

## Travel Angle Control of Quanser Bench-top Helicopter based on Quantitative Feedback Theory Technique

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### Abstract

A three degree of freedom (3-DOF) bench-top helicopter is a simplified aerial vehicle which is used to study the behaviors of the helicopter as well as testing multiple flight control approaches for their efficiency. Designing helicopter's dynamic control is a challenging task due to the presence of high uncertainties and non-linear behavior. The main objective of this research is to achieve robust control over the helicopter model regardless parameter variation and disturbances using robust control technique, Quantitative Feedback Theory (QFT). QFT utilizes frequency domain methodology which ensures plant's stability by considering the feedback of the system and thus removing the effect of disturbances and reducing sensitivity of parameter's variation. The proposed technique is tested against LQR-tuned PID controller in both simulation and real hardware environment to verify its performance. The results obtained shown us that QFT algorithm managed to reduce settling time and steady state error of about 80% and 33% respectively over the classical PID controller.

**Keywords:** Quantitative Feedback Theory, bench-top helicopter, robust controller

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### 1. Introduction

Bench-top helicopter is an example of system with high uncertainty. It is very challenging to engineers as well as researchers to exert good stability tolerance and performance attribute for closed-loop system. A three-degree of freedom (3-DOF) laboratory scale bench top helicopter usually been used by engineers and researchers to study the dynamic behavior of the aerial vehicles and set as experimental model for verifying the effectiveness of various flight control algorithms.

Achieving high performance control over 3-DOF helicopter is a difficult task due to the essence of a few challenges. Firstly, it is an under actuated system, which means number of control inputs are less than number of outputs to be controlled; in this case it has two control inputs and three outputs [1]. Secondly, there is some close relationship between movement of pitch and travel; the latter is our main interest in this project. Furthermore, multiple variables such as flight altitude, fuel consumption, airspeed and amount of load could affect the plant parameters of the aircrafts and control structure of the system [2].

Many works has been done to achieve either robust or adaptive control over the helicopter. The method of combination of Linear Quadratic Regulator-Proportional Integral Derivative (LQR-PID) controller was proposed in [3]. However, it is found out that this LQR-PID based controller lacks in terms of accuracy (high steady-state error) and rapidity (settling time) [4]. Another method proposed is multiple-surface sliding controller (MSSC) [5]. Although MSSC was proven to perform better than PID controller, tedious mathematical works are needed to attain the desired equation and gain. Combination of classical PID and fuzzy controller was also proposed in [6] and [7]. It combines the convenient control of PID together with flexible control of fuzzy for 3-DOF model helicopter.

In general, the problems faced by the previous reserchersto control aerial vehicle are lack of accuracy, slow response and slow computational time due to complex mathematical equations. In this research, Quantitative Feedback Theory (QFT) is proposed as the intergratedcontroller for travel angle control. QFT was developed by Prof. Isaac M. Horowitz in the early 1970s, designed to deal with the uncertainty of plant's parameters explicitly to suit the purpose of performance and stability [8]. During the design, the plant uncertainty is defined

upfront; as well as performance specifications. As a result, a robust controller with high accuracy and fast response could be achieved.

In this research, Quanser bench-top helicopter has been chosen as the case study. The existing controller provided by the manufacturer is LQR-PID where the performance is set as the benchmark. The QFT is proposed to be intergrated with PID controller named PID-based QFT. In order to validate the results, performance comparison has been conducted on both simulation and actual bench-top helicopter environment.

Through QFT approach, a combination of linearization, quantization and translation of desired performance such as robust stability and robust performance is carried out on set of bounds in Nichols chart; while uncertainties are converted into areas in Nichols chart called templates. Loop shaping process is then carried out to find the controller parameters by using the Nichols chart that illustrates stability, performance, and disturbance rejection bounds [9]. This can be done by fine-tuning the gains and dynamic elements such as poles, zeros and their complex elements to the frequency response of nominal plant.

This paper is organized as follows. Section 2 discussed the fundamental knowledge about QFT technique. Section 3 is about the methodology of the research while section 4 presented the results and analysis of the simulation as well as the results on the actual bench-top helicopter. Comparison of the performance of LQR-PID and LQR-PID based QFT is also discussed in this chapter. Finally, section 5 concluded the research findings with some recommendations for future work.

## **2. QFT Fundamentals**

### **2.1. Plant Template**

In QFT techniques, the plant's dynamics is represented in the form of frequency response which is founded on the principles of frequency loop shaping mixed with the plants' uncertainties [10]. By considering all set of plants instead of a single plant, the magnitude and phase of the plants generate set of points on the Nichols cart at each frequency rather than a single point. Hence a connected region or called template is composed at each selected frequency, which surrounds this set of points.

### **2.2. QFT Bounds**

The major step in QFT approach is retrieving domains in Nichols chart by means of converting frequency domain specifications situated on the feedback system. 'Bounds' is used to refer these domains in QFT's list of terms. Final step of the design is accomplished when a nominal loop transfer function is shaped such that it achieves nominal closed-loop stability and lies within its bounds.

### **2.3. Loop Shaping**

Design of the controller is carried out by the process of loop shaping in the Nichols chart. The nominal open-loop transfer function characteristics are plotted together with the composite bound which is evaluated at the trial frequencies. Basically, the designing process involves addition of multiple elements such as gain, integrator, pole and zero and their counterparts [11]. By the operations done, shape of the open-loop transfer function is altered so that the boundaries are compensated at each of the trial frequencies.

## **3. Research Method**

The three degree-of-freedom (3-DOF) helicopter setup for the experiment is manufactured by Quanser Consulting Incorporated. The free body diagram (FBD) of the system is shown in Figure 1 below.

### **3.1. Modelling of 3-DOF Bench-top Helicopter**

In this project, our main interest is the control of travel angle of the helicopter. Changing the travel direction is quite a challenging task here. This is because travel angle has direct relation with pitch axis; that is the only way to control travel angle is by pitching the body of the helicopter. Figure 2 shows the FBD for travel angle mechanism.

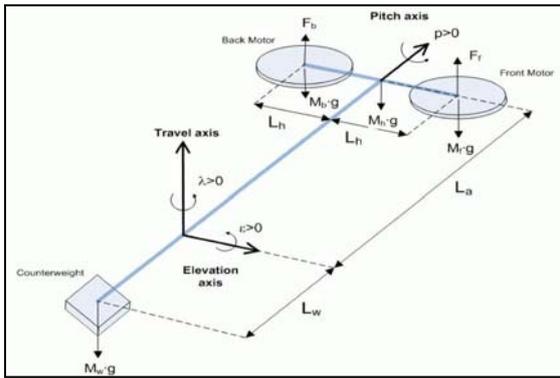


Figure 1. Free body diagram of 3-DOF Helicopter System [12]

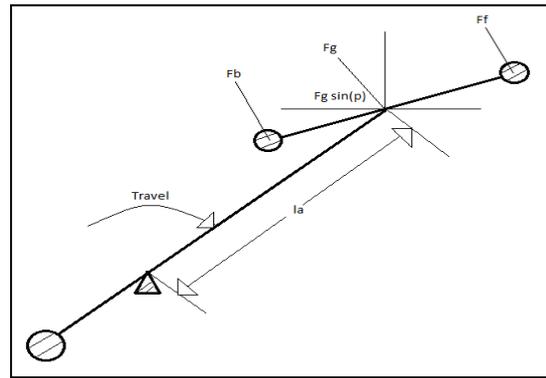


Figure 2. Free body diagram (FBD) for helicopter's travel angle

Referring to figure above, the helicopter's body is assumed to be pitched up by an angle  $p$ . For small angles, the force required to keep the helicopter in the air is approximately  $F_g$ . Acceleration with respect to travel axis is the result due to torque produced by the horizontal component of  $F_g$ . The equation associated with travel angle is given in Equation (1) below.

$$J_t \ddot{r} = -K_p \sin(p) \cdot l_a \tag{1}$$

Where  $r$  is travel rate in radian per second,  $K_p$  is the force required to keep the helicopter overhead which is approximately  $F_g$  and  $\sin(p)$  is the trigonometric sin of the pitch angle. In addition, no force is sent along the travel axis for zero pitch angle case.

### 3.2. QFT Controller Design

This sub-section will review the implementation of QFT design technique and its basic designing procedure. It presents a detailed discussion of the method and steps with the aim to establish a solid understanding of the fundamental concept of this approach. A QFT design technique commonly comprises these three basic steps:

- a) Calculation of QFT bounds (robust stability, robust tracking, etc.)
- b) Designing the controller (or loop shaping)
- c) Evaluating the design

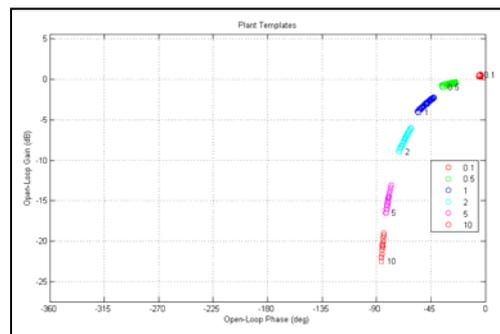


Figure 3. Plant templates with different frequency response

For the systems with parametric uncertainty models, plant templates should be generated before commencing on the first step as in Figure 3. A template is the frequency response of the plant at some fixed frequency. By utilizing the given plant templates, specifications for a closed-loop system is converted into magnitude and phase constraints on a nominal open loop function through QFT process. Term 'QFT bounds' is used to represent the

constraints mentioned above. After the formation of the plant's templates, both plant's templates and specifications are used to develop bounds at the trial frequencies in the frequency-domain.

After stability bound shown in Figure 4, the tracking bounds are being put into consideration next. The tracking bounds (as in Figure 5) descriptions should follow the requirement of the output plant which fulfills the desired plant output. Intersection of bounds is determined and the worst case of all bounds is shown in Figure 6. The composite or intersection bound for each value of frequency  $\omega_i$  is composed of those portions of each respective bound (tracking and disturbance if any) that are most restrictive. When there are intersections between two bounds, the outermost of the two boundaries becomes the perimeter. If there are no intersections, then the bound with the largest value or with the outermost boundary dominates. This is the final bound taken for the design of the feedback compensator.

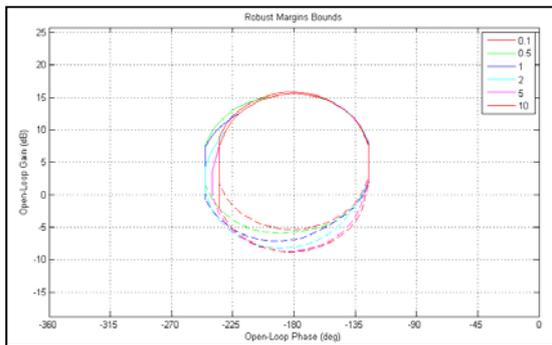


Figure 4. Robust margin or stability bounds

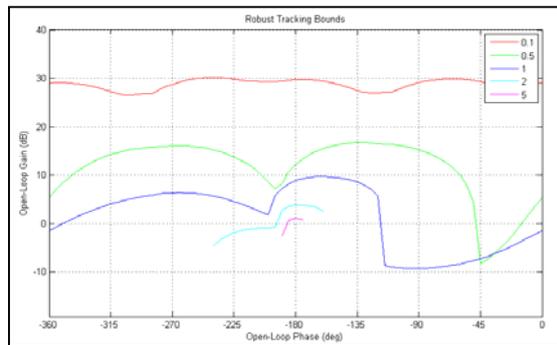


Figure 5. Robust tracking bounds

Having computed the stability and performance bounds, the next step in a QFT design is loop shaping process where the process involves designing a nominal loop function that fulfills its bounds. The nominal loop is the results from combining nominal plant and to be designed controller which has to compensate the worst case of all bounds. In general, the process of loop shaping are composed of addition of poles and zeros as well as gains so that the nominal loop is repositioned near its bounds to ensure stability of the nominal closed-loop function. The loop shaping using Interactive Design Environment (IDE) is shown in Figure 7.

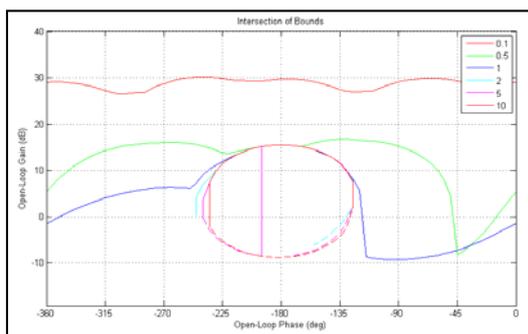


Figure 6. Intersection of robust margin(stability) and tracking bounds



Figure 7. Loop shaping process

The final form of controller  $G(s)$  obtained is shown in the Equation (2) below:

$$G(s) = \frac{2.598 (s - 1.879)(s - 0.2354)(s - 0.0897)}{s(s - 8.774)(s - 0.3064)(s - 0.1003)} \tag{2}$$

### 3.3. Implementation of PID-based QFT Controller to Quanser 3-DOF Bench-top Helicopter Simulation

Before actual run could be conducted on the real bench-top helicopter model as shown in Figure 8, the designed controller should be tested on the simulation file first. This is to ensure that the controller works well with the helicopter system along with its hardware. The simulation file, namely 's\_heli3d' is supplied by Quanser Inc., where it depicts the overall helicopter system in Simulink test environment.



Figure 8. Quanser 3-DOF bench-top helicopter

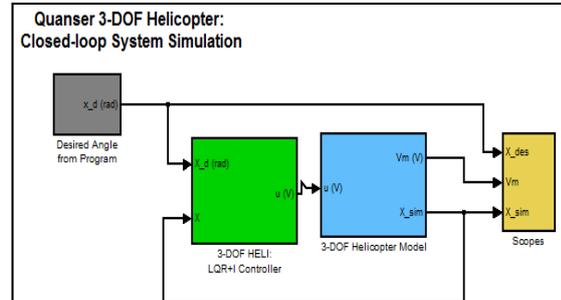


Figure 9. Main Simulink block diagram for Quanser 3-DOF Bench-top Helicopter Simulation

In the Figure 9, the simulation file consists of several blocks. The first one is 'Desired Angle from Program', where the user can input the desired angle to be simulated. Next is the controller block where the previously designed QFT controller is implemented and it is responsible in controlling the movement of the helicopter. The controller is fed with the summation of error signal from the helicopter and the desired angle from the user input. From the controller, the voltage is sent to the helicopter model. Finally, the 'Scopes' block contains a set of oscilloscope that is used to display the results of the simulation process.

### 3.4. Implementation of PID-based QFT Controller to Actual Quanser 3-DOF Bench-top Helicopter

The final part of this project is the implementation of the PID-based QFT controller onto the actual bench-top helicopter. The Quanser 3DOF bench-top helicopter system consists of several components, which are the helicopter model, power amplifier, data acquisition (DAQ) board and real time control software installed on a desktop computer. The control software also utilizes MATLAB Simulink environment which is the same as in simulation carried out before, except few blocks that were interfaced directly with the hardware of the helicopter. Among them are Analog Output block which fed the computed voltage by controller to DAQ board and the Encoder Input block that picked up the encoder measurements for data monitoring purpose.

## 4. Results and Analysis

This chapter discusses the results obtained from the simulation done in Simulink as well as test conducted on actual bench-top helicopter model. It is divided into two parts, in which the first will emphasize on the implementation of the controller onto Quanser 3-DOF Bench-top Helicopter simulation. Finally, the results obtained from implementation of the PID-based QFT controller onto actual bench-top helicopter are shown and discussed in detail.

### 4.1. Quanser 3-DOF Helicopter Simulation Results

As mentioned earlier, three different set points had been chosen that is 10°, 20° and 30°. Three important performance specifications which are percentage of overshoot, settling time and percentage of steady-state error are considered here. The results from simulations conducted are tabulated in Table 1 to Table 3, where the graphs obtained for each case are shown in Figure 10 to Figure 12.

Table 1. Results for 30 degree set point

Specifications	LQR-tuned PID	PID-based QFT
Overshoot	16.49%	5.62%
Settling Time (s)	49.86	9.03
Steady-state error	3.29%	2.18%

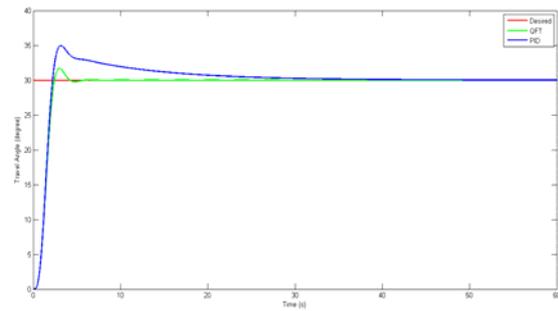


Figure 10. Response of the controllers for 30 degree set point

Table 2. Results for 20 degree set point

Specifications	LQR-tuned PID	PID-based QFT
Overshoot	16.54%	5.62%
Settling Time (s)	48.08	9.05
Steady-state error	3.29%	2.18%

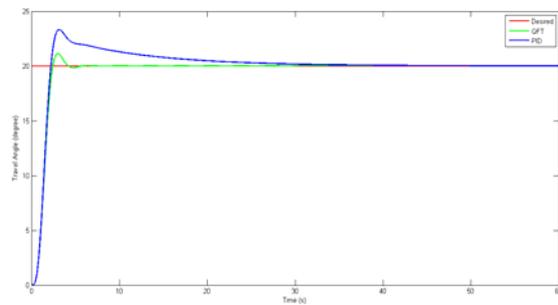


Figure 11. Response of the controllers for 20 degree set point

Table 3. Results for 10 degree set point

Specifications	LQR-tuned PID	PID-based QFT
Overshoot	16.49%	5.63%
Settling Time (s)	46.36	9.17
Steady-state error	3.29%	2.18%

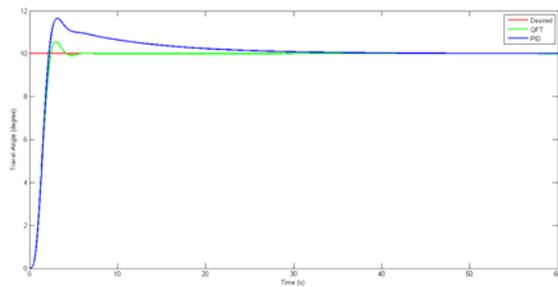


Figure 12. Response of the controllers for 10 degree set point

#### 4.2. Quanser 3-DOF Helicopter Hardware Test Results

The final part of the project is implementation of both LQR-PID and PID-based QFT controller onto the actual Quanser bench-top helicopter. Since the test is conducted in real time environment, the results of the test are represented in sets of graph, each with 10-seconds timeframe.

Response of PID-based QFT controller is shown in Figure 13 to Figure 15 below. The yellow line represents the desired angle which is 10, 20 or 30 degrees. The desired angle is assumed to be input at instantaneous time, which explains the sudden spike of the value. On the other hand, the purple line represents the response of the respective controller.

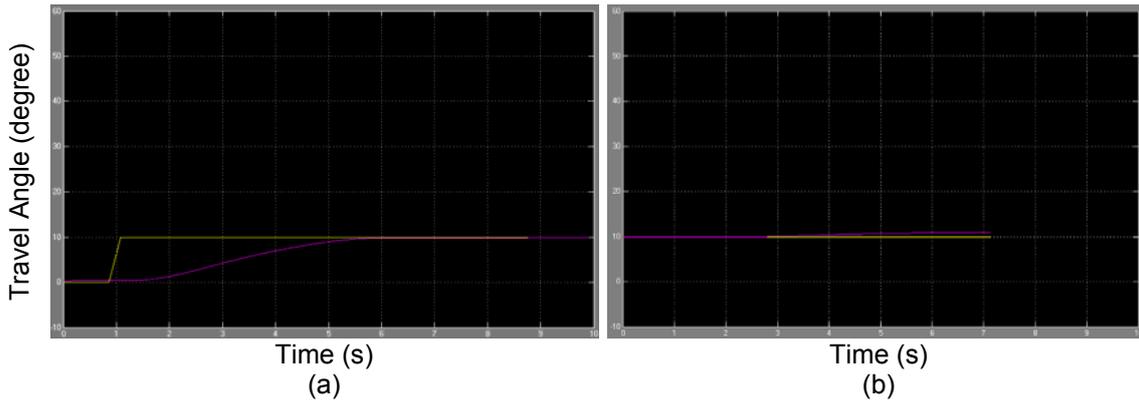


Figure 13. Response of PID-based QFT controller at 0-10 seconds (a) and 10-20 seconds (b) for 10 degree set point

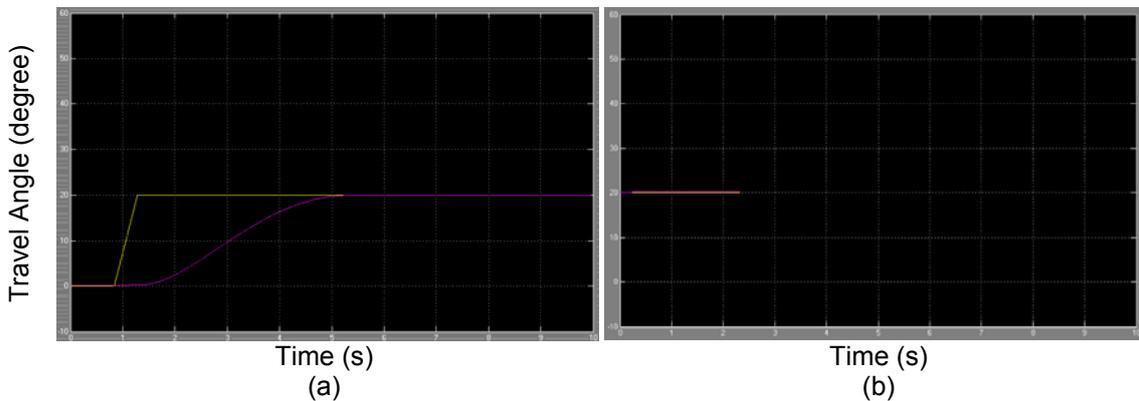


Figure 14. Response of PID-based QFT controller at 0-10 seconds (a) and 10-20 seconds (b) for 20 degree set point

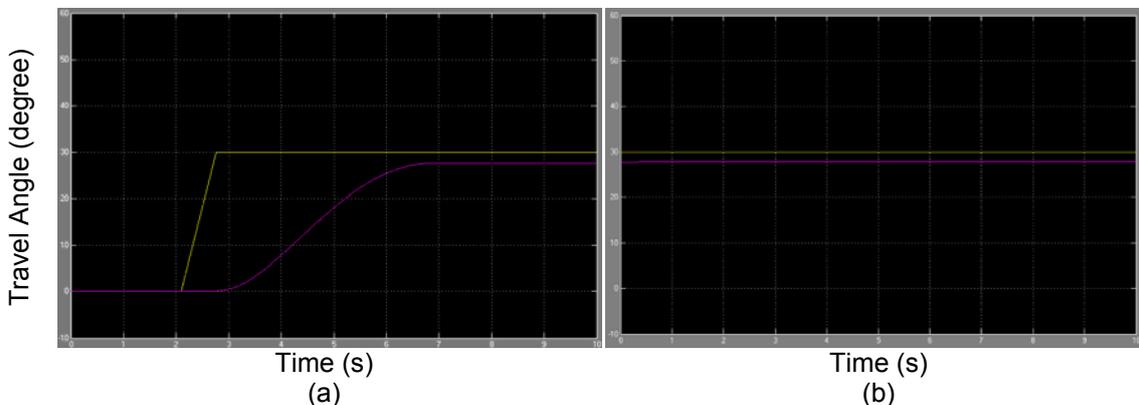


Figure 15. Response of PID-based QFT controller at 0-10 seconds (a) and 10-20 seconds (b) for 30 degree set point

Next is the response of LQR-PID controller, shown in Figure 16 to Figure 18. Since the response is quite slow which is more than 20 seconds, the graphs are shown in three timeframes, each in 10-seconds period. The tested LQR-PID controller is the default file supplied by Quanser Inc., the manufacturer of the bench-top helicopter.

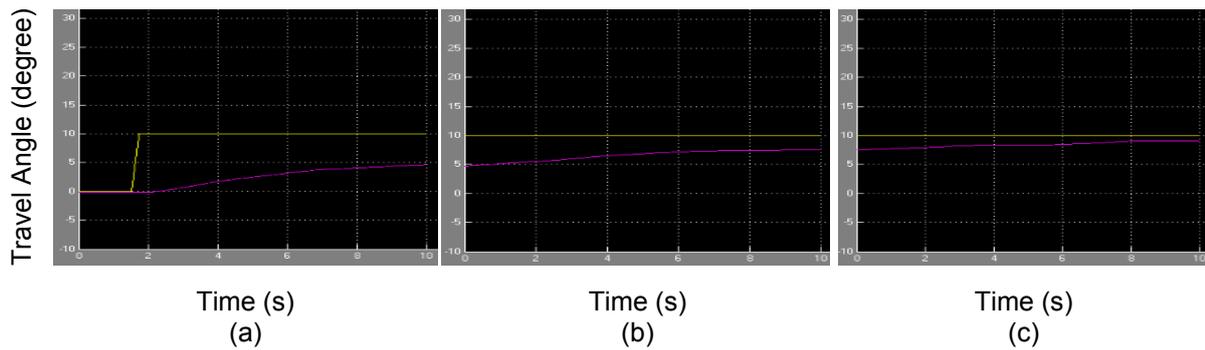


Figure 16. Response of LQR-PID controller at 0-10 seconds (a), 10-20 seconds (b) and 20-30 seconds (c) for 10 degree set point

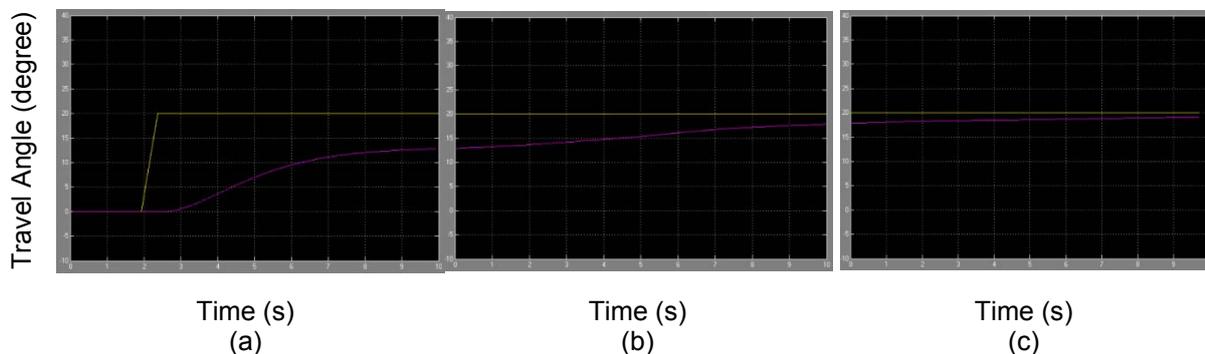


Figure 17. Response of LQR-PID controller at 0-10 seconds (a), 10-20 seconds (b) and 20-30 seconds (c) for 20 degree set point

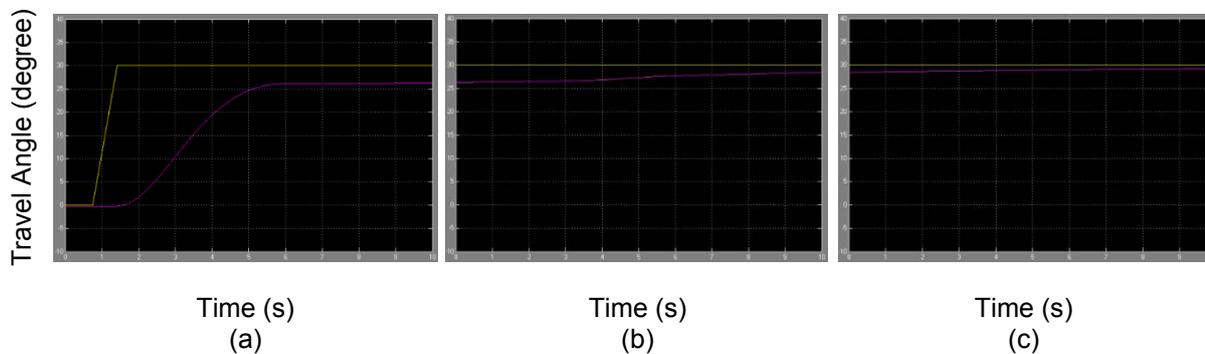


Figure 18. Response of LQR-PID controller at 0-10 seconds (a), 10-20 seconds (b) and 20-30 seconds (c) for 30 degree set point

**4.3. Results Analysis**

Two different modes of testing have been conducted to demonstrate the capability of Quantitative Feedback Theory (QFT) controller as well as comparing its performance against Linear Quadratic Regulator – Proportional Integral Derivative (LQR-PID) controller. The tests cover simulation mode in MATLAB Simulink environment only up to actual run on real bench-top helicopter model.

From the three modes of test, it can be seen that QFT performs best in reducing the time taken to reach steady state or called settling time. The improvements achieved are more than 80% in both simulation mode (Table 1 to Table 3) and also on real hardware test (Figure 13 to Figure 15).

With the great improvement in reducing settling time, it is expected that the achievement would come with the cost of higher overshoot. However it is proven to be not true for this project. From the Quanser bench-top helicopter simulation, PID-based QFT controller scored 10% lesser overshoot as well as much better settling time compared with LQR-PID. Moreover, test conducted on actual bench-top helicopter also revealed great performance of PID-based QFT controller where no overshoot was recorded even though it has much lower settling time than LQR-PID controller (Figure 16 to Figure 18).

## 5. Conclusion

From the simulation done via MATLAB Simulink software as well as test conducted on actual bench-top helicopter model, it can be concluded that the controller design fulfills the desired robust stability and robust tracking performance. This translates to robust control over the uncertainty and disturbances which present in real life situation, in this case helicopter flight dynamics where it is governed by many uncertainties such as air speed, humidity and amount of load carried.

For future improvements, addition of pre-filter to the PID-based QFT controller onto Quanser bench-top helicopter is suggested in order to achieve faster settling time with and reduced steady state error.

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