EML 5211 – Control System Theory

Final Project

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# Design and testing the controller on the unknown Virtual Plant.

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## Introduction:

A **control system** manages, commands, directs, or regulates the behavior of other devices or systems using control loops. It can range from a single home heating controller using a thermostat controlling a domestic boiler to large industrial control systems which are used for controlling processes or machines. In all these cases, we need a controller which gives a desired output. In real time scenario we don't have a well-defined system, but we need to deal with physical plants available. So, we need to be able to do experimentation with available plant, gather data and identify the system which is near same as the original plant. In this project given virtual plant is analyzed by experimentation and then a controller is designed to stabilize the system.

## System identification:

In system identification first thing to learn about plant is its reaction to input. To characterize tis, the frequency of the plant was analyzed using the sine sweep technique. Consider the plant with the actuator saturation $u_{min}$ = -10 and $u_{max}$ = 10, noise n(t), input u(t) and output y(t):

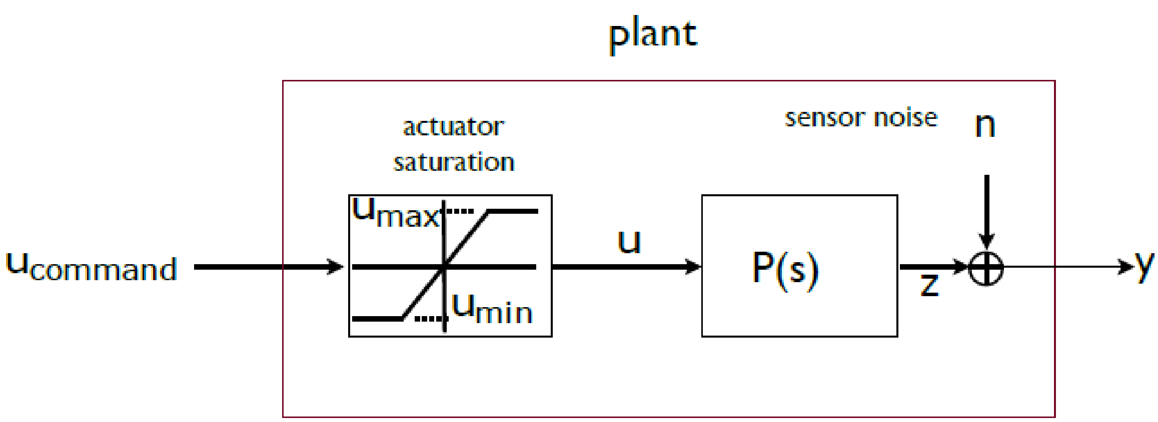


Figure 1 Plant with input and output

For this plant frequency domain parameters are as follows:

Input: $u(t) = A \sin \omega t$

Where A is amplitude of the sinusoid, ω is a given frequency and t time,

Output: $y(t) = A\,|\,P(j\omega)\,|\,\sin(\omega t + \angle P(j\omega)) + \epsilon(t)$

Where | P(jω) | is magnitude of the plant, ∠P(jω) is phase angle and ϵ(t) is the transient response.

After a decay time of 30 secs used in this project steady state response will be

Steady state response: $y_{ss} = A|P(j\omega)|\sin(\omega t + \angle P(j\omega))$

The gain magnitude and the phase terms can be calculated from experimental data on the virtual plant by considering the in-phase and quadrature integrals:

$$I_P^{ss} = \frac{1}{T}\int_0^T y_{ss}(t)\sin(\omega t)\,dt\hat{g}$$

$$I_q^{ss} = \frac{1}{T}\int_0^T y_{ss}(t)\cos(\omega t)\,dt$$

Further these values can be approximated as

$$I_p^{ss} = Ag\sin(\omega t)$$

$$I_q^{ss} = Ag\cos(\omega t)$$

It can be shown that from experimental data gain margin and phase margin at a given frequency ω from the relation:

$$\hat{g} = \frac{2}{A}\sqrt{I_p^{ss\,2} + I_q^{ss\,2}}$$

$$\hat{\phi} = \tan^{-1}\left(\frac{I_q^{ss}}{I_p^{ss}}\right)$$

The sine sweep test was carried out in MATLAB over a different range of frequencies and bode plot reference was estimated. The sine sweep was carried out until an acceptable approximation of plant was estimated. Before sine sweep experimentation was done for individual frequencies at ω = 0.01, 0.1, 1, 10, 100, 1000 and with amplitude 1 to check

(1) To identify frequency band to be experimented by checking if there is any change in magnitude which says the information regarding the poles and zeros if present.
(2) To find the transient response of the system to gather just Steady state data.

Figures 2 and 3 shows the frequency response of the unknown plant at frequencies. For frequency 0.01 rad/sec we can see the gain to be around 32- 35. Whereas for frequency it was found to be 30 which doesn't make any sense in considering the values below 0.1 frequency. Which shows no presence of the pole or zero which is why the gain just change 3. Also, at higher frequencies above 100 it was found the presence of lot of noise, so we just considered the frequencies between 0.1 and 100 for estimating the system properly.

It can be observed in plot with frequency 1 rad/sec transient response decays at around 8-time units but in order to get approximate value transient decay was considered as 30 time units.

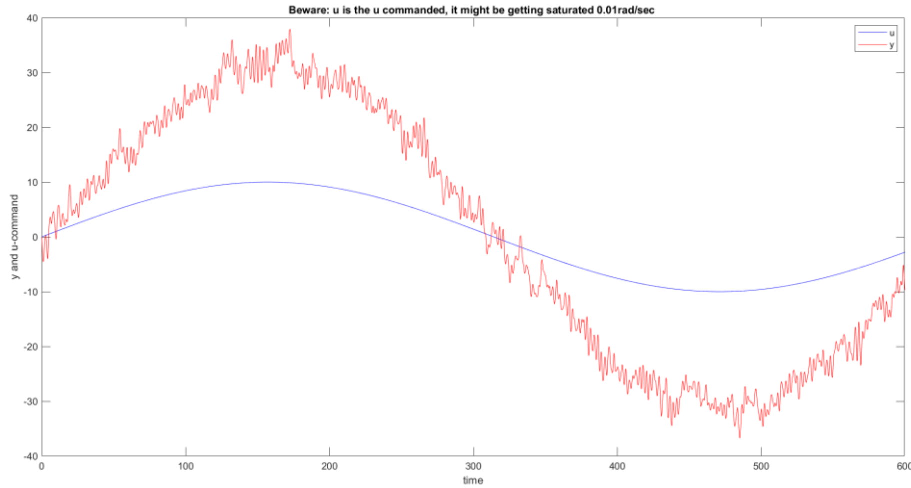


Figure 2 sine sweep at 0.01 rad/sec

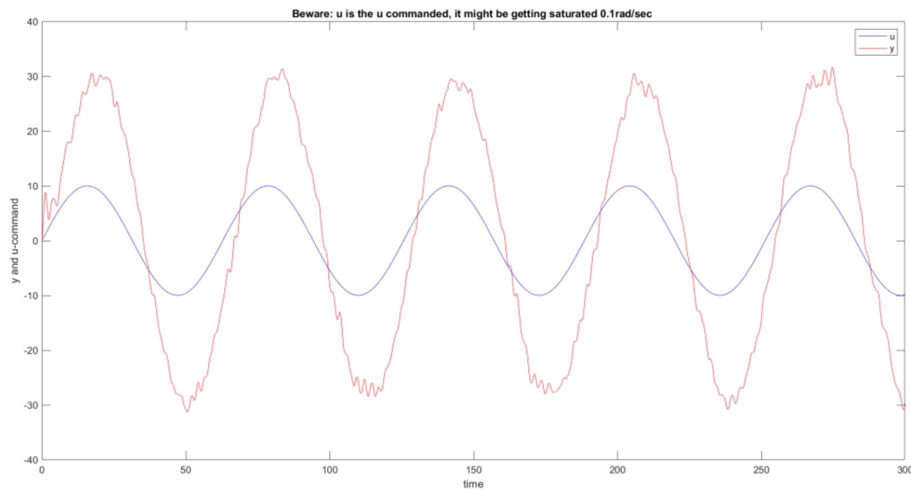


Figure 3 sine sweep at 0.1 rad/sec

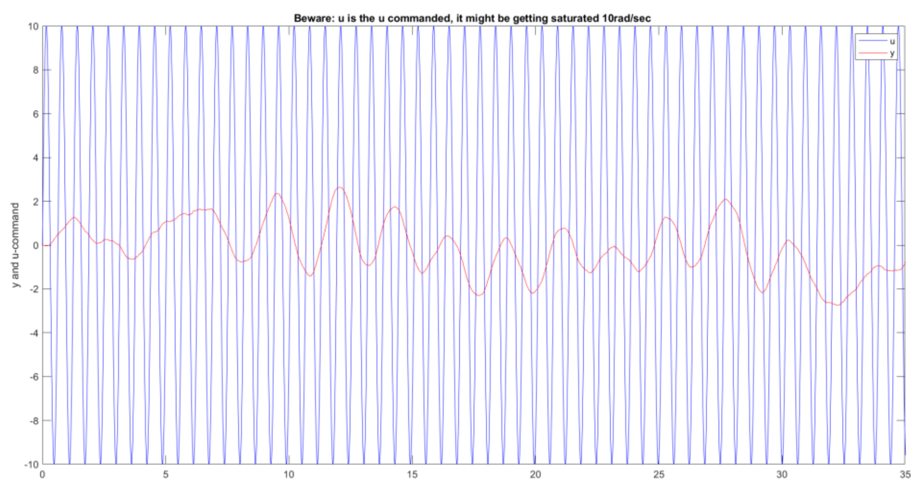


Figure 4 sine sweep at 1 rad/sec

After initial testing was performed, a larger band of frequencies was tested in succession using a MATLAB© loop to gather data from the system response and calculate $\hat{g}$ and $\hat{\phi}$ at each frequency. Tests were performed from $\omega = 0.1$ rad/s to 1000 rad/s, at an even log scale interval of 5 tests/decade using logspace command. To improve the system identification impact from noise, a max input amplitude of $A = 9.9$ was selected knowing the actuator saturation at [-10 10] and thus improved the signal-to-noise (SNR) ratio. To mitigate against transient impact, the previously determined decay time for transients of 20 seconds was used to shift the starting point of data collection. From this data, the nominal frequency response of the plant $P(j\omega)$was approximated across the frequency band. The MATLAB© function **invfreqs** was then utilized to fit an approximate transfer function $\hat{P}_0(s)$ with the experimental data. For using this function, an input array was made calculating the equivalent complex number $h_i = \hat{g}_i e^{j\varnothing}$ at each tested frequency, and the polynomial degree of the numerator and denominator were iterated until the estimated transfer function response matched the test data sufficiently. There was no method to the polynomial degree iteration, simply trial and error until the Bode plot matched the experimental response (by evaluating a graph like that in Figure 1-6). The **invfreqs** function was also formatted to ensure that the resultant transfer function was stable (i.e., poles in SLHP), given that instability was not evident during the sine sweep testing. It was found when trying to fit data across the entire band from $\omega = 0.1$ rad/s to 100 rad/s, that the estimated transfer function from **invfreqs** showed largely varying results.

The estimated transfer function of using the **invfreqs,** as well as its poles, zeros, and gain by using zpkdata, was determined as

**Zeros**

Z = [ -21.6760 +84.0832i, -21.6760 -84.0832i, 2.7579 +18.0402i, 2.7579 -18.0402i].

**Poles**

P = [-2.0436 +47.0606i, -2.0436 -47.0606i, -0.5711 + 2.7029i, -0.5711 - 2.7029i, -0.3446 + 0.0000i].

**Gain**

K = 0.0072.

This yielded the bode plot which was the best fit for experimented data. Figure shows the Bode Plot of the and the transfer function as follows:

```
sys =

  0.007213 s^4 + 0.2729 s^3 + 55.06 s^2 - 195.8 s + 1.811e04
  ----------------------------------------------------------
  s^5 + 5.574 s^4 + 2233 s^3 + 3334 s^2 + 1.782e04 s + 5836

Continuous-time transfer function.
```

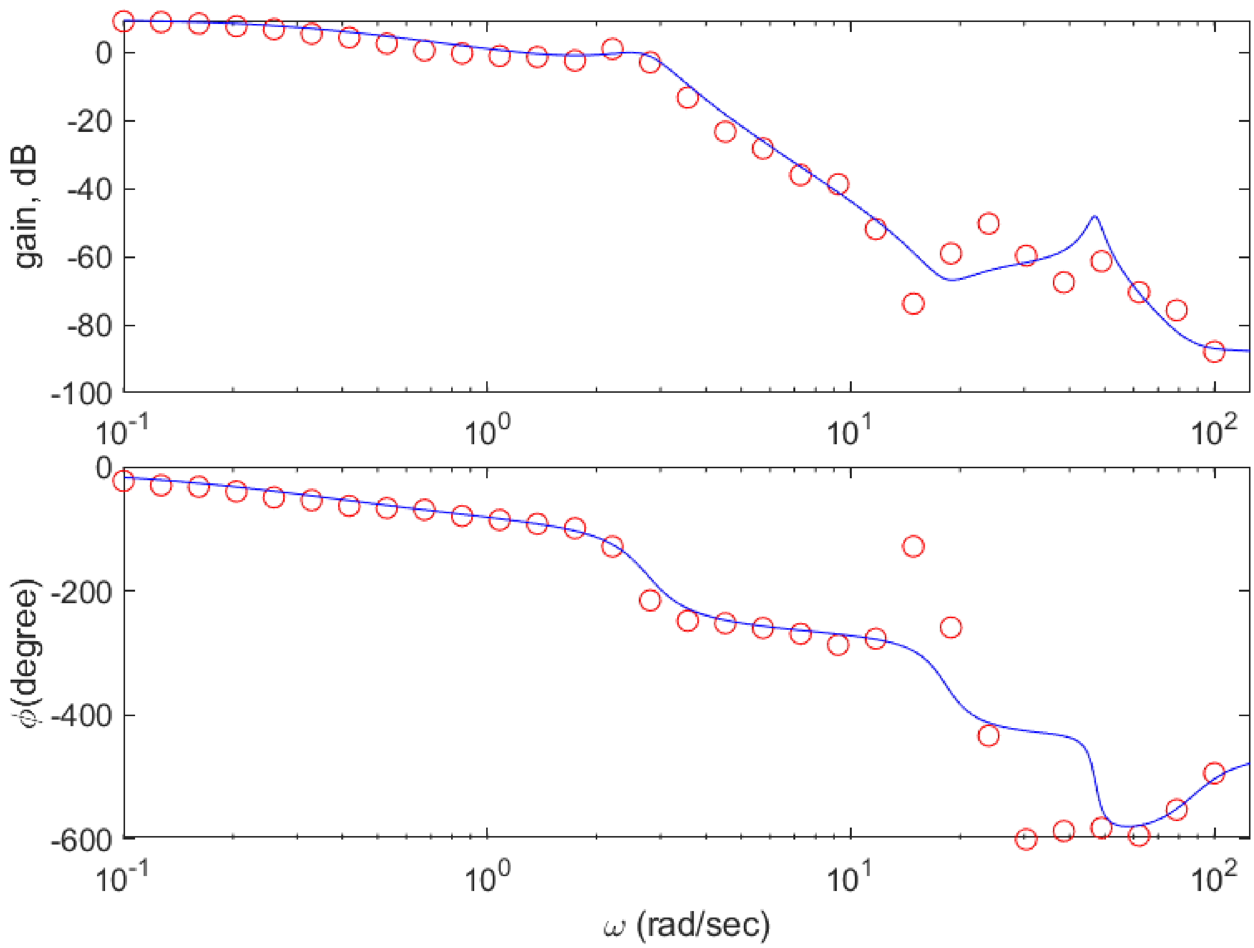


Figure 5 Bode Plots of estimated system vs experimental data

By looking at the poles of the plant we can find that the plant is stable. The order of the system was chosen by deeply analyzing the bode plots and the stability obtained by the The plant can further be fine tuned to estimate for better results even after considering the higher frequencies.

It was found the plants sine sweep output varies as we test with the same parameter due to the presence of noise at the higher frequencies. The estimate of the plant can be further improved by cancelling the poles and zeros but due to the time constrain I was not able to do it.

## Controller Design:

Now the plant has been approximately estimated and the next step is creating the closed loop control system using the state – space technique to achieve the peak overshoot below the 15% and rise time less than 2 seconds.

The plant can be represented in LTI state space form as:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

where A, B, C, D are the LTI state space matrices from a identified plant.

The Observer characteristics in state space model are

$$\begin{bmatrix} \dot{\tilde{x}} \\ \dot{\tilde{e}} \end{bmatrix} = \begin{bmatrix} A - BK & BK \\ 0 & A - LC \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{e} \end{bmatrix}$$

As this is a set point tracking problem. Luenberger observer is used to predict the states and actuator saturation block is attached. The values of the Q and R in the equation are tuned to get the best setpoint tracking possible.

$$[K, S, CLP] = \text{lqr}(SYS, Q, R, N)$$

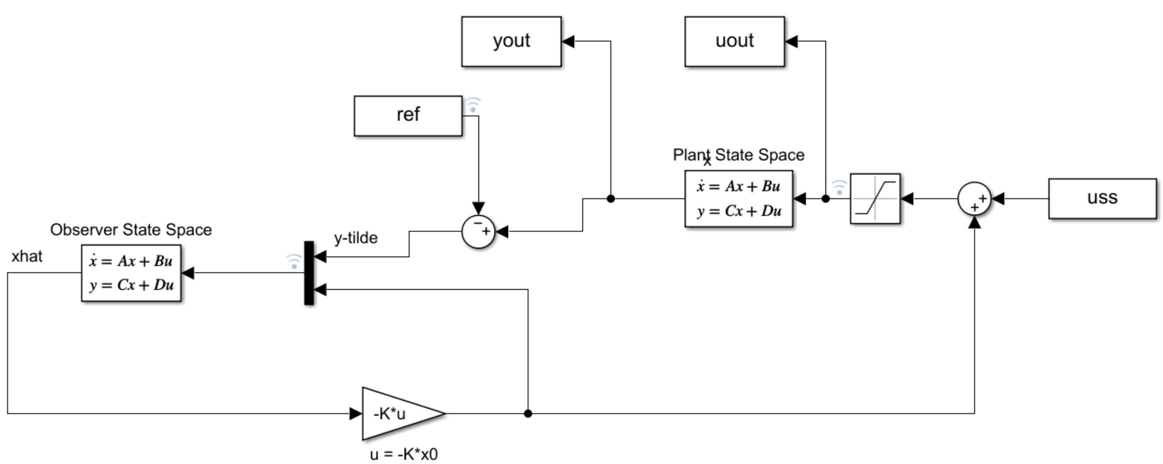


Figure 6 Simulink model of the Estimated plant

The eigen values of the closed loop Design Simulink model is computed and are as follows: The Values of the Q and R are iterated, and best reference tracking of input is finalized by checking the Saturation limits of the plant.

eig (Aobs) = -4.0876 +94.1212i
-4.0876 -94.1212i
-4.3611 + 0.0000i
-2.2822 + 6.5109i
-2.2822 - 6.5109i

This shows that the plant Is stable and is robust.
The Reference to output tracking of the estimated system is as follows:

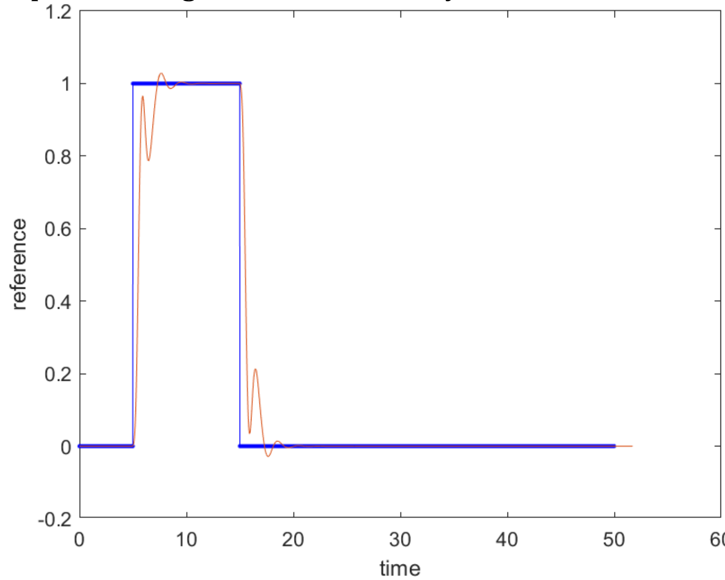


Figure 7 output to reference of the Estimated plant

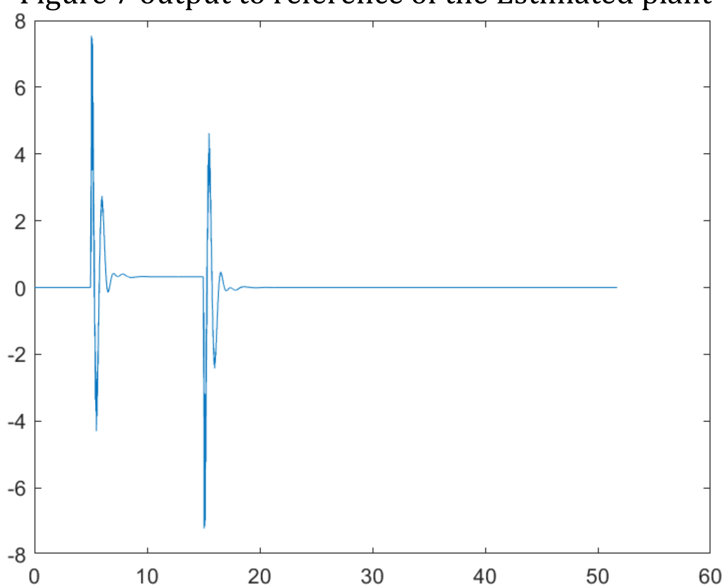


Figure 8 Input of the estimated plant on time scale

From the figure 7 the following characteristics of the estimated system were calculated:

1. Peak overshoot = 2.8%
2. Rise time is 0.9 seconds

Both the desired characteristics of the plant are achieved.

**Controller Testing on the Virtual Plant:**

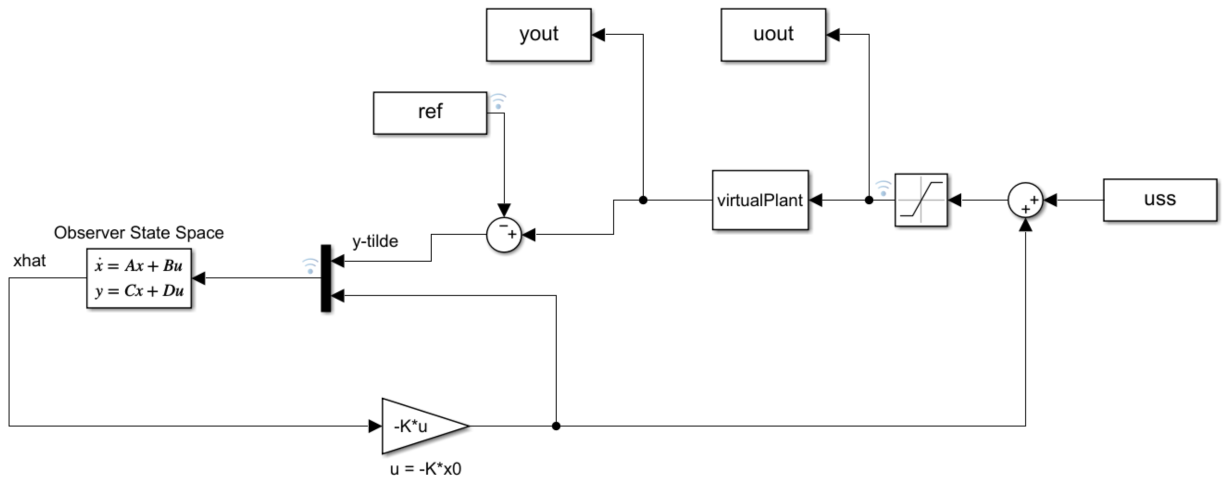


Figure 9 Simulink model of the Controller applied on the virtual plant

In testing the Production output, the state space model of the estimated plant was replaced by the virtual plant and the closed loop controller was used to track reference of the plant.

The simulated results of the controller were as follows:

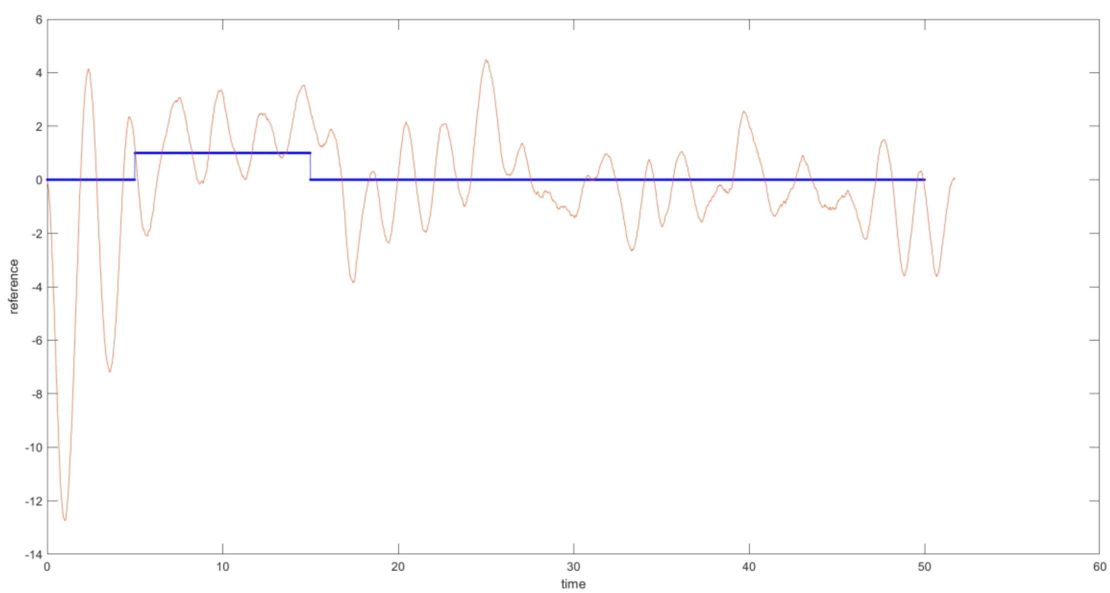


Figure 10 Reference tracking of the controller on the provided virtual plant.

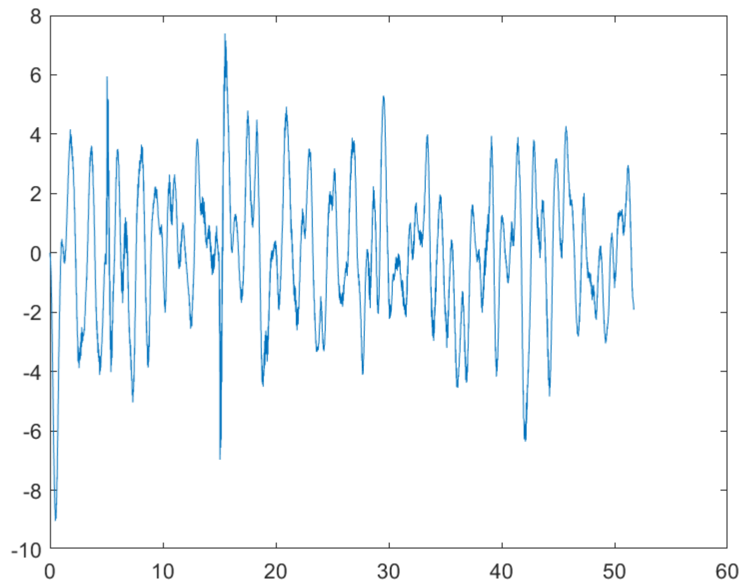

Figure 11 Virtual plant input vs time

The reference tracking of the virtual plant is not so good due to the bad estimate of the system. The miscalculation in the system estimate was because it has lot of noise included which led to mis conduct of the system at the after frequencies of 100.Once if the system is properly estimated the reference can be tracked with perfectly tuning the Q, R values while designing the LQR.

**Scope:**

The system estimate can be improved using the accurate integration approximation of the Quadrature integrals, Proper frequency selection for plant estimation which will give peak and crest values of the phase and magnitude plots, once the plant estimate is accurate the ratio of q/r can be properly selected such that the characteristics of LQR are accurate. i.e., tuning of Q, R. By achieving these values accurately, the reference tracking of the Virtual plant can be achieved to acceptable levels. Also, the noise attenuation can be done using appropriate filters. The robustness can be improved there by leading to perfect controller.

**Conclusion:**

While working with real time plants the scenario of obtaining the exact same theoretical reference is near impossible. They can be made for satisfactory performance which means trading off between the various characteristics of the controller. This project shows the approach of how a controller can be designed for an unknown plant by estimating the unknown plant and then validating it by doing closed loop controller testing on a unknown plant. As said the scope section the achieved controller is not satisfactory, and it can be further improved by doing above mentioned values.

**** All the MATLAB and Simulink files are renamed as suggested in project and are submitted in a folder.**
***** To prevent excess pages than required the index was included in the Title Page.**