LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T11XXXXX–vX** 2023/07/07

LIGO SURF 2023
Interim Report I

Demonstrating Optimal Non-linear Temperature Control

Advait Mehla

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Temperature Sensor

For sensing temperatures, we use a circuit based on the AD590 temperature transducer manufactured by Analog Devices. This sensor produces a current that varies linearly with the temperature, with a dependence of $1\mu A/K$.

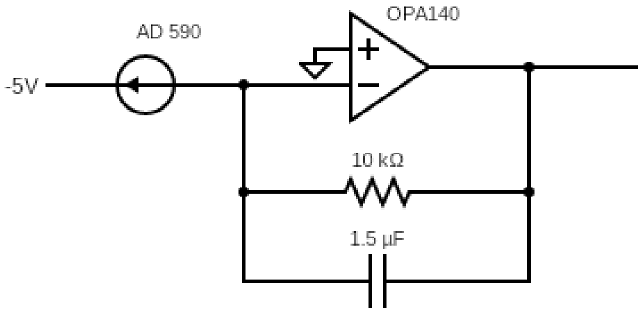


Figure 1: Temperature sensor circuit

We use this sensor with a transimpedance amplifier to convert the current signal to a voltage signal that can be read out by an ADC. We use an RPi with the WaveShare AD/DA board, which is equipped with an ADS1256 ADC chip. This provides 8 input channels with a range of 0 - 5V. The designed circuit outputs a voltage of 2.98 V at a temperature of 298 K, and has a feedback capacitor to act as a low pass filter of roughly 10 Hz to eliminate high frequency noise. OPA 140 was chosen to minimize the noise contribution of the TIA, as it is a JFET low input noise amplifier.

We estimated the amplitude spectral density of the noise source using LTSPice, and compared it to the spectral density of fluctuations of the environment itself. The design goal was to achieve noise that is at least 2-3 orders of magnitude below the ambient fluctuations, and this was successful (Figure 2).

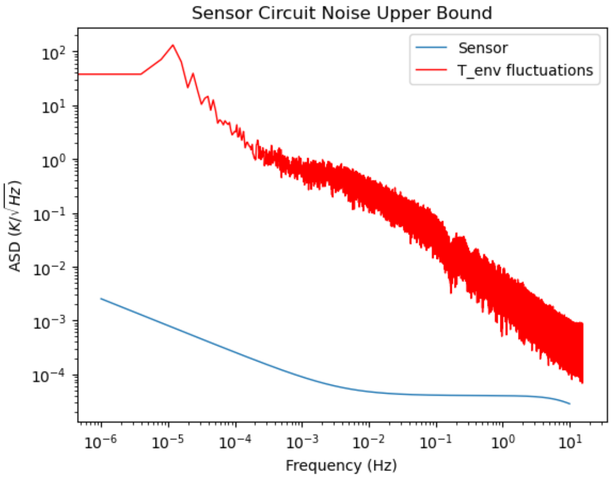


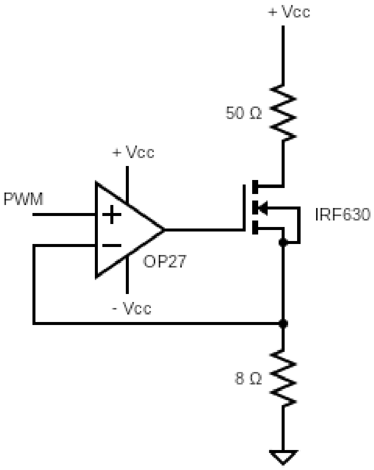
Figure 2: Sensor noise v/s ambient fluctuations

This circuit has been built on a soldered perf-board with 4 TIA channels.

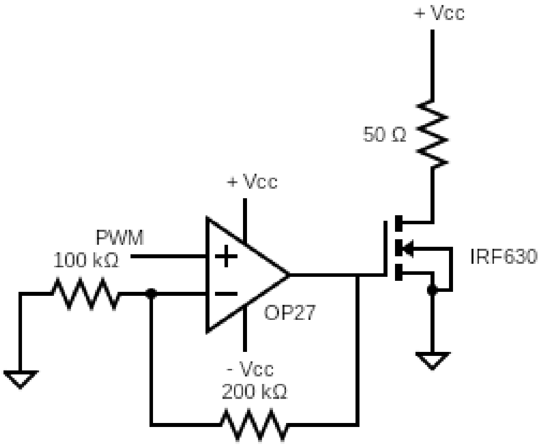
2 Revised Heater Circuit

After discussions with my mentor, we decided to revise the original heater circuit that was mentioned earlier. The old circuit had two major shortcomings -

1. The current through the heater inadvertently depended upon the input signal voltage. We decided that it would be more ideal if the RPi input signal simply served as a switch instead.
2. A sizeable proportion of power was wasted across the 8 Ω resistor attached to the source of the MOSFET. We wanted to maximise efficiency and have a circuit that allowed us to use the full V_{cc}^2/R_H that the power supply can provide.



(a) Original circuit



(b) Revised circuit

Keeping this in mind, I realised that given our use-case of just making a PWM-controllable switch, a feedback loop was unnecessary. We only wish to switch between two operating points, the MOSFET being fully-on and fully-off. Given this, I switched to a much simpler design where the MOSFET is simply being switched on and off by the PWM signal fed through a non-inverting amplifier. The amplifier is used in order to exceed the V_{GS} threshold of the op-amp to ensure it is able to switch on fully.

One concern with this design was that the MOSFET would not behave linearly at intermediate voltages, and a delay in slewing from on to off would lead to dissipation of heat. Figure 4 shows the drain voltage waveform with this circuit, which shows a rise time of roughly 500 ns. This is a negligible fraction of the time period, which is 1 ms, and thus this effect is not relevant. The MOSFET does not heat up appreciably during operation.

We are discussing further improvements to this circuit in order to make it resistant to noise in the power supply, as currently the heating power is directly sensitive to this.

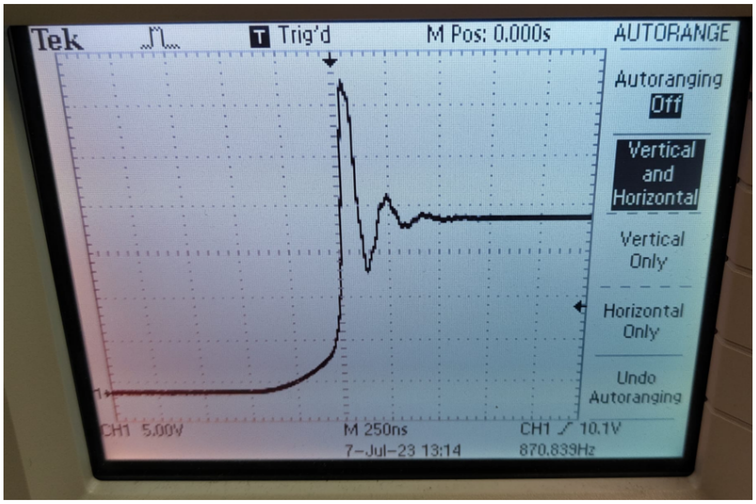


Figure 4: Drain voltage waveform with a 1 kHz PWM

3 Thermal Model Fitting

I also fit parameters to the un-insulated puck model that was discussed in the previous report, as a precursor to the insulated experiment and to test the validity of the convective component specifically. The time evolution of the temperature was assumed to dictate the following equation -

$$\frac{dQ_p}{dt} = m_p c_p \frac{dT_p}{dt} = -hS\left(T_p - T_{env}\right) + H$$

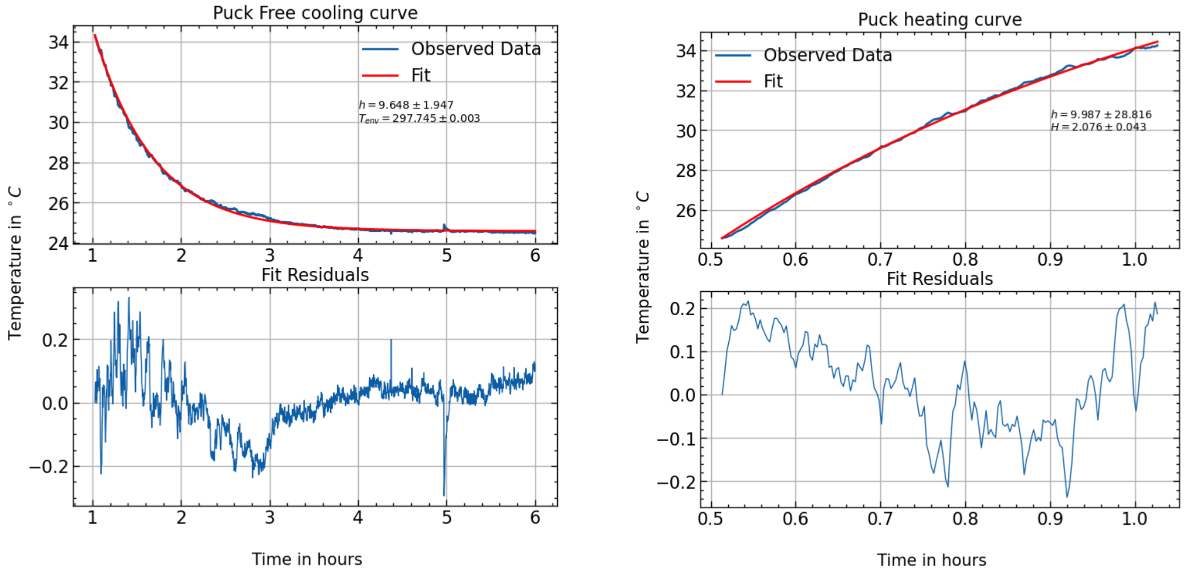


Figure 5: Fits to the heating and cooling curves

Here, h is the convective heat transfer coefficient, S is the total exposed surface area, and H is the rate at which heat is supplied. I used the `lmfit` package to fit parameters of this model. The only free parameters here are h, which is completely unknown, and H which is known up to a constant, since the heat supplied is not completely delivered to the puck due to losses from the heater resistor itself. T_{env} was also left as a free parameter as it was not actively monitored with a sensor.

One limitation of the fitting routine is that it cannot accommodate time varying parameters, in a step response test, the heating section and freely cooling section needed to be fitted independently. Figure 5 shows the results of this fit, and the parameter h is in agreement in both cases.