

## 6.302 Feedback Systems

Spring Term 2007  
Thermal Design Problem

Issued : April 20, 2007  
Due : Friday, May 11, 2007

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### Introduction

This lab gives you the opportunity to evaluate the dynamics of a temperature control system and design a compensator for it. The system that you will investigate is patterned on one that was developed at Lincoln Laboratory to control the temperature of a laser diode that is part of a space-based optical-communication experiment.

The Lincoln Lab system has demonstrated long-term temperature stability within  $100\mu^{\circ}C$ . Your system has a somewhat higher noise floor, primarily because the control circuitry has been simplified as compared with the original system.

This type of system can be used in any application that requires precise temperature control. One possibility involves stabilizing the operating temperature of inertial measurement components such as gyroscopes.

For this lab, you will need to check out a proto-board from the fifth floor equipment desk (38-501). You will need your parts box from 6.002. If you have lost your parts box (or never had one,) make a list of the parts that you need after you design your compensator, and ask at the desk for them.

There is a non-trivial amount of work to be done for this lab. Please start early.

### Experimental Configuration

Important structural features of the thermal system are shown in Figure 1. A functional block diagram of the temperature control system is shown in Figure 2.

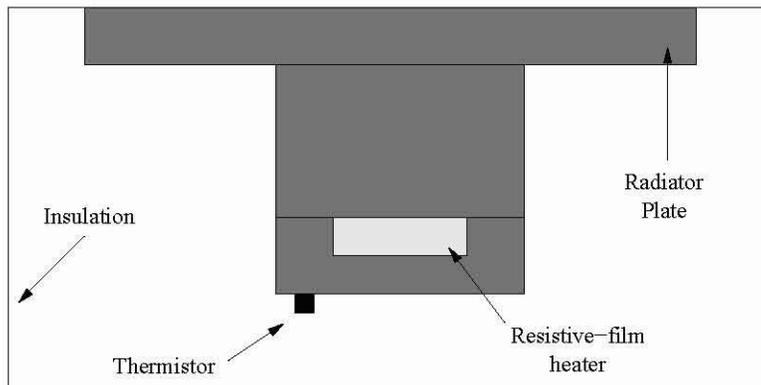
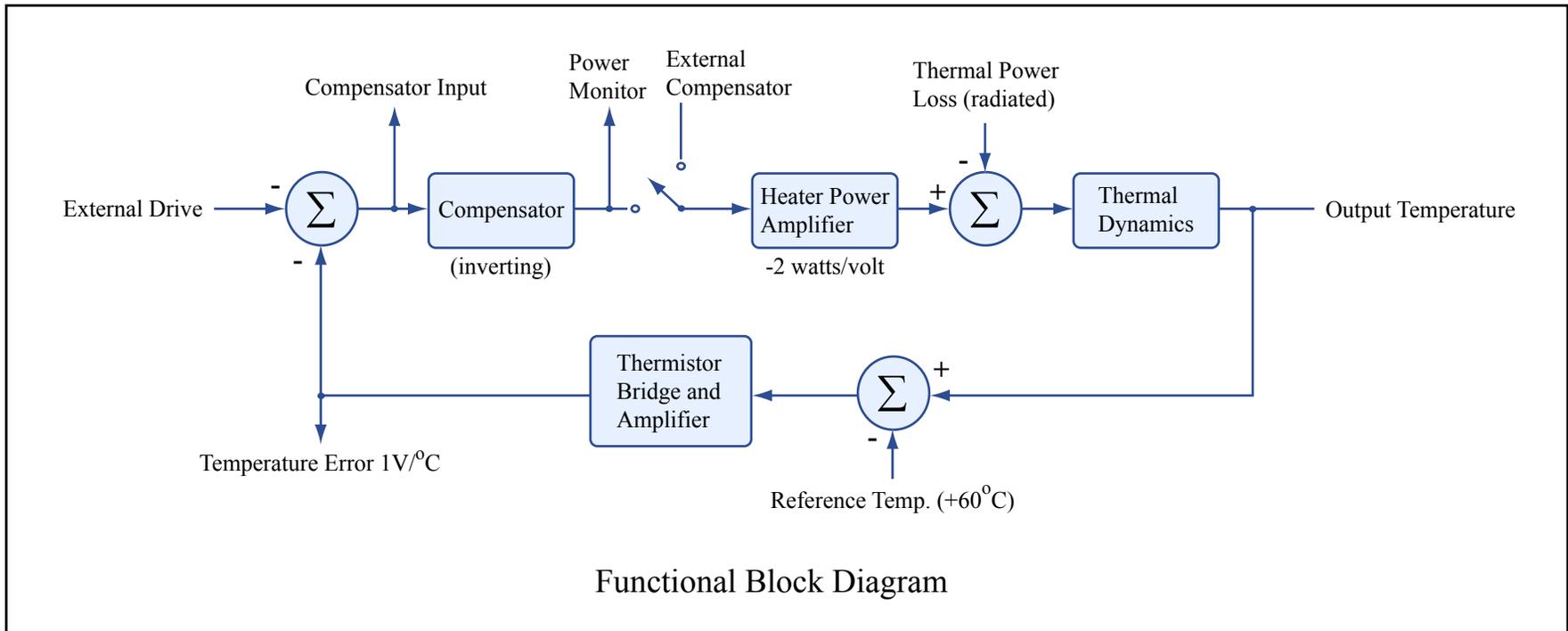


Figure 1: Thermal Structure

The temperature of the controlled surface of the thermal structure is sensed with a device whose resistance is a function of temperature. This device is called a thermistor. This thermistor forms one leg of a 4 element bridge. The bridge null temperature has been set to approximately  $60^{\circ}C$ , and this value is the system reference temperature. A differential amplifier connected to the bridge provides a linearized output of  $1V/^{\circ}C$  of temperature error. This signal is available externally to enable you to measure the dynamics of



Functional Block Diagram

Figure by MIT OpenCourseWare.

the thermal system. Provision to add an input to the error signal is also available. This test input is also used to evaluate thermal dynamics.

The sum of the error signal and the test signal provide the input to the system compensation amplifier. The input and output points of the compensator are available along with a switch that disconnects the internal compensation amplifier. This combination allows you to use the compensator that you designed to close the loop.

The output of the compensator is applied to a power amplifier that drives a heater located on the opposite surface of the plate on which the thermistor is mounted. The power amplifier is designed so that the heater power is linearly proportional to the voltage applied to its input. This type of amplifier is required since temperature and power are linearly related in thermal systems.

The voltage at the power amplifier input is also available for use in evaluating loop dynamics. The scale factor that relates the voltage monitored to heater power is -2 watt/volt. Note that this monitor voltage is valid only when the internal compensation is being used. However, the scale factor of -2 watt/volt remains true when using external compensation.

The thermal system loses power constantly through the uninsulated radiator plate. Since the ambient temperature and the temperature of the thermal structure remain essentially constant, this heat loss is constant. The net power applied to the thermal structure is the difference between the power delivered by the heater and the power lost through the radiator. The power lost via the radiator allows the system to either raise or lower temperature using only a controlled heater.

## Prelab

1. Explain why the compensator in the block diagram on the next page has to be inverting.
2. Consider the circuit in Figure 3.

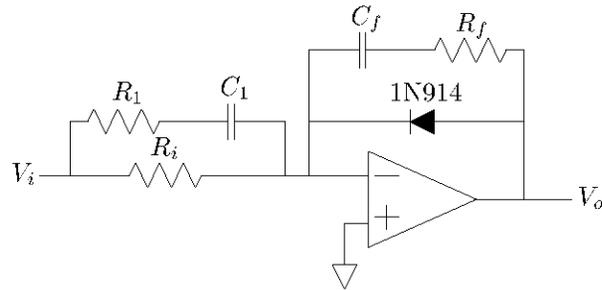


Figure 3: One possible compensator topology.

Ignoring the diode, determine the transfer function  $\frac{V_o(s)}{V_i(s)}$ . Use the form  $(\tau s + 1)$  for poles and zeros. What purpose does the diode serve?

3. Go into lab and do the “Initial Measurements” section, measuring the open-loop behavior of the thermal system. Turn in a MATLAB Bode plot of your data.
4. (Optional) Explain how to design a heater power amplifier such that output power is linearly related to input voltage. If you have had 6.301, draw the circuit schematic.

## Laboratory Setup

We will attempt to have at least three (3) complete, identical thermal systems available in the laboratory at all times. At least one of these will be connected to a signal generator and storage oscilloscope so that you can measure the relatively slow transient response of the system. A separate system is permanently connected to a dynamic analyzer that allows you to measure the transfer function of the thermal system.

NOTE: You should not change any of the connections in the dynamic analyzer configuration. Additionally, you should not change any of the connections in the step response setup until you are ready to try out your compensator.

The thermal system takes about 30 minutes following turn on to stabilize, and thus will be left running during normal laboratory hours. *Do not turn off the system!* If you are concerned that a system is not stabilized or not operating properly, check the voltage at the Power Monitor BNC connector. If this voltage is not in the range of -0.5 to 5V, something is wrong.

## Caution

The radiator plate must face upward during operation, and normally is at about  $+60^\circ$ . While this temperature is not dangerously hot in short doses, you would not want to touch the plate for very long. Abnormal operation (such as putting a negative voltage of more than a few volts on the external compensation connector, or circuit failure) can result in dangerously high plate temperatures. The plate will be located toward the rear of the lab bench, and there is no reason for you to touch it. Do not put anything on top of it!

## Initial Measurements

It is difficult to experimentally evaluate the open-loop performance of this system. This is a complication shared by many feedback systems, since keeping them in the linear region without feedback is generally difficult. We have included compensation in our electronics so that you can make your measurements with the loop closed. While our compensation does stabilize the system, the performance which it achieves is extremely sluggish when compared with the ultimate system capability.

First, measure the closed-loop step response between the External Drive and the Temperature Error points. Note from the block diagram (Figure 2) that the feedback loop for this measurement has unity gain in the feedback path. You should adjust the amplitude of the low frequency square wave which provides the steps so that the system stays in the linear region. You can check the performance of the system by observing the Power Monitor point. Under normal conditions, the voltage at this point will be -1.5 to -3V, corresponding to 3 to 6 watts of heater power. Adjust the square wave amplitude to give peak deviations from this operating point of about  $\pm 1V$  ( $\pm 2W$ ). The power monitor voltage must remain negative at all times to insure linear operation. Your objective is to get a large enough signal as to allow accurate measurements while maintaining linearity.

Assume that the system response can be accurately represented as that of a complex pole pair. Estimate parameters  $\omega_n$  and  $\zeta$  for the approximating pole pair. Also estimate the closed loop bandwidth ( $\omega_h$ ) for this configuration from your step response measurement.

Next use the HP 3562A Dynamic Analyzer to measure the transfer function from heater power to temperature error. Note that this transfer function includes all of your elements in the loop except for the compensator, and thus contains all of the information you need to successfully design your compensator.

As mentioned earlier, the connections between the thermal system and the dynamic analyzer are in place and must not be changed. Channel 1 on the analyzer is connected to the power amplifier input  $P(t)$ , and channel 2 is connected to the temperature error output  $T(t)$ . The analyzer drives the system from its internal source and characterizes the transfer function between channel 1 and channel 2, considering channel 1 to be the input to the system under test.

The analyzer is a very capable and correspondingly complex instrument. In order to simplify its use in lab, we have pre-programmed the necessary test steps. There are two options which you may choose in

testing the thermal transfer function. One uses random noise for the drive signal, the other uses a swept sine wave.

These two programs are accessed by pushing the AUTO SEQ key which is located on the upper right portion of the front panel. After you push this key, labels will appear next to the row of soft-keys along the right hand edge of the analyzer CRT. The two upper keys are labeled 6.302 RANDOM and 6.302 SWEEP, corresponding to random noise testing and swept sine testing, respectively. You may measure the transfer function using either one, or both if you like. The test is started by pushing the appropriate soft-key, and each requires about two minutes to complete.

In the random mode, two transfer function samples are averaged in order to reduce the effects of noise. No data appears until the first measurement is complete, at which point a field in the upper part of the CRT will indicate 1 AVG. When the second measurement is complete, the field will indicate 2 AVG. In the swept sine mode, the sweep starts at low frequencies, and data points are displayed as they are measured. In both modes, the test signals may be observed on channels 1 and 2 of the oscilloscope.

The measurements cover the frequency range 0.1 Hz to 10 Hz, as this is the region of interest. Because we are measuring low frequency behavior, the measurements require a long time to complete. In other words, the several minutes involved are not due to processing time in the analyzer; they are due to the rather long time constants of the thermal system. For your interest, we have included a plot in Figure 4 which shows the transfer function measured from 0.01 Hz to 0.1 Hz. This test required several hours to complete.

When the transfer function measurement is complete, you may use the cursor to take data on magnitude and phase as a function of frequency. The cursor is the small circle which appears on the two plots. Its position is controlled by the large knob to the right of the CRT. The frequency, magnitude, and phase appear in fields on the CRT. On this display, magnitude is indicated in dB (defined as  $20 \log_{10} \left| \frac{T(s)}{P(s)} \right|$ ). The phase is indicated in degrees. Note that zero degrees of additional phase shift corresponds to  $+180^\circ$  on the analyzer plots due to the inversion from power amplifier input to temperature error.

The analyzer occasionally enters an autocalibrate cycle which requires about a minute to complete. During this time, keyboard input is disabled, and the autocal status is indicated on the CRT.

If you are interested in learning more about the analyzer, a copy of its introductory user's manual is available in the lab. The detailed operating manual is in the instructor's office, and may be read there but not removed.

## Discussion of Measured Frequency Response

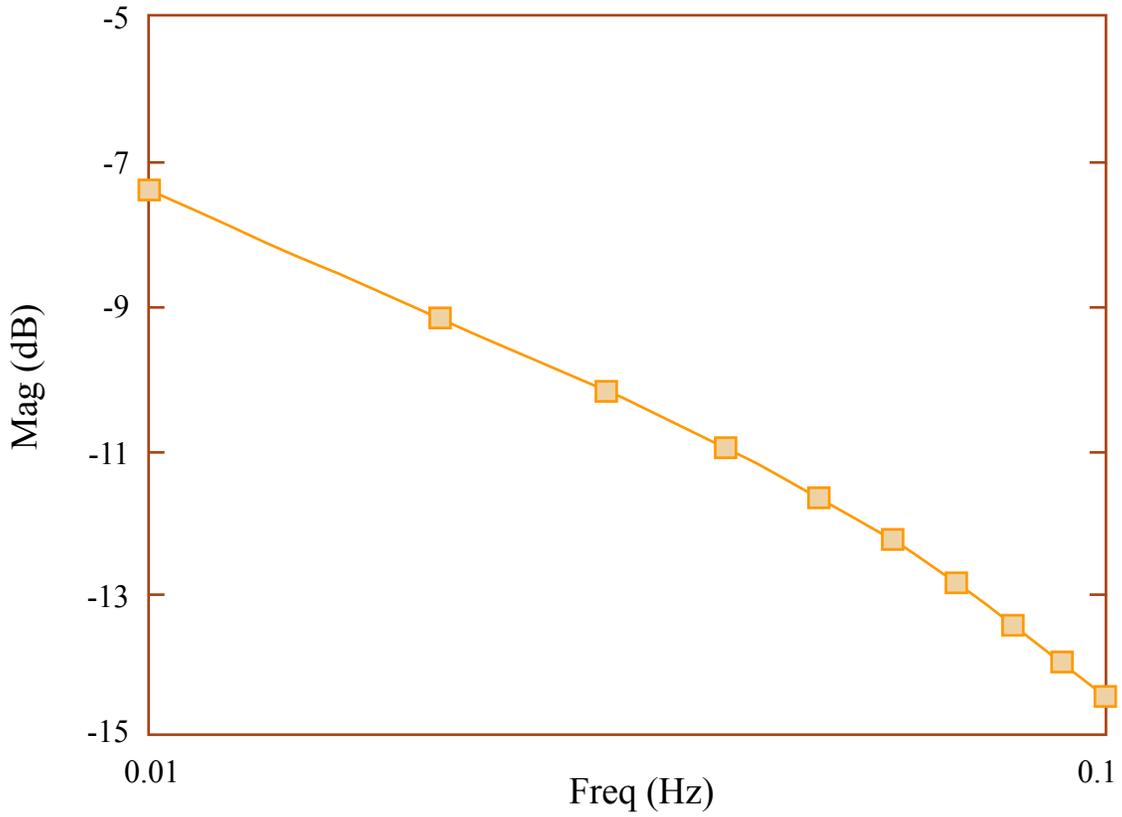
Certain aspects of this transfer function can be estimated from the properties of thermal structures. Consider a semi-infinite constant cross section bar of heat conducting material that is thermally insulated except at one end. It can be shown that the thermal impedance, or the ratio  $\frac{T(s)}{P(s)}$  for thermal variables, at the end of the bar is proportional to  $\frac{1}{\sqrt{s}}$ . Even though there are very significant differences between this idealized model and our thermal system, the transfer function shows a fairly wide range where the angle is close to  $-45^\circ$  and the magnitude is proportional to  $\frac{1}{\omega}$ .

At higher frequencies, the transfer function exhibits non-minimum phase low-pass characteristics. Non-minimum phase means that there are other transfer functions with identical magnitude characteristics which exhibit less negative phase shift. A pure time delay ( $e^{-sT}$ ) is an example of a non-minimum phase system. Such characteristics can be shown to place important limits on the ultimate system performance that can be achieved. This portion of the transfer function reflects thermal diffusion from the heater to the thermistor and through the thermistor itself.

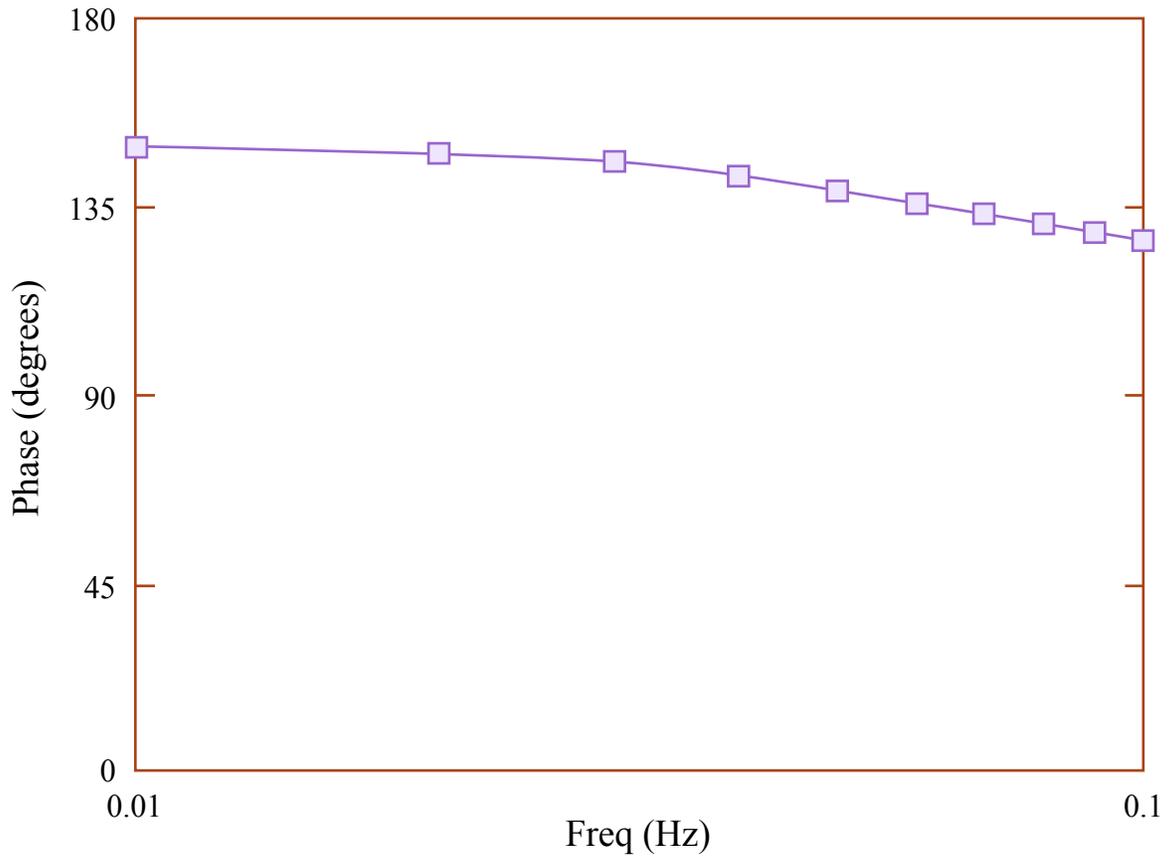
## Compensator Design and Evaluation

Since power is lost through the radiator plate continuously, it is necessary to apply heater power continuously to make up for this loss. In order to supply this required power with nominally zero temperature error, your compensator design should include a pole at the origin. A suggested topology for the compensator was analyzed in the prelab.

Low Frequency Transfer Function Data



Low Frequency Transfer Function Data



Design a compensator that achieves a system phase margin of  $50^\circ$ , and try to maximize the crossover frequency as is consistent with this phase margin. Your compensator may or may not use all of the components shown in the prelab. You should feel free to use a different compensator topology if you wish, but it should not be much more complicated than this topology. If you do use  $R_1$  and  $C_1$ , make  $R_1 > \frac{R_i}{10}$ . You should find that starting with  $C_F = 0.1\mu F$  will result in reasonable component values.

Build your compensator on your protoboard, and connect it to one of the thermal systems with BNC cables. The input to your compensator comes from the BNC labeled Compensation In, and its output goes to External Compensation. To measure the step response of your final closed loop system, you may find that borrowing two “E-Z hook BNC leads” from the component desk is helpful in hooking up your circuit to the thermal system in lab.

Note that since your compensator has a pole at the origin, its operation cannot be checked on an open loop basis.

Monitor the output voltage of your compensator and switch the system from Internal to External compensation. If the voltage out of your compensator does not settle to the range  $-0.5$  to  $-5$  volts, within a few seconds, switch back to Internal Compensation and figure out what you did wrong. (Long periods of large negative voltages will cause the radiator plate to get extremely hot!)

Once the system is working properly with your compensation, measure the step response of the linear region. Compare the performance with that of the original system to show the improvement achieved by your compensator.

When you are ready to disconnect your compensator from the system, first switch back to internal compensation. If you remove or turn off your compensator with your system still operating in the External Compensation mode, the system temperature will destabilize and the next user will be very unhappy with you!

## Write Up

Your lab write up should include the following information:

1. The step response of the system with our compensation, as well as an estimate of  $\omega_n$ ,  $\zeta$ , and  $\omega_h$  based on a dominant pair approximation.
2. The transfer function you chose for your compensator. Support your choice with analysis and Bode plots to show that you obtain  $50^\circ$  of phase margin.
3. The circuit you used to implement your compensator.
4. The step response and the estimated quantities requested in part 1 for the system with your comparison.
5. A comparison between the actual performance and the predicted performance.

Your report should be typed and clearly written. You may hand-draw block diagrams and any other sketches provided they are easy to read. Tabulate data in tables. When presenting experimental data, you should clearly explain exactly what experiment is being done. This includes neatly sketching (with accurate labels) the system input, output, and any measured quantities.

## Check Off

Make sure that you do not disassemble your compensator until after checkoff, as the TAs will want to see the circuit which you built.