UNIVERSITY OF CAPE TOWN

Department of Electrical Engineering

EEE3094S – Control Engineering
Project 2019 Report

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14th September 2019

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Date: 14th September 2019

Executive Summary

Given an individualized simulation of the vertical motion of a helicopter that was actuated by an external voltage that sets the angle of the main rotor blades, the following was done:

(a) SYSTEM IDENTIFICATION:
Techniques of control engineering were applied to establish the form of model needed for the problem, determine the model (continuous and the discrete model) parameter values (i.e. gain, time constant, etc) and then validating this model.

(b) PROCEDURAL DESIGN:
Using root locus and its extended versions and frequency methods to produce a control system to attain and hold its altitude at a given setpoint.

(c) HARDWARE REALIZATION:
Implement the design in electronics via OpAmp circuits.

(d) COMMISSIONING:
Demonstrate that the circuits performed as designed.

Contents

1. Introduction and Background on Helicopter Control

Helicopter flight procedures are relatively unstable and difficult to deal with, and hence the use of Control systems engineering is vital to stabilize and ease the helicopter altitude when given a setpoint height.

The simulated helicopter takes in an electrical input voltage which powers the engine and sets the main rotor blades running to put the helicopter in vertical motion. The outputs of this system are the helicopter speed and altitude. For our case, the controlled output is the helicopter altitude.

In the real world, the helicopter controller would meet with disturbances (both input and output disturbances). Input disturbances could be in the form of changes in the wind speed and direction and also air pressure changes while the output disturbances could be wear and tear of rotors in the motors. These disturbances often affect the control action and thus have to be taken into account while designing a controller. For this project, the input disturbances were already accounted for in the plant and the output disturbances were taken to be a step (a sudden change), as it would be in reality.

The environment concerns a helicopter carries in the real world could be that of contributing to the greenhouse effect by emmiting greenhouse gases while burning fuel to power its engine. But since this project is a purely simulated experiment, there are no environmental concerns associated with it.

As far as the cost is concerned, the control action is in the form of electrical voltage, which in reality would mean fuel input or rotor angle change. The amount of such inputs supplied is often proportional to the cost of supplying them. Hence, the control action is just one way of measuring cost. However, quality of products of the control system also quantify the cost and all these physical costs would further help in optimization analysis between speed, stability and tracking.

2. Technical Specifications

After analyzing the helicopter system, the following technical specifications were formulated:

1. The helicopter must have a steady state error in tracking fixed altitudes.
   - A worst case of 5% steady state tracking error
   - Steady state disturbance and noise response should also be within 5% of setpoint

2. The system should efficiently attenuate system disturbances.
   - Less than 20% peak over/undershoot in transient tracking and disturbance responses

3. The closed loop helicopter system should not be slower than half of the plant
4. No oscillations at steady state. Means closed loop poles should be on or close to the real axis

Steady State error:
To have a zero steady state error, the POSITION error has to be zero. This is achieved by having a minimum of type 1 forward loop equation. This means that if the plant is a type 0, the controller has to be a minimum of type 1 and if the plant is type 1, the controller has to be a minimum of type 0. However, if we want a finite steady state error, the forward loop has to be a type 0. This would however during implementation might go over the required steady state error. Hence, a type 1 forward loop is chosen to have a zero error.

Peak Over/under shoot:
Peak overshoot is the maximum value to which the output goes to before finally settling. The peak overshoot is directly related to the phase margin, which inturn is related to the damping ratio via the following formulas:

%Peak Overshoot = 75-Phase Margin;
Phase Margin ≈ 100*Damping Ratio

Hence, given a maximum overshoot of 20%, this would mean a minimum phase margin of 55, meaning a minimum damping ratio of 0.55

Closed Loop Speed:
This was determined by looking at the settling time from the helicopter app in the lab. The settling time for this helicopter system was 10 seconds (0.1 Hz)

3. Modeling, System Identification and Problem Formulation

a) System Modeling:

Simulation was carried out in sCAD by supplying an input voltage to turn on the helicopter engine. Once the engine was ready, voltage was steadily increased until lift off. Voltage was then controlled until a stable altitude was achieved. A step was then introduced, making the helicopter rise exponentially (confirming that the initial design was unstable), until a final speed was reached. Data was logged throughout the process and system identification was carried out.

The nominal model was used to describe the helicopter system. This model illustrates the plant as simple as possible while capturing all vital data of the system. This system is modelled by the block diagram in Figure 1 which explains the flow of the plant between the input voltage, angle, speed and position.

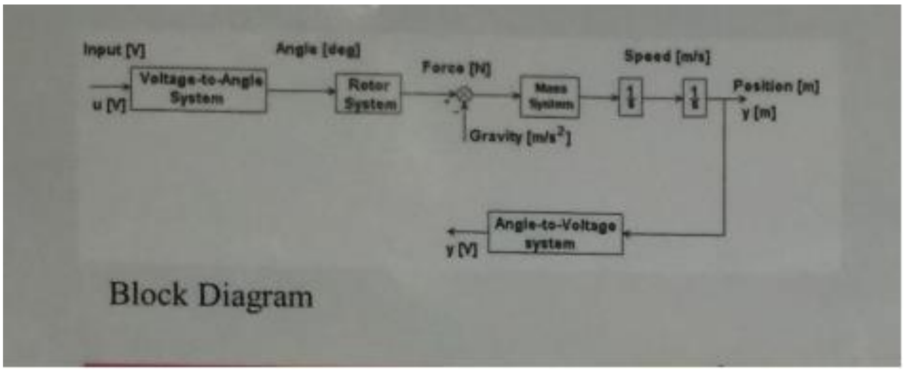

Figure 1: Block diagram of the plant

b) <u>System Identification:</u>

During System Identification, the data gathered for the input (voltage) and output (voltage and height) parameters were recorded in a spreadsheet and plotted against each other. Since the height was exponentially rising, this was differentiated w.r.t. time to get the speed of the plant. The final constant value of speed was found to be 54.45 m/s. The input had an initial value of 2.5V and a final value of 5V. These are represented in Figure 2 below and plotted against time.

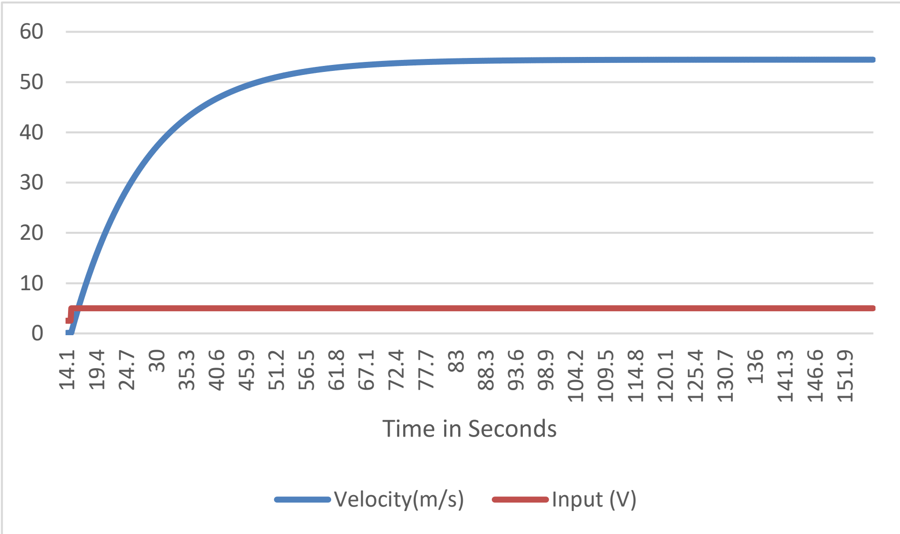

Figure 2: Plot of input voltage and output speed of the simulated helicopter against time

The simulation was carried three more times, and the gain, time constant and sensor value were then obtained. The calculations for each are shown below:

i) Gain, A = $\dfrac{Final\ Velocity - Initial\ Velocity}{Final\ input\ voltage - Initial\ inputvoltage} = \dfrac{54.45 - 0}{5 - 2.5} = \dfrac{54.45}{2.5} = \underline{\mathbf{21.782}}$

ii) Time Constant, τ = [Time taken for 0.63*Final_velocity] – [Time when input reached 5V]
Time Constant, τ = 28.22 – 15 = <u>**13.22s**</u>

iii) Sensor Value = $\dfrac{Output\ Voltage}{Output\ Height} = \underline{\mathbf{0.86}}$ (Average of sensor value readings until output was constant)

The plant had a model equation of g(s) = $\dfrac{A}{s(\tau s+1)}$,where A is the gain and τ is the time constant i.e. time required to reach 63.3% of final value.

From the above values, the plant transfer function was:

$$\boxed{g(s) = \frac{21.782}{s(13.22s+1)}}$$

Equation 1: Plant Transfer function

This transfer function indicated that the plant was of Type 1, order 2 and had two poles; one at s = 0 and the other at s = -0.0756. The pole at s=0 also meant the system was only marginally stable.

c) <u>Problem Formulation:</u>

Having found the plant transfer function, the project now moved forward to formulate the problem of designing a suitable controller for this helicopter system. A closed loop model as shown in Figure 3 was designed in Simulink to give an idea on how to plan for the controller.

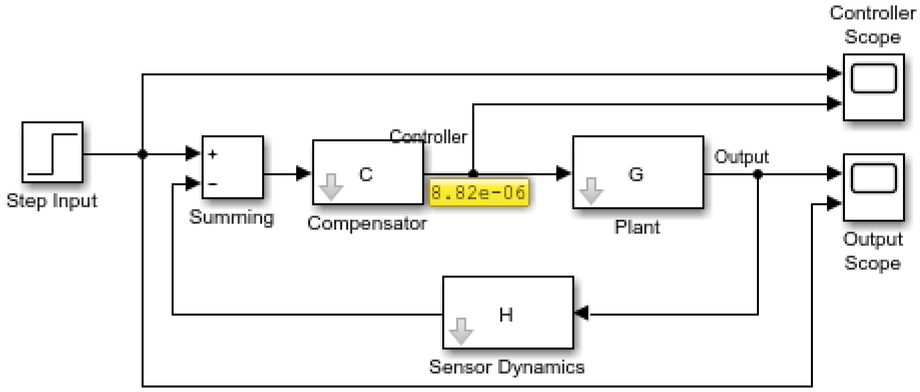

Figure 3: Closed Loop System

4. Controller Design and Simulation

Before choosing the controller type, it was necessary to look at the root locus of the plant because this would show the location of poles and zeros that would need to be placed for the system to work as desired. Thus, Figure 4 below shows the root locus and step response of the helicopter plant.

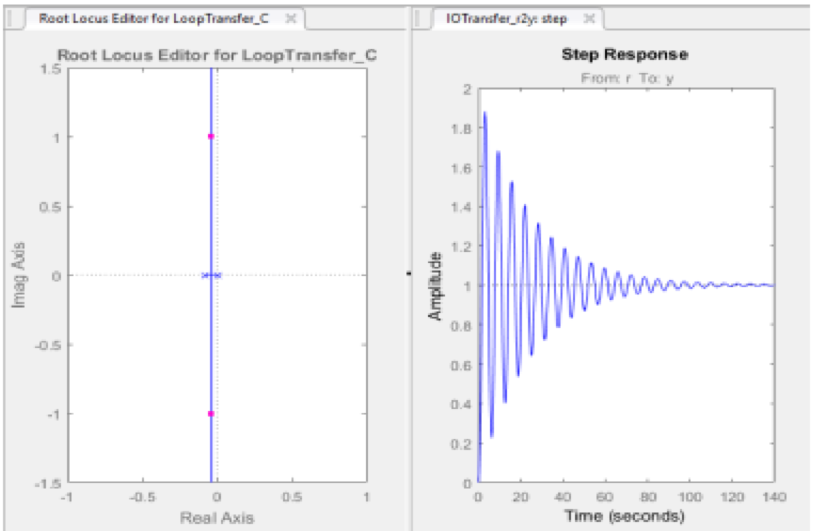

Figure 4: Root Locus (Left) and Step Response (Right) of the Open loop plant

The technical requirements mentioned at the beginning also needed to be met inorder to design a good controller. Figure 5 below indicates the desired region of poles and zeros made by the speed constraint line and the damping lines.

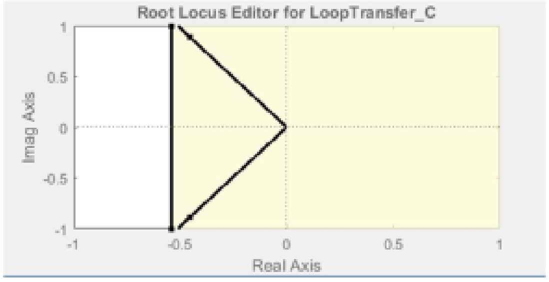

Figure 5: Desired region (Unshaded) for the closed loop poles

Controller Types:

There are various controllers available for various purposes but for this project we will look at the Proportional controller, the Lead controller and Lag controller.

a) Proportional Controller:

This is the simplest of the controllers as its value is just a constant gain i.e. output of the controller is the multiplication of the error signal and the proportional gain. The disadvantage of this type of controller is that it can not eliminate offset error (i.e. difference between the desired value and actual value) as it requires an error to generate an output.

The closed loop system for a proportional controller is always stable for all values of k > 0

$$g_{CL}(s) = \frac{k(s)g(s)}{1 + k(s)g(s)h(s)} = \frac{21.782k}{13.22(s^2) + s + 18.73k}$$

Equation 2: Closed loop plant function using P-Controller

If we consider k = 0.00287 for the P-controller, its root locus as shown in Figure 6 would make the system stable but the closed loop poles would not adhere to the speed requirement as they are placed before the speed line limit.

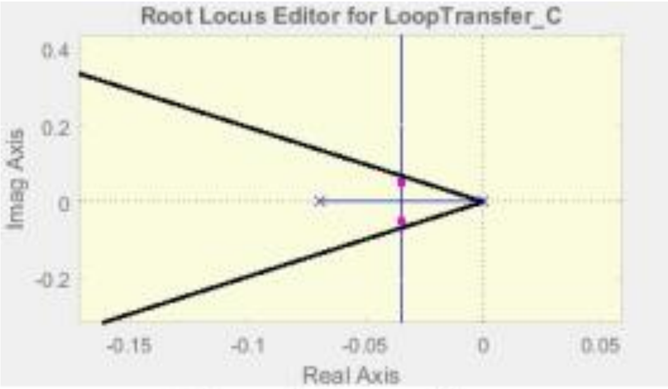

Figure 6: Root Locus for Proportional Controller

b) <u>Lead Controller:</u>

This is a controller with a zero closer to the imaginary axis than its pole.This controller amplifies high frequencies and contributes a positive angle to the phase of the system. It reduces the DC gain of the system and hence is, bad for setpoint tracking. However, for this project, the plant was already a type 1 and hence, the error should not be a problem. Lead controller also improves stability.

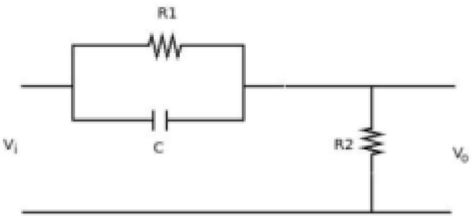

Figure 7: Lead Circuit

The Lead controller transfer function is k(s) = $\frac{1+aTs}{1+Ts}$, where a = $\frac{R1+R2}{R2}$ and T = $\frac{CR1R2}{R1+R2}$

From Matlab Control system designer, the desired lead controller function was found out to be:

$$\boxed{\mathbf{k(s)} = \frac{\mathbf{6.702\ (s + 0.2812)}}{\mathbf{(s + 5.817)}} = \frac{\mathbf{0.324\ (1 + 3.556s)}}{\mathbf{(1 + 0.172s)}}}$$

Equation 3: Lead Controller Transfer function

From the above Equation 3, it was evident that the values for ‘a’ and ‘T’ were:
<u>T = 0.172</u>

aT = 3.556
<u>a = 20.67</u>

Figure 8 below shows the pole at s = -5.817 and zero at s = -0.2812 of the Lead controller transfer function. It also shows the step response which meets all the technical requirements mentioned earlier.

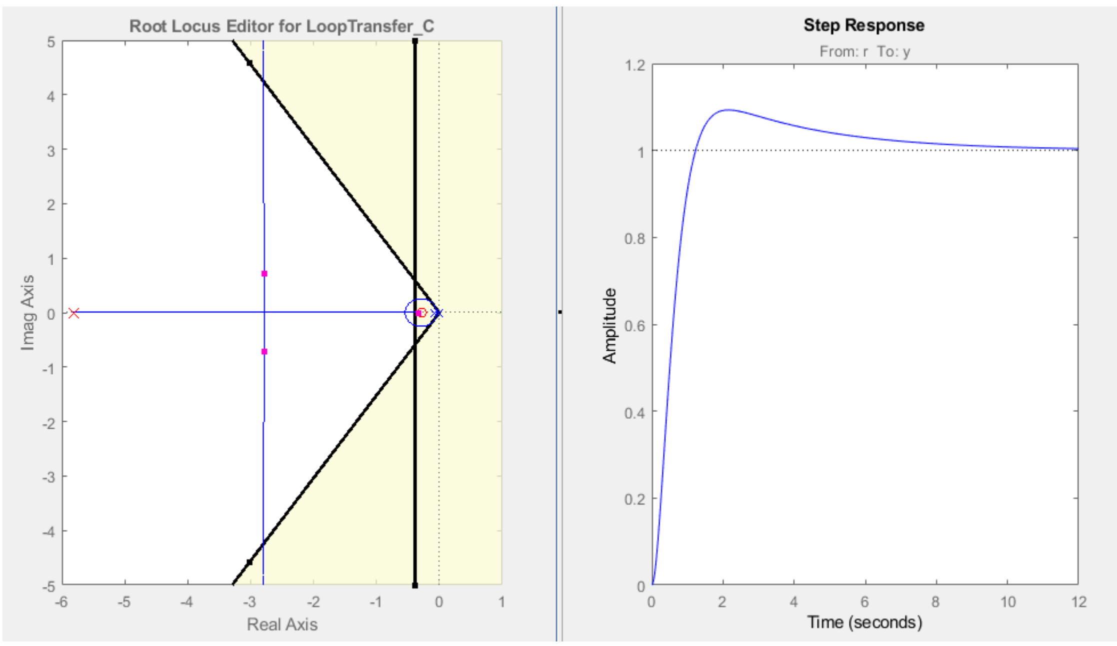

Figure 8: Root Locus (left) and Step Response (right) for the Lead Controller

c) <u>Lag Controller:</u>

This is a controller with a pole closer to the imaginary axis than its zero. Although this is helpful in improving set point tracking, the report will not be using this controller as the system must have a zero closer to the imaginary axis than a pole to ensure causality and stability.

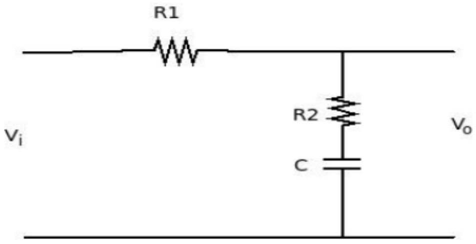

Figure 9: Lag Controller Circuit

The Lag controller transfer function is k(s) = $\frac{1+Ts}{1+aTs}$, where a = $\frac{R1+R2}{R2}$ and T = CR_2

d) <u>Selecting the Optimal Controller:</u>

Looking at the behaviours and root locuses of the Proportional, Lead and Lag controller, the Lead Compensator controller was selected as the best fit controller for this helicopter system. This is because as seen from Figure 6, the proportional controller did not meet the speed requirement, and the Lag controller was not optimal to ensure stability, while on the other hand, the Lead compensator fulfilled all the technical requirements and also provided the system with stability.

5. Controller Implementation

a) <u>Proportional Controller:</u>

As mentioned earlier, the proportional controller has a contant gain and hence it could be represented by an inverting amplifier of gain k.

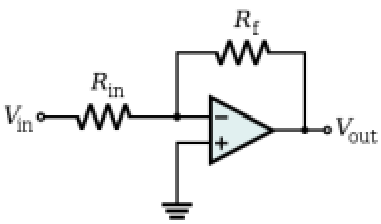

Figure 10: Analogue representation of P-Controller

The gain is then controlled by setting the resistor values, where k = Rf/Rin

If we were to implement a proportional controller, then the gain value would be determined by:

k = $\frac{Product\ of\ distance\ from\ poles}{Product\ of\ distance\ from\ zero}$

But we know from Equation 1, that the plant only had poles and no zeros and thus the distance from zeros would basically be undefined or infinity; which means the k value must be very small.

Thus, the following step responses were obtained using Equation 2 and various k values:

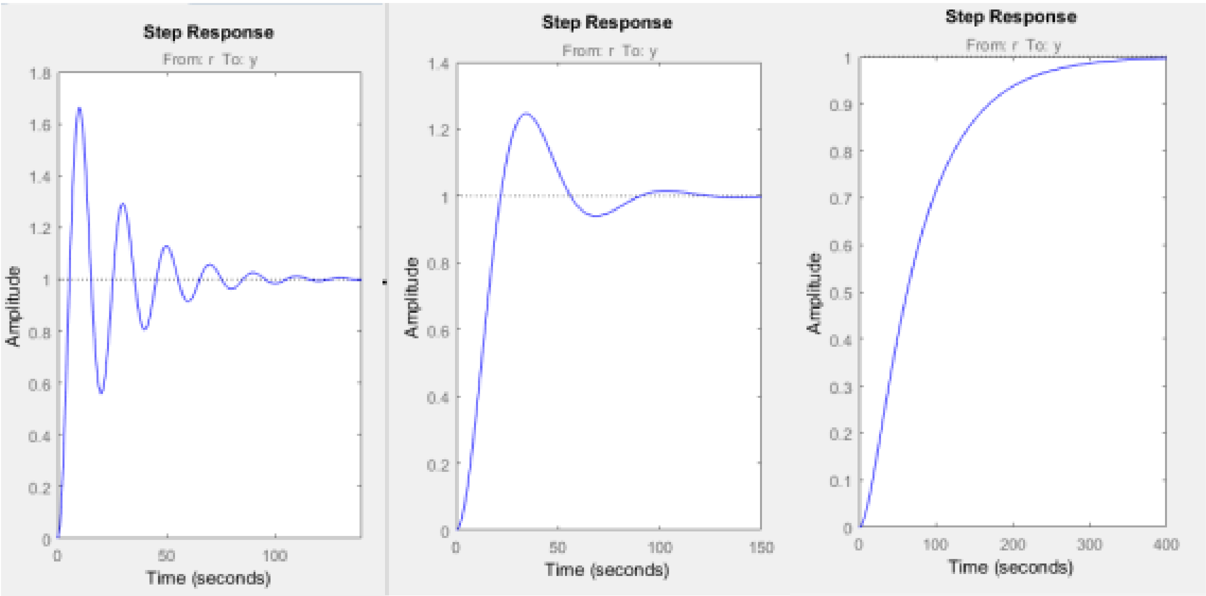

Figure 11: Step responses with P-Controller of gain value 0.1(left), 0.01(middle), 0.001(right)

As seen from the figure, as k decreases, overshoot and oscillations are controlled. However, the settling time increases. Hence, this controller would not agree to the speed specifications mentioned.

b) <u>Lead Controller:</u>

From the Lead controller Equation 3, we found that a = 20.67 and T = 0.172 and we can thus implement the analogue circuitry of Figure 7 using equations:

$$a = \frac{R1+R2}{R2} = 20.67 \quad \text{and} \quad T = \frac{CR1R2}{R1+R2} = 0.172$$

Solving these two equations, we get R1 = 3556 Ω, R2 = 180.78Ω and C = 1000uF

But since we only get E12 Resistor values from the lab, the values of R1 and R2 used were:

R1 = 3300 Ω + 270 Ω = 3570 Ω
R2 = 180 Ω

//R1 was labeled as R5 and R6 in the Figure 12 schematic below

//R2 was labeled as R7 in the Figure 12 schematic below

Some more calculations for the full analogue circuit implementation in Figure 12 below:

From Equation 3 we saw the constant 6.702, which indicated a gain of 6.702. Hence,
6.702 = R3/R1 ; <u>R3 = 6800 Ω</u> and <u>R1 = 1000 Ω</u>

Also R3=R4 and R1=R2 (Differential Amplifier)
And R8, R9, R10, R11, R12 = 1000 Ω

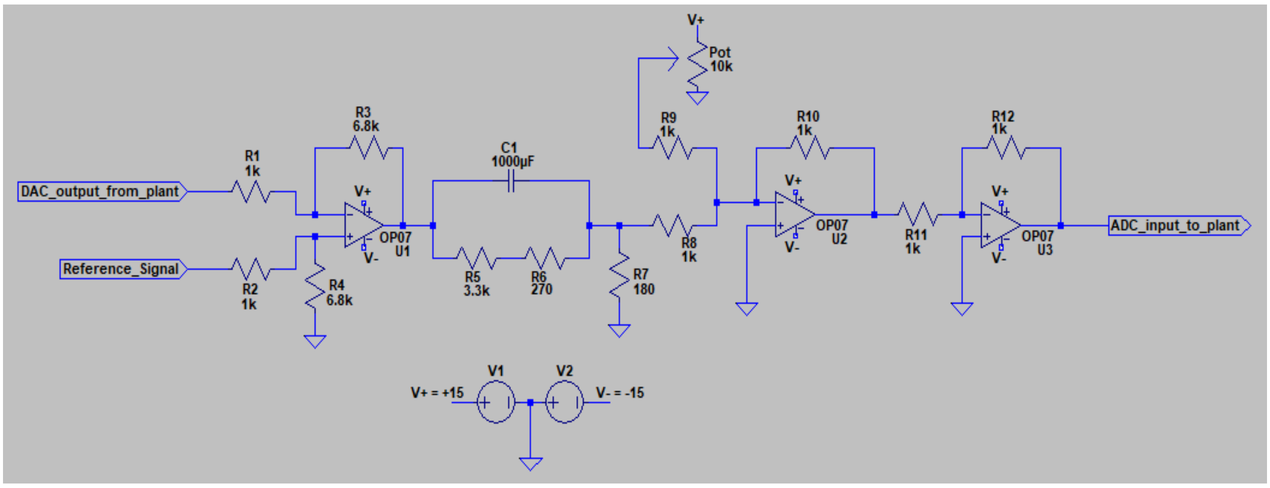

Figure 12:Complete analogue implementation of the Lead compensator controller

In Figure 12 above, the first op-amp circuitry is the differential amplifier with the Reference_Signal being the non-inverting input and the DAC_output_from_plant being the inverting input. The output of this amplifier goes to the Lead Compensator controller whose values were calculated above and the output of this is combined with an offset signal (to set a 2.5v input for takeoff) and both these signals serve as the inverting inputs to the summing amplifier. The output from this summing amplifier is then connected to an inverting amplifier to revert the gain sign and this output is then connected to the ADC_input_to_plant.

6. System Testing

Since it was evident that the Proportional controller did not meet some of the requirements, thus this report only tested for the Lead Controller in simulation testing and analogue testing.

a) <u>Simulation Testing:</u>

The Lead compensator was tested in the sCAD software before implementation. Output disturbances and noise were added to the system and the results obtained were presented below:

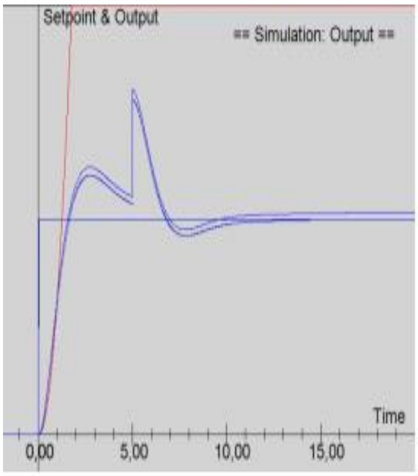

Figure 13: Output disturbance Effect

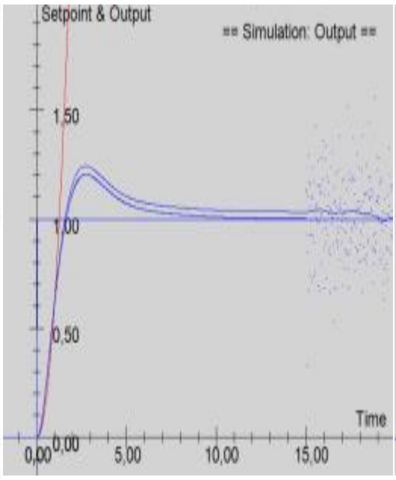

Figure 14: Noise Effect

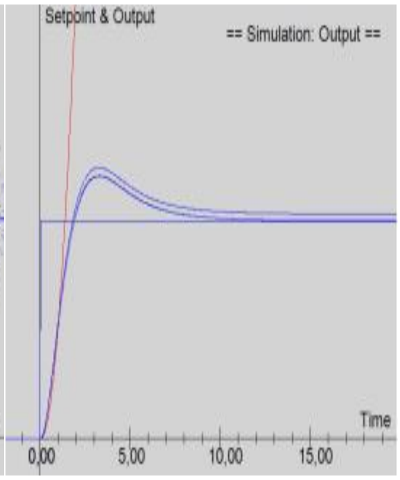

Figure 15: Nominal parameter response

From Figure 13, 14 and 15, we see that the results of the lead compensator from the sCAD simulations met most of the technical requirements. The system rejected the output disturbance but failed to reject the noise effects. It was also noted on how the overshoot was <20% and settling time was 9s. Since these are simulation results, they may slightly differ from actual results due to component tolerances.

b) Practical Implementation Testing:

The Analogue implementation from Figure 12 was tested in the Lab Helicopter App. Output disturbances were also added to the system and the results obtained were presented below:

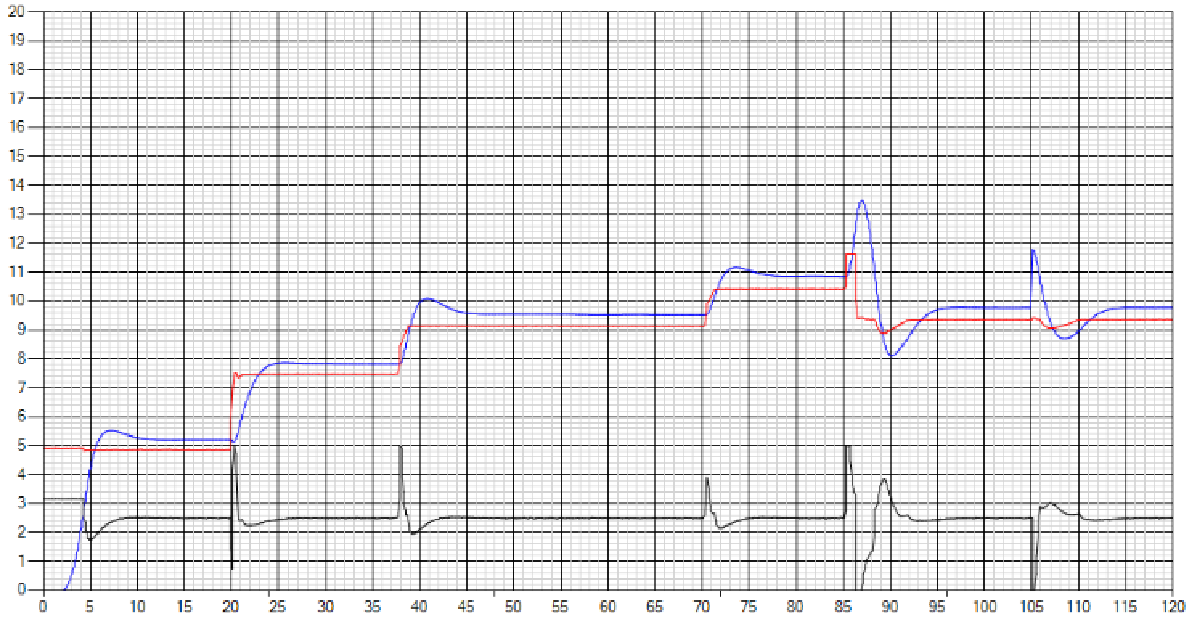

Figure 16: Test Results of the Closed Loop System

From Figure 16 above, it is noticed that the overshoot was about 12% with a settling time of about 9s (better because it was even less than the recommended lab settling time of 10s). Also, the steady state error was less than 5% worst case (which was inside the recommended range). The test results agree with the simulated results because the component values chosen were not considerably large, meaning the tolerance would have played negligible effect on the controller values. When disturbances were injected at 88s and 106s, the controller worked to correct it (as seen by the black curve) and brought the helicopter to settle again within 9s without any oscillations at steady state. Hence, the implemented lead compensator controller passed all the specifications.

7. Conclusions

The lead compensator performed better than the Proportional and Lag controller in the closed loop configuration. The root locus design method was used to design the lead compensator. The system desired output specifications were converted into the s-plane speed and damping lines and a zero and poles were placed according to the root locus method while adhering to the lead compensator conditions. The lead compensator was tested in a closed loop system both in simulations and in the laboratory. The results obtained from the practical testing of this system were:

- The system achieved a steady state error of 4.6% which is within the 5% worst case range
- The system also achieved a settling time of 9 seconds which is well under half plant time
- Percentage overshoot was of 12% with no oscillations at steady state
- The system managed to reject output disturbances, but failed in the presence of noise (this was in simuation because no noise effect was implemented in the practical testing)

Finally, the cost for controlling the helicopter for a given time would be the cost of the components used to build the controller, fuel for the helicopter in order to control height and rotor angle, as well as the actual time used in creating the controller. The quality of components used would be another determining factor for the cost. All these physical costs would further help in optimization analysis between speed, stability and tracking.

8. References

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