Final Report

Estimation of Coil Thermal Model in Slip Control System

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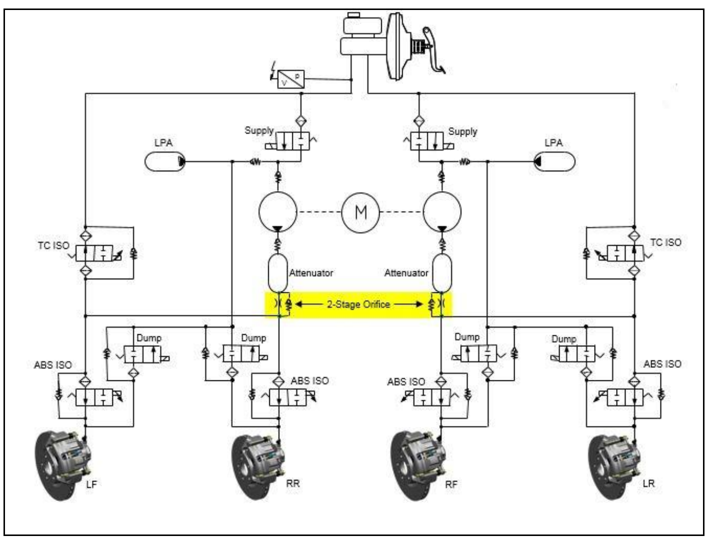
***Abstract*—This report presents how digital signal processing methods are applied in the real automotive industry. It shows the how accurate the estimation of thermal model in slip control system can predict the actual temperature.**

Keywords—Slip Control System; Thermal Model; Comparison

I. Introduction

In the braking system of a vehicle, the applied pressure is controlled by the current of different solenoids. And the current of each solenoid is determined by two factors, voltage and resistance. Moreover, the resistance is affected by the temperature. For the reason of cost and installation, there is no temperature sensors to measure the temperature of the coils of the solenoids. Thus it is very important to build an estimation model to estimate the temperature of different solenoid coils. And the figure below shows the configuration of the most common vehicle, and the setup of different valves- TC Supply, TC ISO and ABS ISO.

Fig.1. Configuration of Slip Control Systems



In this project, I have several thermal couples installed in the lab to measure the actual coil temperature to calibrate the thermal estimation model. I conducted several tests, measured the actual temperature, also I used CAN cable to get the estimated temperature directly from the ECU, which is the data of thermal model. Totally, I have both estimated and actual temperature data for the TC Supply, TC ISO and ABS ISO. And I finished some digital data processing to compare the estimation model with actual better. I implemented a low pass filter to the actual data to remove the noise, and then I used moving average method on both actual and estimation data to get better results. Also, I used the Savitzky–Golay filter which is not in class to compare the effect with moving average method. In the end, I used the data I have to estimate the performance of the estimated model at different temperature with input at different frequency.

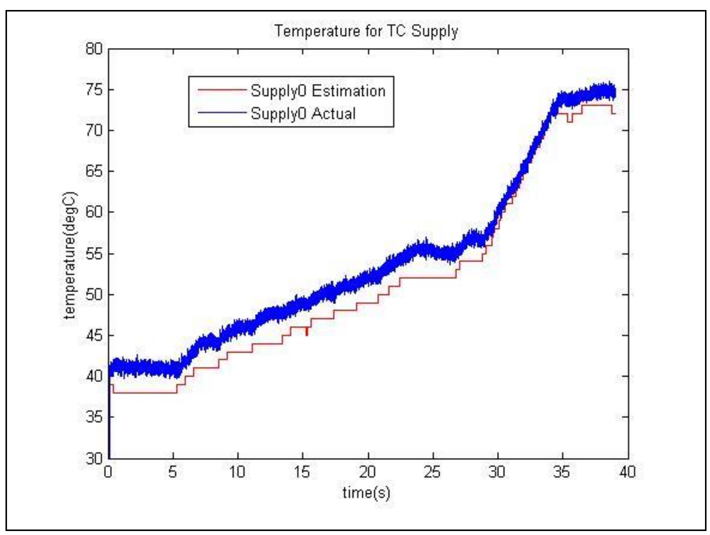
II. TC Supply

First, I will process the data for TC Supply.

A. Collected Data

First, the figure blow shows the data I collected for the TC Supply solenoid.

Fig.2. Collected Data for TC Supply



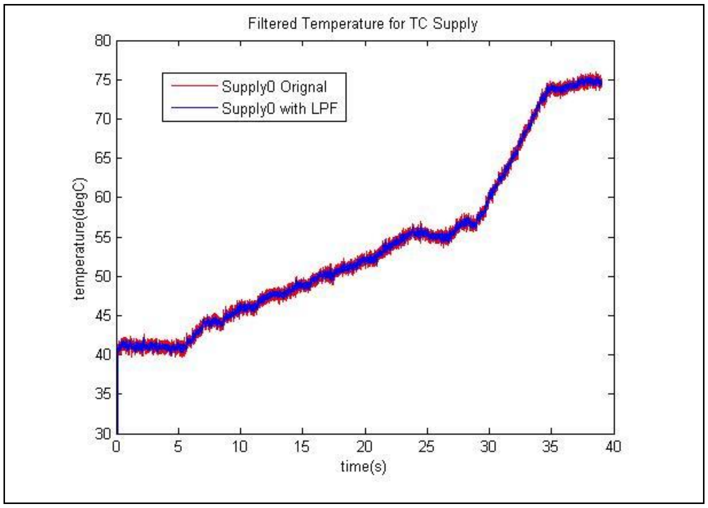
B. Implementing Low Pass Filter (In- Class Method)

From the collected data, we noticed that there is some noise in the actual temperature. To remove the noise, I implemented a low pass filter. The low pass filter I implemented is the following.

$$H(z) = \frac{1}{0.25z^3 + 0.25z^2 + 0.25z + 0.25}$$

From the plot below, we can see that after implementing the low pass filter, the noise in the actual signal decreases. But there still exists some noise.

Fig.3. TC Supply Actual Signal with Low Pass Filter

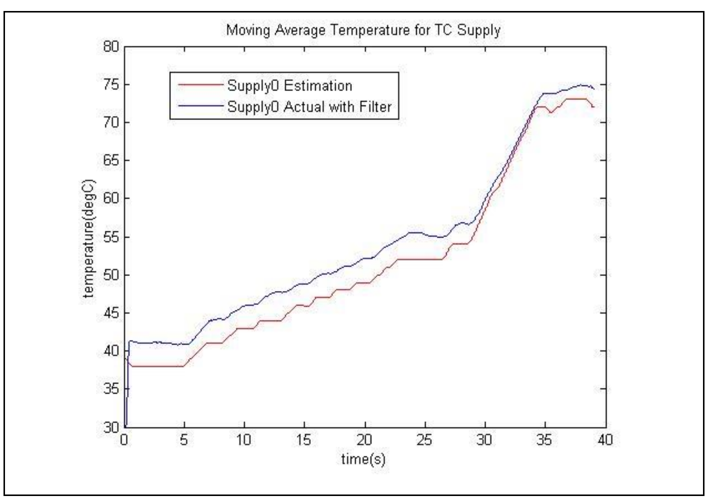


C. Implementing Moving Average Method (In- Class Method)

From the plot above, we can see that there still exists noise in the actual temperature, so I implemented moving average method to smooth the signal.

And for the estimated signal, because the resolution for the model is 1 degree, so I also needed to smooth the signal. Thus moving average is also applied. And I chose 600 points to smooth the data. Here are the results.

Fig.4. TC Supply Signal with Moving Average



From the plot, we can see that both of the signals became much smoother.

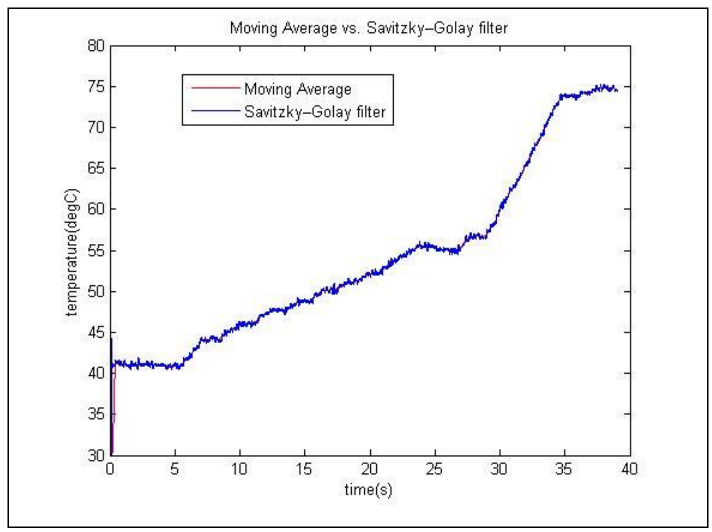
D. Implementing Savitzky- Golay filter (Out of Class Method)

Besides the above two in- class methods, I also tried to use the out of class method (Savitzky- Golay filter) to smooth the data, and to compare the result with that of moving average method.

A Savitzky–Golay filter is a digital filter that can be applied to a set of digital data points for the purpose of smoothing the data, that is, to increase the signal-to-noise ratio without greatly distorting the signal. This is achieved, in a process known as convolution, by fitting successive sub-sets of adjacent data points with a low-degree polynomial by the method of linear least squares . When the data points are equally spaced an analytical solution to the least-squares equations can be found, in the form of a single set of "convolution coefficients" that can be applied to all data sub-sets, to give estimates of the smoothed signal.

In MATLAB, I used the function 'sgolayfilt' to implement the filter. And here is the result.

Fig.5. TC Supply Signal with Savitzky- Golay filter



From the figure above, we can see that after implementing Savitzky–Golay filter, there signal still has some noise, and it is not smooth as the result of moving average method.

But actually, information is lost or distorted because too much statistical weight is given to points that are well removed from the central point. Moving average method is particularly damaging when the filter passes through peaks that are narrow compared to the filter width.

And at the same time, the Savitzky–Golay filter is better because a set of integers could be derived and used as weighting coefficients to carry out the smoothing operation.

E. Estimation (In- class Method)

Because the requirement of the working temperature is from -40 degC to 120 degC, then I need to estimate the estimation model performance at both high temperature and low temperature and at different changing frequency of the actual temperature.

I chose 5 seconds data which the estimated data can follow the actual temperature best. Then I regard the actual temperature as the input to the estimation model, and the estimated temperature as the output. And the way to analyze if the estimation model is good enough is to check if the output follows the input. Based on the input and output, I can use deconvolution for the output from input to get the system transfer function.

To estimate the performance at different condition, I used a sinusoid signal as the temperature input, and simulated both at high and low frequency. In the end, I convolute the input and the system transfer function to get the output, and compare it with the input.

Fig.6. The estimation of TC Supply at low temperature

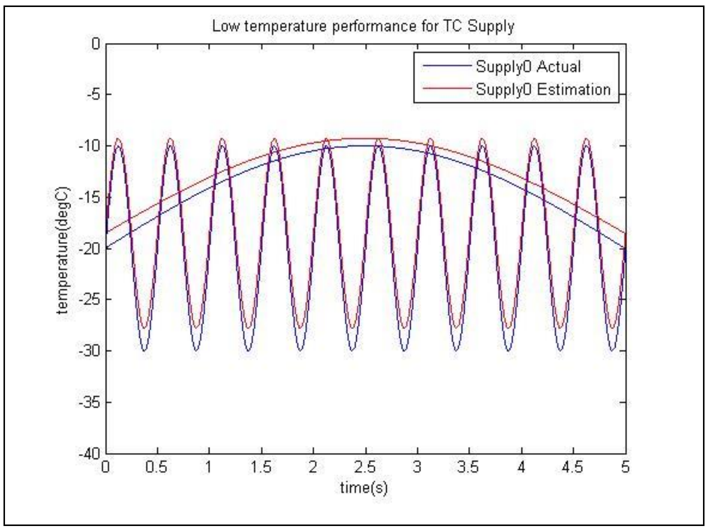
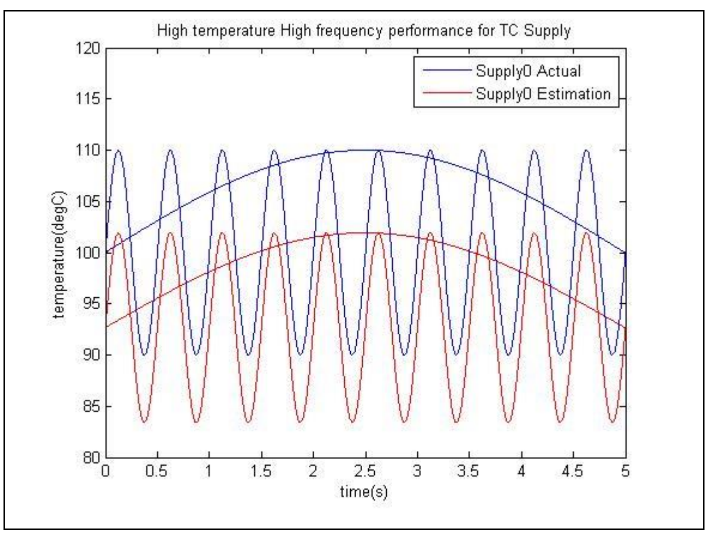
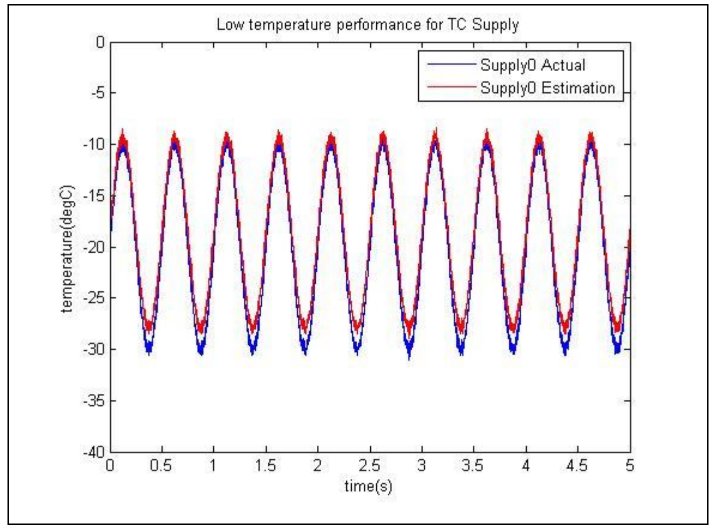


Fig.7. The estimation of TC Supply at high temperature



Then to check the robustness, that is whether the model can predict the temperature well if there is noise in the input signal, I added noise to the input and simulated it. From the result, we can see that the model can still predict the temperature well with noise.

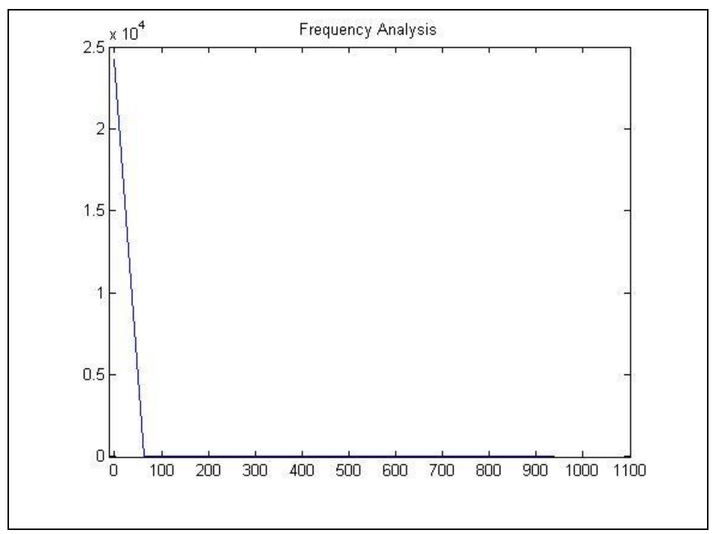
Fig.8. Estimation with Noise



F. *Frequency Response (In- Class Method)*

In the end, I would like to see the error between actual and estimated temperature in frequency domain. Thus I calculated the error, and then did FFT for it. The result is shown in the following figure.

Fig.9. Frequency Analysis of TC Supply



From the result we can see that the power of error is very large at low frequency, but decrease to zero at high frequency. And it did not help a lot in comparing the estimation model with actual temperature.

G. *Conclusion*

From the comparison between the estimated temperature from the thermal model and the actual measured temperature, we can see that when the ambient temperature is 30 degC, estimated temperature can follow the actual change of the temperature very well when the temperature is not changing too fast. When the change rate is large, it could not follow very well, but the error is less than 5 degree, which is still acceptable.

When the ambient temperature is low, the input frequency is low, the estimated model can follow the actual temperature very well, but there always exists an offset, which is about 2 degC. When the input frequency is high, the error is changing, so the model could not follow the input very well, but the error is still under acceptable range. When the ambient temperature is high, both high and low input frequency, the model can follow the input, but the offset is about 5 degC, which is larger than that at low temperature.

Thus we can see that the estimation model can predict the actual temperature very well at low temperature, with error less than 2 degC. But at high temperature, the model could not predict the temperature very well, which will have about 5 degC error.

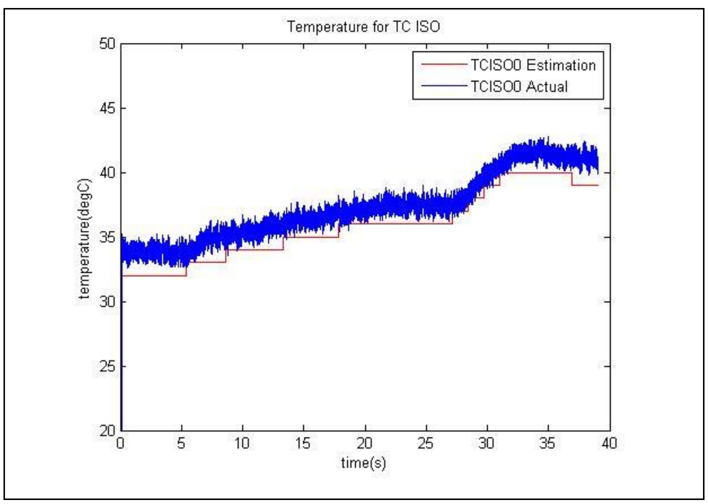
III. TC ISO

Same as before, I processed the data for TC ISO.

A. *Collected Data*

The plot below is the collected data for TC ISO.

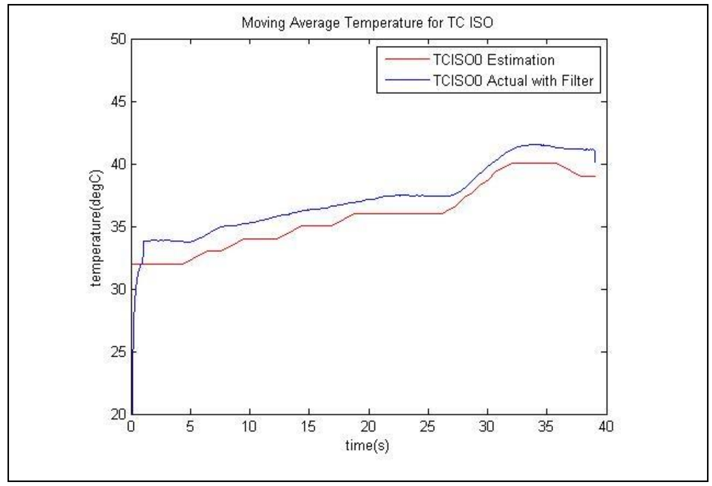
Fig.10. Collected Data for TC ISO



B. *Implementing Low Pass Filter and Moving Average Method (In- Class Method)*

The same low pass filter and moving average method as TC Supply is applied to the actual temperature of TC ISO. This time I used 2000 points to have better results.

Fig.11. TC ISO Signal after smoothing



C. *Estimation*

To estimate the performance of TC ISO model at other temperature, I simulated similarly at both high and low temperature with different frequencies.

Fig.12. The estimation of TC ISO at low temperature

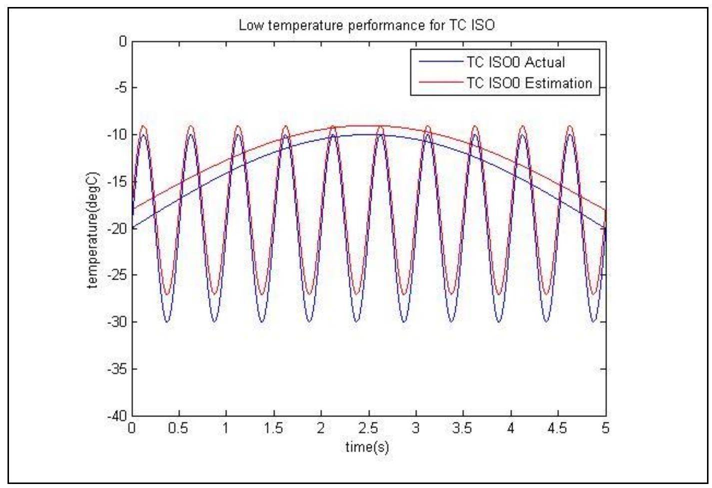
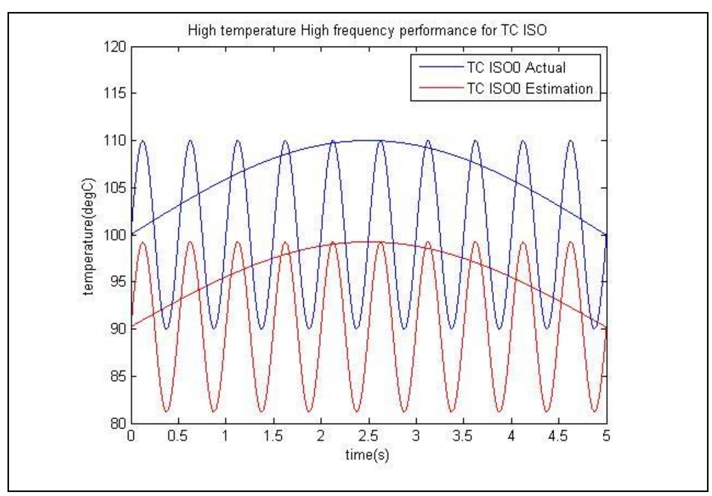


Fig.13 The estimation of TC ISO at high temperature



D. Conclusion

From the figure above, we can see that the estimated temperature can follow the actual change of the temperature well at different temperature. There exists some offset. But overall, the estimation model is acceptable.

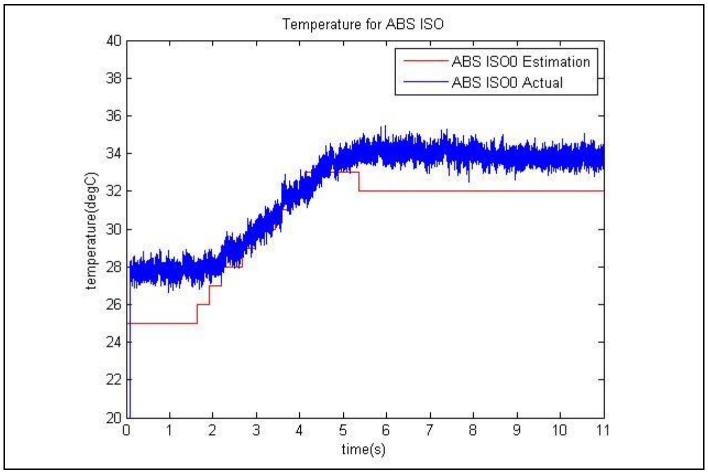
IV. ABS ISO

In the end, I did the same things to deal with ABS ISO.

A. Collected Data

The plot below is the collected data for ABS ISO.

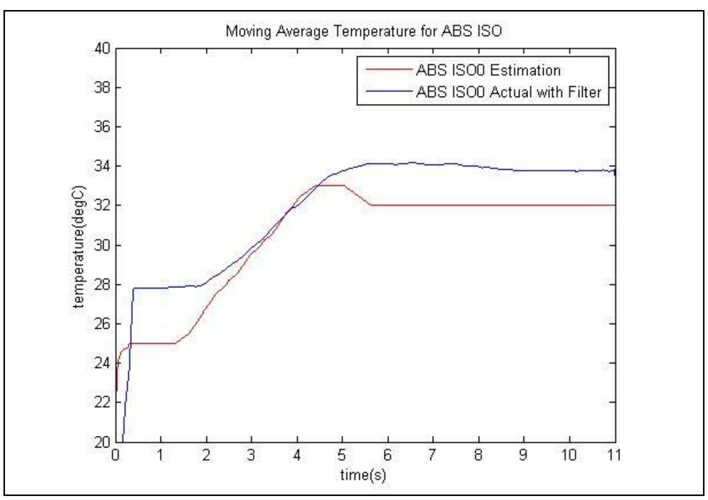
Fig.14 Collected Data for ABS ISO



B. Implementing Low Pass Filter and Moving Average Method (In- Class Method)

The same low pass filter and moving average method as before is applied to the actual temperature of ABS ISO. This time I used 2000 points to have better results.

Fig.15. ABS ISO Signal after smoothing



C. Estimation

To estimate the performance of ABS ISO model at other temperature, I simulated similarly at both high and low temperature with different frequencies.

Fig.16. The estimation of ABS ISO at low temperature

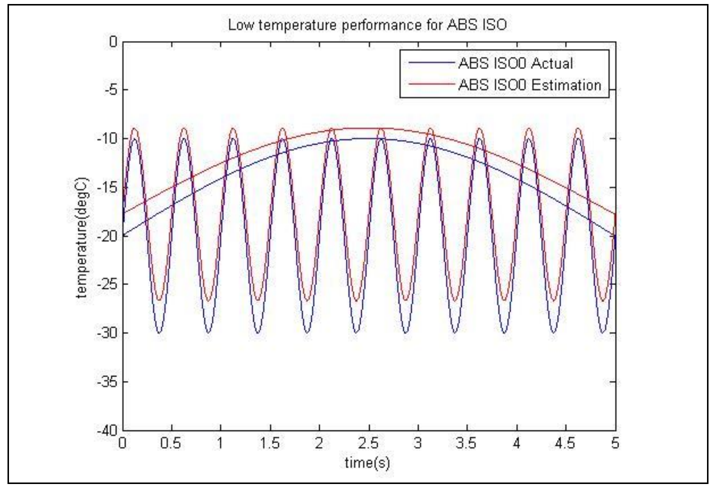
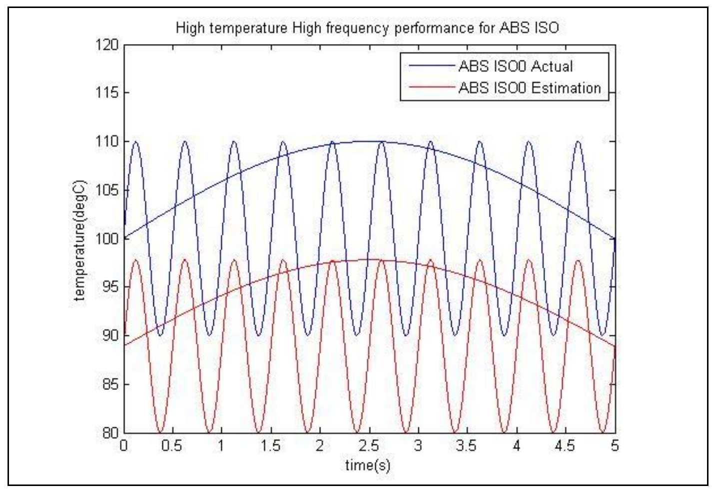


Fig.17. The estimation of ABS ISO at high temperature



D. Conclusion

The estimated temperature can follow the actual change of the temperature well at different temperature. There exists some offset. But overall, the estimation model is acceptable.

V. SUMMARY

From this project, I used three methods from class (moving average, low pass filter and convolution) and one out of class method (Savitzky- Golay filter) to the data I have. After processing, I can have better data with less noise, so that it is easier to compare and use the data to predict. Then I used the data I have to predict the performance of the estimation model at different temperature with different input frequency. So we can see that the DSP methods can help predict the performance of the estimation model with different input