LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Temperature control system and Seismic heat map

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1 Introduction

The Laser Interferometric Gravitational Wave Observatory (LIGO) is designed to detect and study gravitational waves.To detect these gravitational waves, perturbations of the order 10^{-19} m have to be detected by the system. These changes are so small that nothing short of an engineering miracle has occurred to reduce the noise and to detect the signal in these systems. On careful study and analysis of the noise, researchers found that the lower range of the device bandwidth, lesser than 10Hz, was dominated by seismic noise[1]. For the next generation of LIGO detectors, increasing the sensitivity and the bandwidth of the device is of the utmost importance. Hence suppression and study of seismic noise are critical to meet this goal.

The first step to understand and characterise seismic noise, is to study the motion of the ground. Sensors called as seismometers are used to detect ground motion and help us map the sesimic activity in the surrounding region. These sensors need to be maintained at optimal environment conditions so that reliable readings can be obtained. Hence strict isolation from the surrounding environment and vigilant control of parameters, such as temperature is very much necessary to obtain data with the least amount of noise from the seismometers.

Multiple such sensors can be used to create a "Seismic Heat Map" of the area it is placed in. Heat maps help us better visualize the spatial distribution of the intensity of seismic activity, present in the region under study. On creating such heat maps we can use techniques of data analysis to help us identify and classify the sources of disturbance.

2 Objective

The parameters of the seismometer, most important being the temperature need to be strictly controlled, so that the seismic data made available to us can be further used to make reliable heat maps of the surrounding area. Such type of control can be implemented using a feedback control system, to keep the temperature of the seismometer as stable as possible. The nature of how the temperature affects the seismometer data will also be studied.

To accomplish this, the seismometer under study will be mathematically modelled and simulated in the time as well as in the frequency domain. Linear PID controller will be implemented,so that the temperature of the seismometer tracks the reference temperature with the least amount of error and with the fastest time constant possible.

The project also aims to reduce power losses in the heater circuit by replacing the linear voltage output with a PWM waveform.

PID control has it's limitations in the sense that it can only be applied to linear systems. However practical systems under study will tend to have non-linear elements which cannot be ignored. The main non-linearity of the system will be the asymmetric response of the system to heating and cooling, since we can only control the amount of heat added. Methods of linearising the system, such as shifting the operating temperature will also be studied. The final objective of the project will be to implement a machine learning based non-linear feedback controller to learn the inverse non-linear plant dynamics and to predict the necessary actuation to the system.

Therefore the entire project can be seperated into four major sections :

- Development of Seismic Heat Map
- Design of the PWM heater circuit
- Time domain simulation of the system and implementation of PID control
- Implementation of a machine learning based non-linear feedback controller

The entire project is a collaborative effort between three students. The sections of the project that I will be working on would be the Temperature feedback control system and the design of the PWM circuit.

3 Project details and implementation

Sesimometers work on the principle of a spring-mass system. Once mounted on a flat and stable surface, any changes in the ground motion leads to a change in the position of the spring and these changes are recorded as voltages. The stiffness of these springs change due to tempertaure changes and the delicate equilibrium of forces in astatic suspensions makes them susceptible to external disturbances such as the ones cause by temperature. Hence temperature fluctuations of the sensor leads to increased noise in the output data. The seismometer which we will be using for the project will be the Guralp [3] and the Trillium seismometers [4].

To circumvent the problem caused by temperature fluctuations, the need for a temperature control feedback system for the seismometer is of the utmost importance.

The design of the control system will be implemented in the following order :

1. Understanding the seismometer setup and modelling this setup in the frequency domain.
2. Implementation of the PWM circuit and subsequent modelling.
3. Controller implemented as a linear PID and tuning of the PID parameters.
4. Time domain simulation of the entire setup.
5. Introducing non-linearities and noise in the system.
6. Controller implemented as a neural network to handle the non-idealities in the system

3.1 The Seismometer heating apparatus

The seismometer heating apparatus has various components that has to be accurately modelled. These include:

- The stainless steel box housing the seismometer: Attached to this housing is a temperature sensor.
- Resistive mesh wrapped around the stainless steel box: The heater circuits supplies power to this mesh to heat the stainless steel box.The resistance of the mesh is taken to be around 30Ω.
- A layer of insulation in the form of a foam layer is provided around the mesh to minimize heat losses to the surrounding environment.

3.1.1 Modelling of the seismometer apparatus

The seismometer heating apparatus can be mathematically modelled using the heat equation as :

$$P_{in} = M_{ss}C_{ss}\frac{dT_{ss}}{dt} + P_{loss} \tag{1}$$

The loss for this initial model is assumed to be purely conductive in nature, due to the presence of the foam wrapping between the environment and the stainless steel box.

$$P_{loss} = \frac{k_{foam}A_{foam}}{t_{foam}}(T_{ss} - T_{amb}) \tag{2}$$

Considering the mentioned assumptions, we get the relation between the input heating power and the temperature of the stainless steel box, in the laplace domain as:

$$T_{ss}(s) = \frac{P_{in}(s) + B}{M_{ss}C_{ss}s + A} \tag{3}$$

$$B = k_{foam}A_{foam}t_{foam}T_{amb} \quad A = k_{foam}A_{foam}t_{foam}$$

Refer to Appendix A for complete derivation of the mathematical model.

3.2 PWM and heater circuit

The current heater circuit provides a linear voltage to the power MOSFET, to regulte the power input to the seismometer. However some of the problems with this would be the MOSFET power losses due to the finite resistance it provides to the drain current when it is not completely turned off.

The Pulse Width Modulated (PWM) signal is a periodic square pulse whose duty ratio is determined by an input control signal.This can be better visualised by referring to Figure 1. Transforming the input voltage from a linear input to a PWM waveform provides us with an additional degree of freedom which is the duty ratio, to control the average power input to the system.

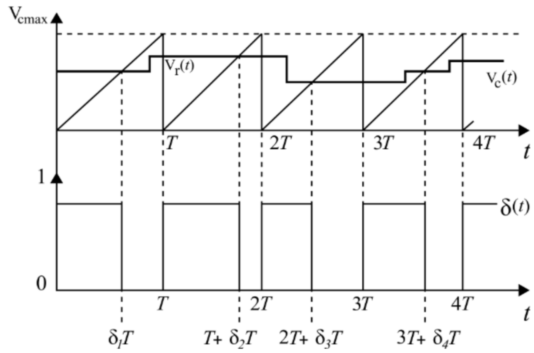

Figure 1: Input and Output waveforms of the PWM circuit

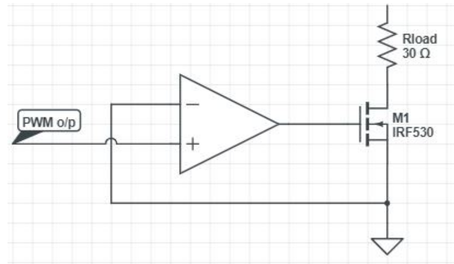

Figure 2: Power MOSFET Circuit

3.2.1 Generation of the PWM waveform

There are mainly two possibilities that can be explored to generate the PWM waveform from the error i.e. the control signal. Depending upon the ease and flexibility required for the output signal, one approach will be chosen to generate the PWM waveform.

- Programming the Real time Control System : The control system present in the lab can be utilised to generate a PWM waveform, by providing the block level implementation of the circuit to the system. The design can be done remotely by using the SIMULINK software.
- Circuit design : The PWM waveform can also be generated through a custom designed circuit. The circuit has two parts that has to be accurately designed. These are :
  1. Reference signal generation : The reference signal is a periodic triangle, sawtooth or a ramp signal.
     - These can be generated by using opamp circuits which are configured in a positive feedback loop (Example : Schmitts trigger).
     - Use of timers : Popular timers such as the 555 IC can be used in a positive feedback loop to generate the required reference signal.

     Both implementations will be explored to see which approach would be the most feasible for our application.
  2. Error comparator : This comparator compares the voltage values between the control and the reference signal to generate the final PWM ouput. The voltage values of the "ON" and "OFF" state of the PWM will be determined by the saturation voltages of this comparator.

The generated PWM waveform will be fed to a low pass filter to get the analog value of the voltage which is to be fed to the gate of a MOSFET through a low noise amplifier. As shown in Figure 2 the MOSFET in turn supplies current to the resistive mesh for heating the stainless steel compartment.

3.2.2 Modelling of the PWM and heater circuit

The PWM circuit will be modelled in the laplace domain as a simple gain bock whose value is given as :

$$K_{pwm} = \frac{1}{V_M}\ V/V \tag{4}$$

Where V_M is the maximum amplitude of the reference signal.

In the time domain simulation, implementation of the PWM will be done in python as a code block, which determines the duty ratio of the output square pulse.

The heater block, which converts the voltage into power will also be modelled as a pure gain block, since it is a resistive heater and the power can be written as:

$$P_{in} = \frac{V^2}{R_{load}} \tag{5}$$

Where V is the input voltage to the resistive mesh from the heater circuit.

3.3 Introducing non-linearities and noise

The time domain simulation of the plant will be the final model that will be taken into consideration. The laplace modelling linearises the complete system around a particular set point. Hence this approach greatly simplifies the actual system under study. To model the system with non-linearities, the system will be modelled in the time doamin.The nonlinearity for our system would be the radiative losses, hence the modifed P_{loss} would be:

$$P_{loss} = k_{foam}A_{foam}t_{foam}(T_{ss} - T_{amb}) + \sigma A_{foam}(T_{ss}^4 - T_{amb}^4) \tag{6}$$

The sensor which is used to detect the temperature of the apparatus is not noiseless. Hence study and impact of the sensor noise to system will be done.

Simulations of the system model will be carried out with the actual sensor temperature data. Techniques will be implemented to reduce the impact of the sensor noise on the system.

A modified system model will be presented after including the above non-idealities.

3.4 Design of controller

Two types of controller will be implemented:

- Proportional-Integral-Derivative(PID) controller.The parameters to be tuned for such a controller and their effect on the system is explained below:
  1. K_P : The proportional constant, this parameter helps to move the closed loop poles along the root locus, to get the best transient response.

2. K_I : The integral constant is varied to reduce the steady state error of the output signal.
3. K_D : The derivative constant is tuned to get the best transient response, when the desired values that is expected of the output response are outside the root locus.

Combining all the above constants, the PID block in the laplace domain is defined as:

$$K_{PID} = K_P + \frac{K_I}{s} + sK_D \tag{7}$$

The same thing in the time domain can be represented as:

$$e_{PID}(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau \ + K_D \frac{de(t)}{dt} \tag{8}$$

where e(t) is the error signal that is passed through the PID block and then e_{PID} is fed into the PWM circuit.

To determine the values for the PID parameters different methods and alogorithms will be used.

- Nueral Network: Studies [2] have shown that neural network controllers provide better transient response and performance when compared to PID controllers, especially in non-linear systems.

  A tensorflow flow model of a simple feedforward network will be made, for which the following will be decided :

  1. The inputs that will be require to generate the output parameters
  2. The number of output parameters and their corresponding effect on the system
  3. Number of hidden layers
  4. Type of learning that will be implemented

  The above information can be used to convert the simple feedforward network into more complex models.

4 Timeline

Due to the onset of COVID-19 ,the tentative schedule for the summer break in India has been cut down.

Hence this lost time will be compensated in August, which has been given as a break before the start of the next semester.

The following tasks will be the outline for the entire project:

- **Week 1-2 :** Modelling and temperature simulation of seismometer heating apparatus.
- **Week 3-4 :** Time domain simulation of system and implementation of PID control.
- **Week 5-6 :** PID tuning and cost function optimisation.
- **Week 7-8 :** PWM heater circuit schematic and simulation.
- **Week 9-11 :** Controller implemented as a Neural network :
  1. Implementation in OpenAI gym
  2. Supervised learning algorithm
  3. Reinforcement Learning

A Derivation of the mathematical model for seismometer heat apparatus

The seismometer heating apparatus was mathematically modelled using the heat equation :

$$P_{in} = M_{ss}C_{ss}\frac{dT_{ss}}{dt} + P_{loss} \tag{9}$$

The loss for this model is assumed to be purely conductive in nature, due to the presence of the foam wrapping between the environment and the stainless steel box.

$$P_{loss} = \frac{k_{foam}A_{foam}}{t_{foam}}(T_{ss} - T_{amb}) \tag{10}$$

Substituting (10) in (9) and integrating (9), we get:

$$T_{ss}(t) = \frac{1}{M_{ss}C_{ss}}[\int_0^t P_{in}(\tau)d\tau - \int_0^t \frac{k_{foam}A_{foam}}{t_{foam}}(T_{ss}(\tau) - T_{amb})d\tau] \tag{11}$$

Rearranging the terms we have :

$$T_{ss}(t) + \frac{1}{M_{ss}C_{ss}}\int_0^t \frac{k_{foam}A_{foam}}{t_{foam}}T_{ss}(\tau)d\tau = \frac{1}{M_{ss}C_{ss}}[\int_0^t P_{in}(\tau)d\tau + \frac{k_{foam}A_{foam}}{t_{foam}}T_{amb}t] \tag{12}$$

Differentiating (12):

$$\dot{T_{ss}}(t) + \frac{1}{M_{ss}C_{ss}}\frac{k_{foam}A_{foam}}{t_{foam}}T_{ss}(t) = \frac{1}{M_{ss}C_{ss}}P_{in}(t) + \frac{1}{M_{ss}C_{ss}}\frac{k_{foam}A_{foam}}{t_{foam}}T_{amb} \tag{13}$$

Converting the time domain equation to laplace domain:

$$T_{ss}(s) = \frac{P_{in}(s) + B}{M_{ss}C_{ss}s + A} \tag{14}$$

$$B = \frac{k_{foam}A_{foam}}{t_{foam}}T_{amb} \quad A = \frac{k_{foam}A_{foam}}{t_{foam}}$$

References

[1] M G Beker, J F J van den Brand, E Hennes1 and D S Rabeling *Newtonian noise and ambient ground motion for gravitational wave detectors*. Journal of Physics:Conference Series,Volume 363.

[2] M. Khalid and S. Omatu *"A neural network controller for a temperature control system,"* IEEE Control Systems Magazine, vol. 12, no. 3, pp. 58-64, June 1992, doi: 10.1109/37.165518.

[3] Guralp CMG40-T datasheet : *https://www.guralp.com/documents/MAN-040-0002.pdf*

[4] Trillium 240 datasheet : *https://www.passcal.nmt.edu/webfm_send/220*