in a control system that improves an undesirable frequency response in a feedback and control system [17].

Electronic Filters: Electronic circuits which perform signal processing functions, specifically intended to remove unwanted signal components and/or enhance wanted ones [11].

Frequency Response: The measure of any system's spectrum response at the output to a signal of varying frequency (but constant amplitude) at its input [13].

MEMS: "Microelectromechanical systems" is the technology of the very small, and merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are made up of components between 1 to 100 micrometers in size. MEMS devices generally range in size from 20 micrometers to a millimeter [20].

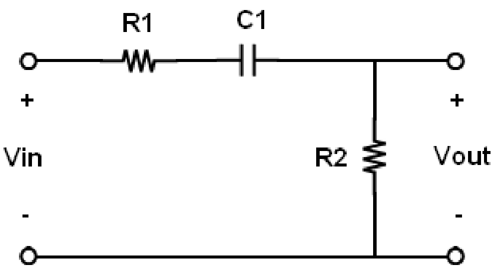
MEMS Thermal Actuator: A micromechanical device that typically generates motion by thermal expansion amplification. A small amount of thermal expansion of one part of the device translates to a large amount of deflection of the overall device [19].

Nanopositioner: A device used for precision movement and manipulation at the nano scale [9].

Transfer Function: A mathematical representation of the relation between the input and output of a (linear time-invariant) system [22].

Appendix B: Calculations

Circuit Concept #1



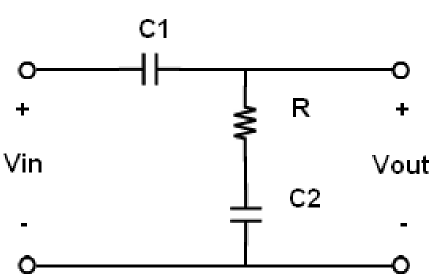
$$Z_c = \frac{1}{sC} \qquad R_{eq} = R_1 + Z_c = R_1 + \frac{1}{sC}$$

$$V_{out} = \frac{R_2}{R_2 + R_{eq}} V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{R_2}{R_2 + R_1 + \frac{1}{sC}} \cdot \frac{(sC)}{(sC)} = \frac{R_2 Cs}{(R_1 + R_2)Cs + 1}$$

$$H(s) = \frac{R_2 Cs}{(R_1 + R_2)Cs + 1}$$

Circuit Concept #2



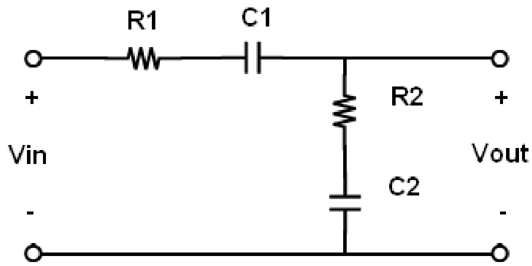
$$Z_c = \frac{1}{sC} \qquad R_{eq} = R + \frac{1}{sC_2}$$

$$V_{out} = \frac{R_{eq}}{R_{eq} + \frac{1}{sC_1}} V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{R + \frac{1}{sC_2}}{R + \frac{1}{sC_2} + \frac{1}{sC_1}} = \frac{R + \frac{1}{sC_2}}{R + \frac{C_1 + C_2}{sC_1C_2}} \cdot \frac{(sC_1C_2)}{(sC_1C_2)}$$

$$H(s) = \frac{RC_1C_2 s + C_1}{RC_1C_2 s + C_1 + C_2}$$

Circuit Concept #3



$$Zc = \frac{1}{sC}$$

$$Req_1 = R_1 + \frac{1}{sC_1}$$

$$Req_2 = R_2 + \frac{1}{sC_2}$$

$$Vout = \frac{Req_2}{Req_2 + Req_1} Vin$$

$$\frac{Vout}{Vin} = \frac{R_2 + \frac{1}{sC_2}}{R_2 + \frac{1}{sC_2} + R_1 + \frac{1}{sC_1}} = \frac{R_2 + \frac{1}{sC_2}}{R_1 + R_2 + \frac{C_1 + C_2}{sC_1C_2}} \frac{\bullet (sC_1C_2)}{\bullet (sC_1C_2)}$$

$$H(s) = \frac{R_2 C_1 C_2 s + C_1}{(R_1 + R_2) C_1 C_2 s + C_1 + C_2}$$

Appendix C: Preliminary Test Results

C.1. Trial 1: Circuit Concept #1

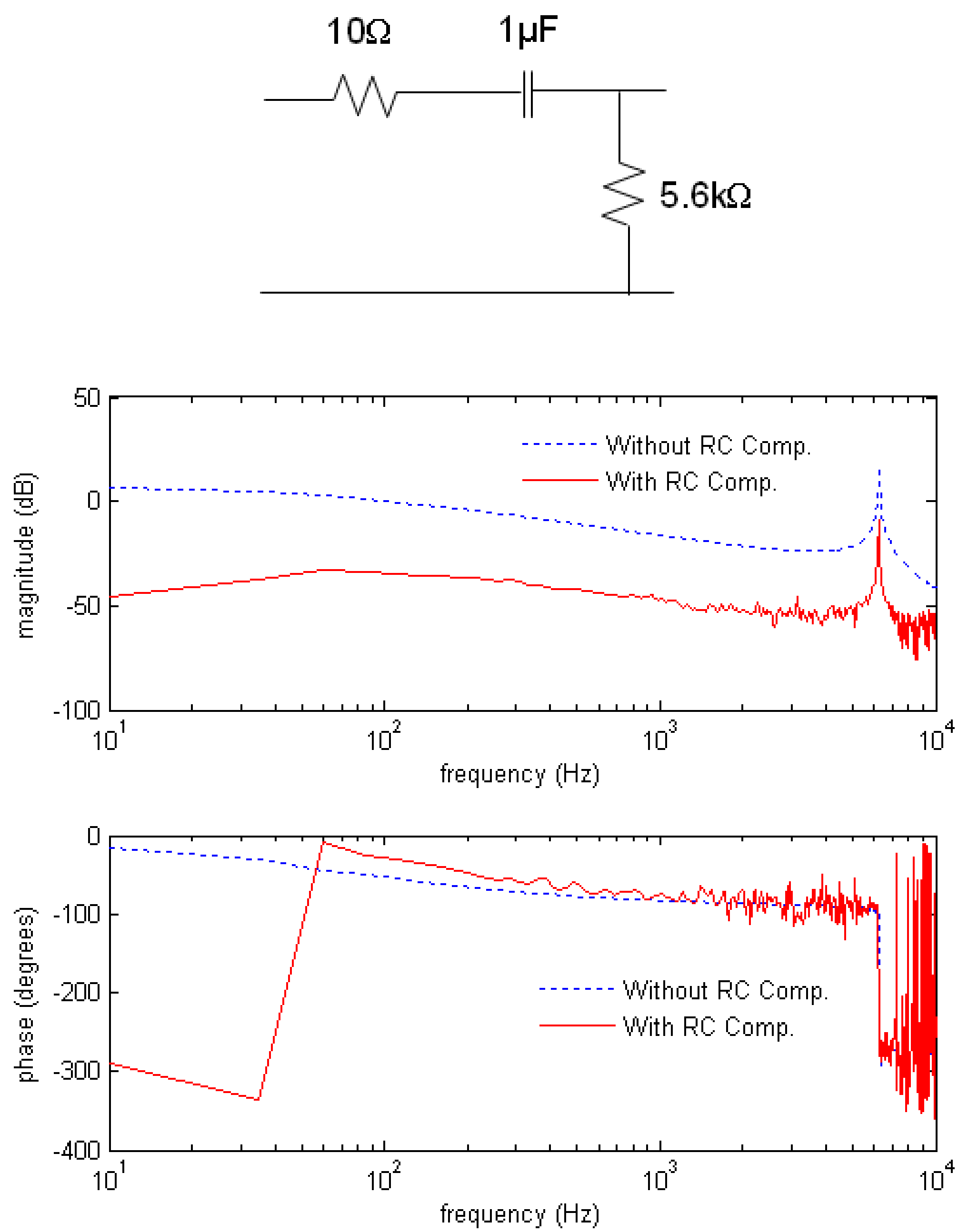


Figure C.1: Trial 1 Circuit Diagram and Test Results

C.2. Trial 2: Circuit Concept #3

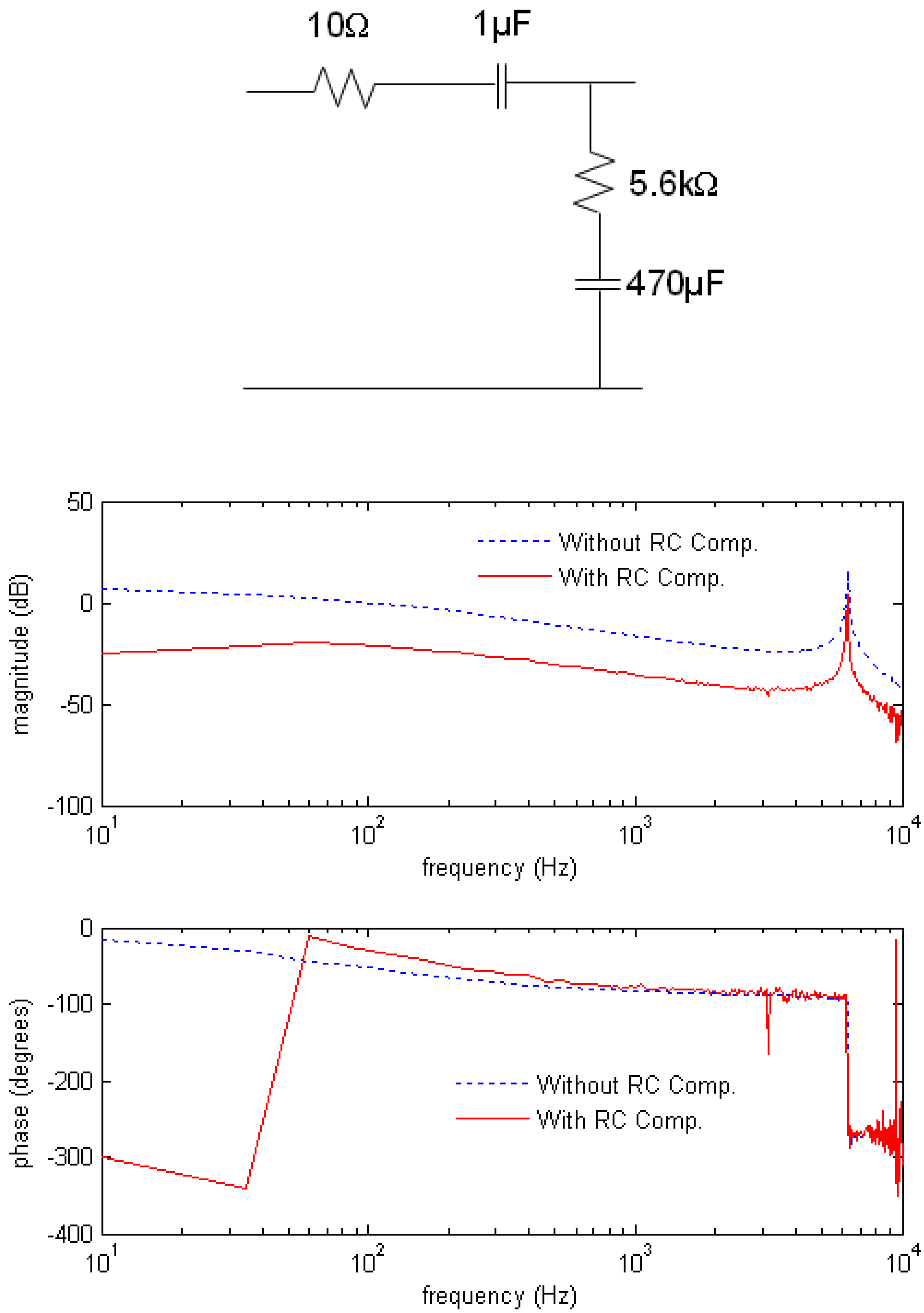


Figure C.2: Trial 2 Circuit Diagram and Test Results

C.3. Trial 3: Original Circuit Concept #2

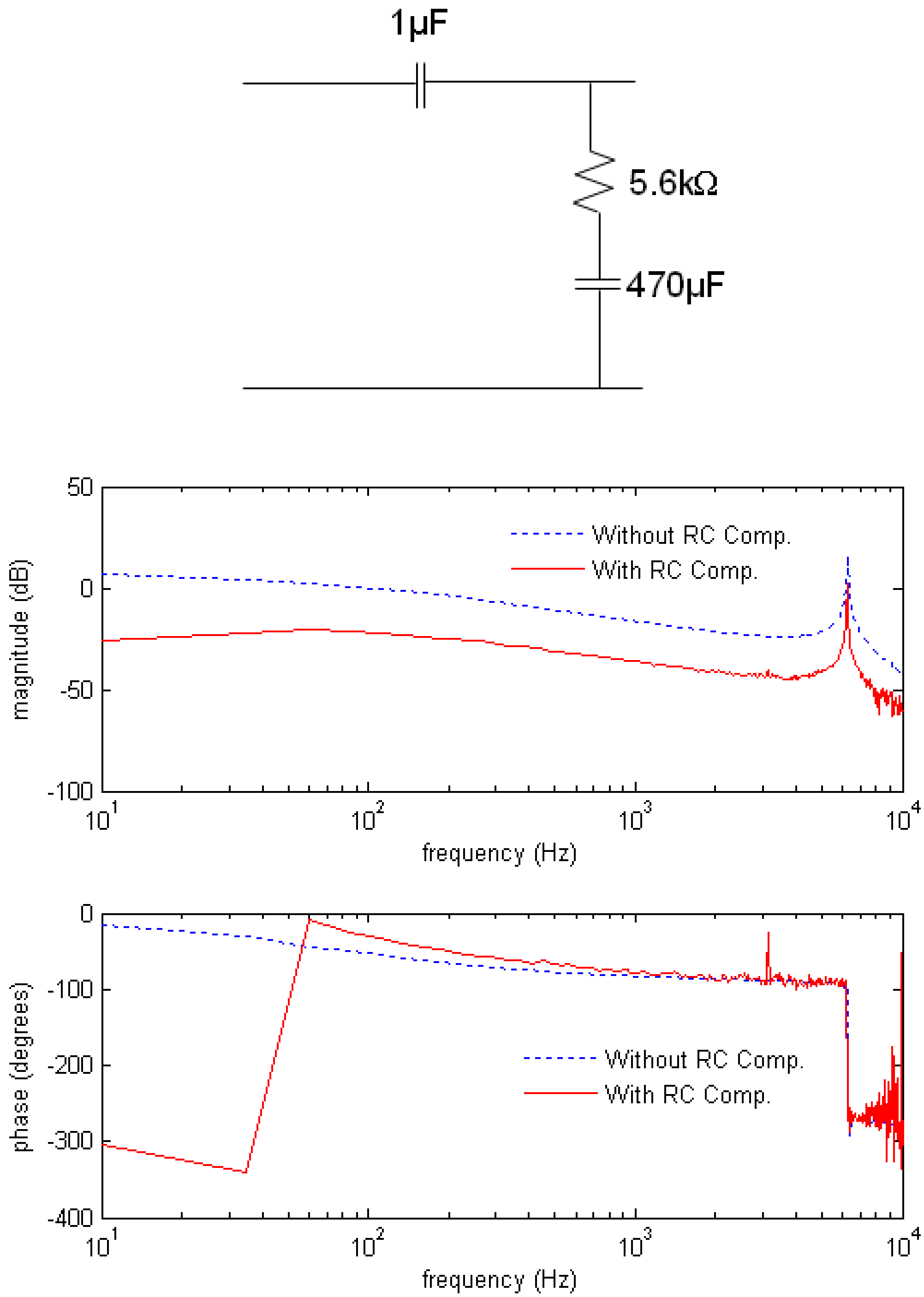


Figure C.3: Trial 3 Circuit Diagram and Test Results

C.4. Trial 4: Concept #2 with 10μF Capacitor

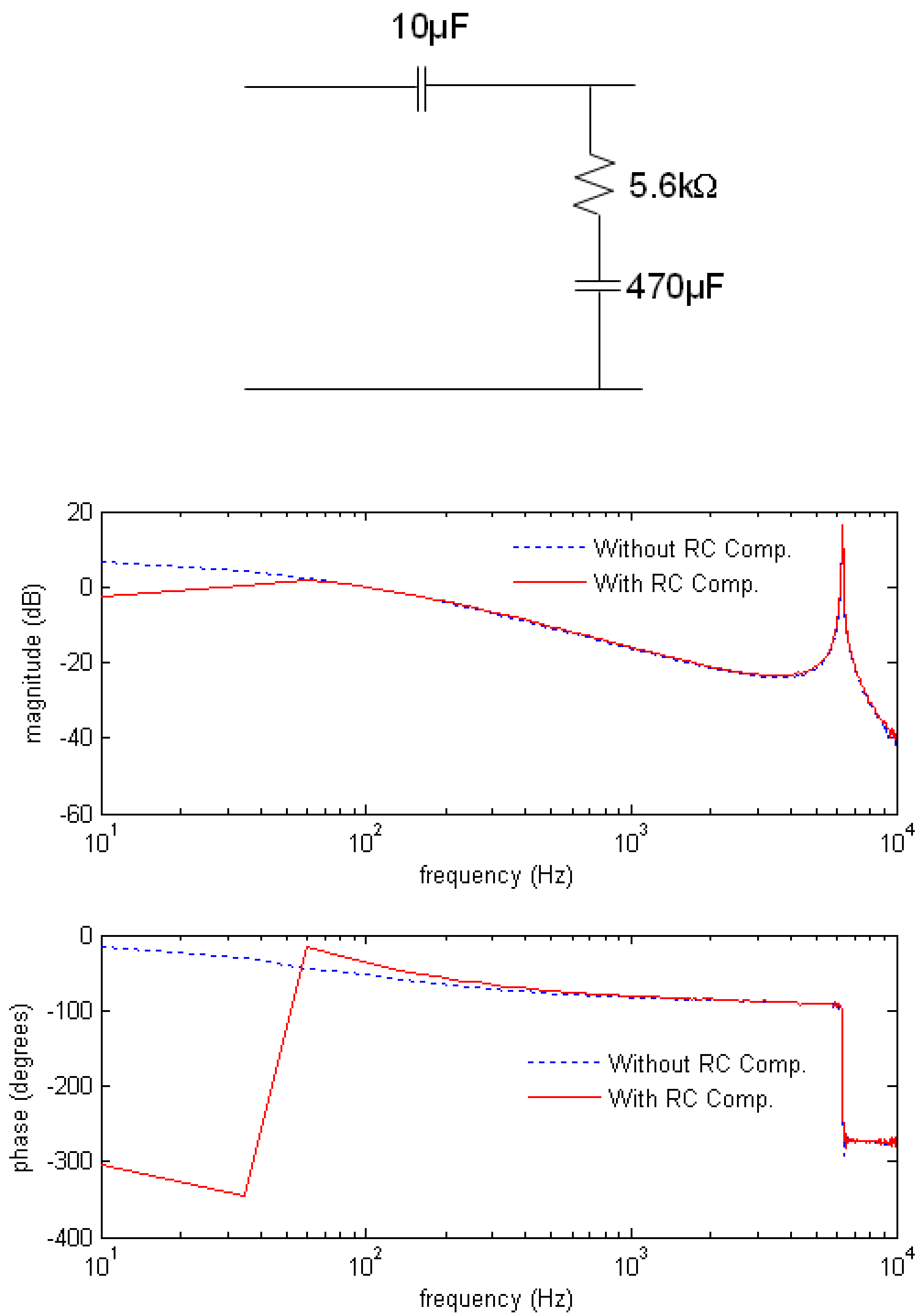


Figure C.4: Trial 4 Circuit Diagram and Test Results

C.5. Trial 5: Concept #2 with 20 μF Capacitor

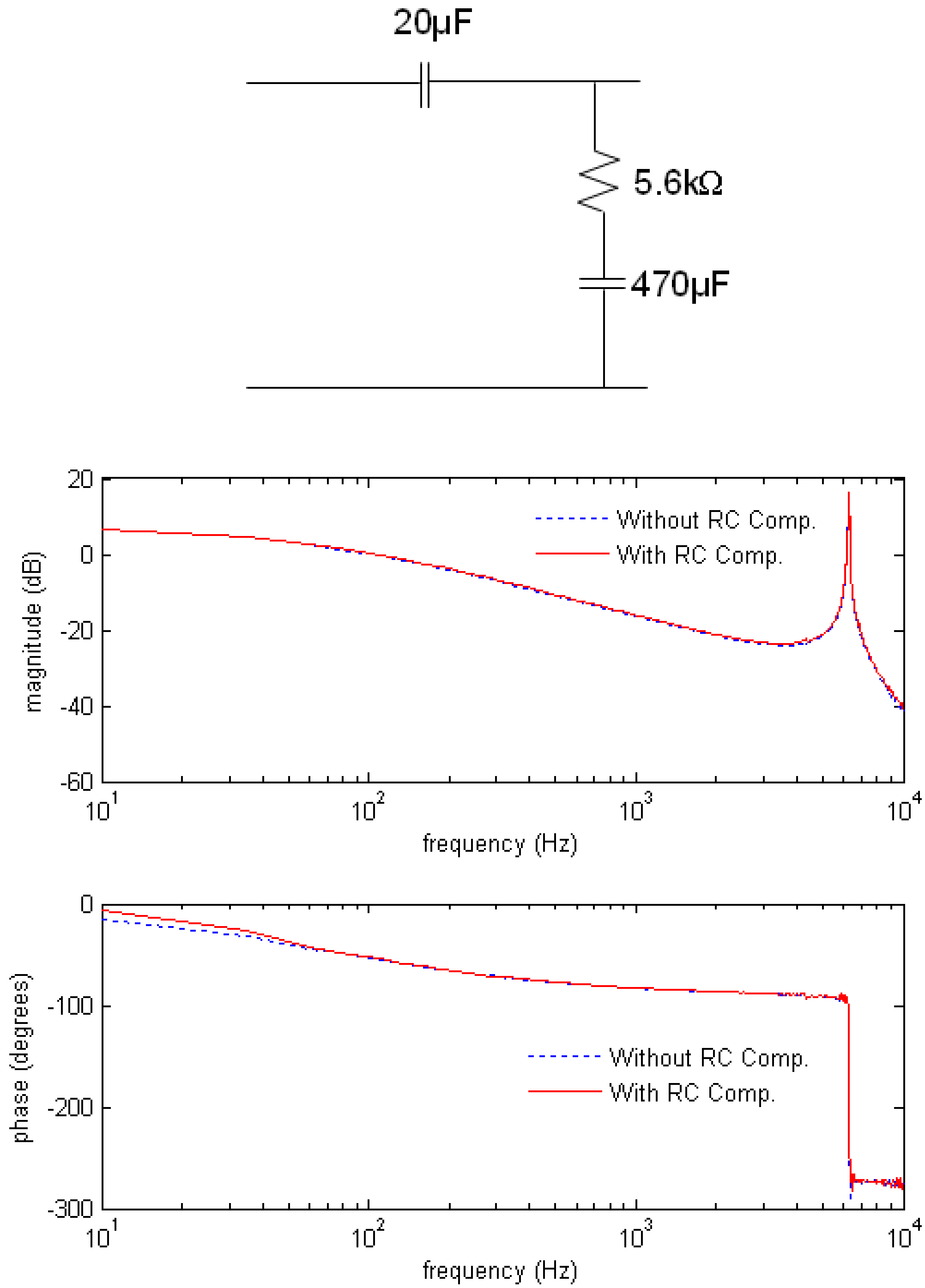


Figure C.5: Trial 5 Circuit Diagram and Test Results

C.6. Trial 6: Concept #2 with 20μF Capacitor and 1kΩ Resistor

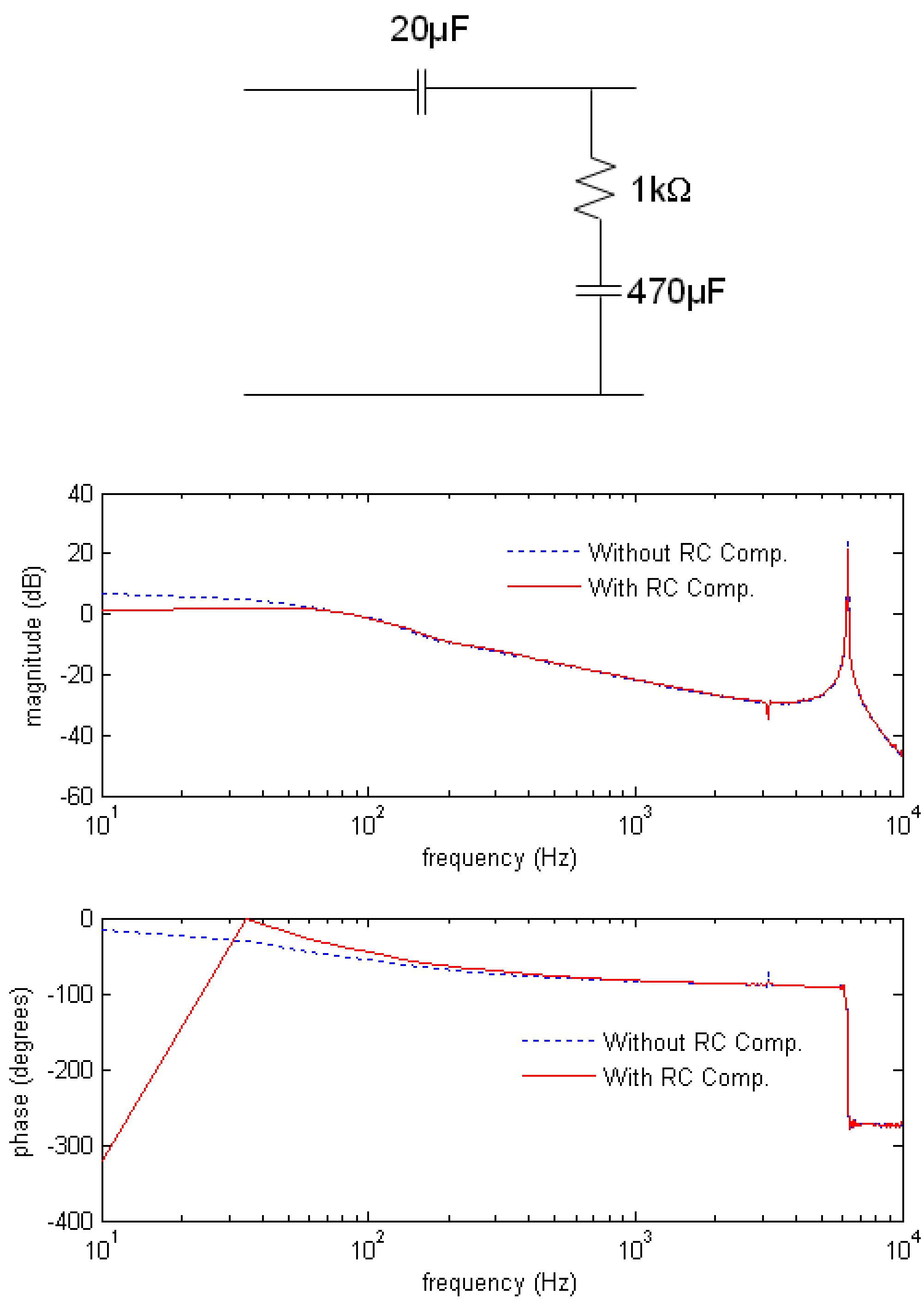


Figure C.6: Trial 6 Circuit Diagram and Test Results

References

[1] "Bandwidth." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/Bandwidth>.

[2] Beale, Guy. "Phase Lead Compensator Design Using Bode Plots". 18 June 2008 <http://teal.gmu.edu/~gbeale/ece_421/comp_freq_lead.pdf>.

[3] Bérgna, S., Dagalakis, N.G., and Gorman, J.J.. "Design and modeling of thermally actuated MEMS nanopositioners," *ASME International Mechanical Engineering Congress and Exposition*, Orlando, FL, 2005, IMECE2005-82158.

[4] Bolton, W.. Instrumentation and control Systems. Newnes (An Imprint of Elsevier), 2004.

[5] Dagalakis, N.G., and Gorman, J.. "Probe-based micro-scale manipulation and assembly using force feedback," *International Conference on Robotics and Remote Systems for Hazardous Environments*, Salt Lake City, UT, 2006, pp. 621-628.

[6] Dagalakis, N.G., Gorman, J.J., Kang, B.H, and Wen, J.T.-Y.. "Analysis and design of parallel mechanisms with flexure joints," *IEEE Transactions on Robotics*, vol. 21, pp. 1179-1185, 2005.

[7] Dagalakis, N.G., Gorman, J.J., Kang, B.H, and Wen, J.T.-Y.. "Design optimization for a parallel MEMS mechanism with flexure joints," *ASME Design Engineering Technical Conferences*, Salt Lake City, UT, 2004, DETC2004/MECH-57455.

[8] Dagalakis, N.G., Gorman, J., and Kim, Y-S.. "Control of MEMS Nanopositioners with Nano-Scale Resolution," Proceedings of the ASME International Mechanical Engineering Conference and Exhibition, 2006.

[9] Dagalakis, N.G., Gorman, J., Kim, Y-S., and Vladar, A.E.. "Design of an On-Chip Micro-Scale Nanoassembly System," Proceedings of the International Symposium on Nanomanufacturing, 2006.

[10] Dukkipati, Rao. Control Systems. Harrow, U.K.: Alpha Science International Ltd., 2005.

[11] "Electronic Filter." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/Electronic_filter>.

[12] Fortman, Thomas E., and Hitz Konrad L.. An Introduction to Linear Control Systems. New York: Marcel Dekker INC, 1977.

[13] "Frequency Response." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/Frequency_response>.

[14] Jamshidi, M., and Malek-Zavarej M.. Linear Control Systems: A Computer Aided Approach. Pergamen Press, 1986.

[15] "Lag Compensators". 18 June 2008 <http://www.facstaff.bucknell.edu/mastascu/econtrolhtml/Comp/Comp2.htm#BodePlotEffects>.

[16] "Lead Compensators". 18 June 2008 <http://www.facstaff.bucknell.edu/mastascu/econtrolhtml/Comp/Comp3.htm>.

[17] "Lead-Lag Compensator." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/Lead-lag_compensator>.

[18] Lurie, B.J., Enright, P.J., "Classical feedback control with MATLAB," Marcel Dekker Publisher, 2000.

[19] "MEMS Thermal Actuator." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/MEMS_thermal_actuator>.

[20] "Microelectromechanical Systems." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/MEMS>.

[21] Smetana, Frederick O.. Introduction to the control of Dynamic Systems. AIAA Education Series, 1994.

[22] "Transfer Function." Wikipedia. 19 June 2008 <http://en.wikipedia.org/wiki/Transfer_function>