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Performance Comparisons between PID and Adaptive PID Controllers for Travel Angle Control of a Bench-Top Helicopter

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***Abstract*—**This paper provides a comparative study on the performances of standard PID and adaptive PID controllers tested on travel angle of a 3-Degree-of-Freedom (3-DOF) Quanser bench-top helicopter. Quanser, a well-known manufacturer of educational bench-top helicopter has developed Proportional Integration Derivative (PID) controller with Linear Quadratic Regulator (LQR) for all travel, pitch and yaw angle of the bench-top helicopter. The performance of the PID controller is relatively good; however, its performance could also be improved if the controller is combined with adaptive element. The objective of this research is to design adaptive PID controller and then compare the performances of the adaptive PID with the standard PID. The controller design and test is focused on travel angle control only. Adaptive method used in this project is self-tuning controller, which controller's parameters are updated online. Two adaptive algorithms those are pole-placement and deadbeat have been chosen as the method to achieve optimal controller's parameters. Performance comparisons have shown that the adaptive (deadbeat) PID controller has produced more desirable performance compared to standard PID and adaptive (pole-placement). The adaptive (deadbeat) PID controller attained very fast settling time (5 seconds) and very small percentage of overshoot (5% to 7.5%) for 10° to 30° step change of travel angle.

***Keywords*—**Adaptive control, bench-top helicopter, deadbeat, pole-placement, self-tuning control.

I. INTRODUCTION

BENCH top helicopter is a simulation helicopter that is placed on a bench, usually used for experimental purposes. The bench-top helicopter has very similar dynamic behavior of real helicopter. Like a real helicopter, a bench-top helicopter also exposed to uncertainty in the form of parameter variations, inaccurate plant modelling, affected by disturbances such as strong wing/turbulence and hardware tear and wear. Therefore, bench-top helicopter is suitable to be used as the testing platform to determine the efficiency of any proposed controllers.

Quanser bench-top helicopter has been used in this research. This 3-degree-of-freedom bench-top helicopter composed of three angles to be controlled which are travel, elevation and pitch angles. In this paper, travel angle is the only angle of interest. Elevation and pitch angles are made zero during the simulation process.

The angles of any similar bench-top helicopter have been control by using Proportional Integral Derivative (PID) and Quantitative Feedback Theory (QFT) [1], [2]. Mansor et al. successfully controls the pitch angle using QFT, a type of robust controller [2]. However the result only showed a small angle variation, i.e. 4°. Wider ranges of angles should be considered to verify the efficiency and the generalization of the QFT controller. In this project, the Quanser bench-top helicopter has been installed by the manufacturer with PID controller that is tuned by Linear Quadratic Regulator (LQR) algorithm. Constructive comparison between the proposed controller and the existing PID controller is performed later in Section III (Results and Discussion).

Hybrid controller is proposed where adaptive controller is combined in cascade form with the existing PID controller. Two different algorithms namely pole-placement and deadbeat of adaptive controllers have been tested on the bench-top helicopter model. Adaptive controller has been chosen as part of the controller due to its ability to cover wider range of uncertainty [3]. The main principle of adaptive controller is that the controller parameters are changing as there are changes in the plant's parameter. There are many existing methods or algorithms used to find the optimal controller such as deadbeat, pole-placement, fuzzy and Quantitative Feedback theory (QFT) [4]-[7].

In this project, the existing PID controller is integrated with adaptive controller to improve the performance of travel angle control of Quanser bench-top helicopter. Deadbeat and pole-placement algorithms have been chosen as the technique to obtain optimal controller. Deadbeat is known for producing very fast response in very minimal step size. In the application of grain dryer plant, deadbeat algorithm with integration with robust control (QFT) has been proven to have better efficiency in terms of response time and percentage of overshoot compared to QFT and deadbeat standard controller [4]. On the other hand, pole-placement controller works based on assignment of poles in a closed feedback loop. The controller aims to stabilize the closed loop and achieves the pre-set poles of the characteristic polynomial based on the transient response and/or frequency response requirements such as damping ratio, bandwidth and steady state requirement [8].

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Successive simulation tests have been carried out on the bench-top helicopter to compare and discuss the performances of standard PID, adaptive PID (pole-placement) and adaptive PID (deadbeat).

II. METHODOLOGY

The 3-DOF bench-top helicopter, shown in Fig. 1 consists of a base mounted on a bench with a support of an arm. The arm has counterweight that helps the propellers lift the body weight. With 3-DOF, roll angle, pitch angle and yaw angle can be measured by an absolute encoder and controlled by any kind of controllers such as PID controller [9]. This research will only focus on improvement of travel angle control.

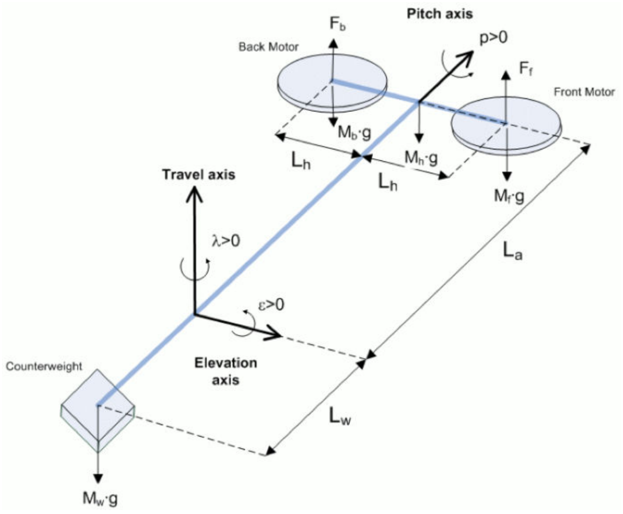

Fig. 1 Free-Body Diagram of 3-DOF Helicopter [9]

Parameters of 3-DOF helicopter are described as follows:

Mh	Mass of the helicopter
Mw	Mass of counter weight
Mf	Mass of front propeller assembly
Mb	Mass of back propeller assembly
La	Distance between travel axis to helicopter body
Lh	Distance between pitch axis to each motor
Lw	Distance between travel axis to the counter weight
g	Gravitational constant
Fb	Back force
Ff	Front Force
p	Pitch

A. Modelling of 3-DOF Bench-top Helicopter

The mathematical model of the Quanser 3-DOF helicopter has been derived using Maple software which evaluated the kinematics of the system those are front motor, back motor, helicopter body and counter weight relative to the base of the system, as shown in Fig. 1. The dynamics behavior of pitch, travel and elevation angles are described using Euler-Lagrange formula therefore the nonlinear equation of motion of the 3-DOF helicopter system are derived. The complete state-space model of the Quanser 3-DOF helicopter system can be found from [9].

As this paper is focused on travel angle control, Fig. 2 shows a very basic schematic diagram for travel angle mechanism.

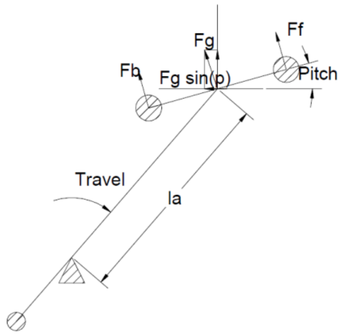

Fig. 2 Travel angle axis [9]

The only way to apply force in the travel direction is to pitch body of the helicopter. Assuming the body of the helicopter has been pitched up by an angle (p) as shown in Fig. 2. For small angles, the force required to keep the boy in the air is approximately Fg. The horizontal component will caused a torque about a travel axis which results in an acceleration about the travel axis:

$$J_t\dot{r} = -F_g \sin{(p)} l_a \tag{1}$$

$$J_t\dot{r} = F_g \sin{(p)} l_a \tag{2}$$

where J_t is the moment of inertia of the system about the travel axis; r is the travel rate in rad/sec; Kp is the force required to maintain the helicopter in flight and is approximately Fg; sin(p) is the trigonometric sin of the pitch angle. If the pitch angle is zero, no force is transmitted along the travel axis.

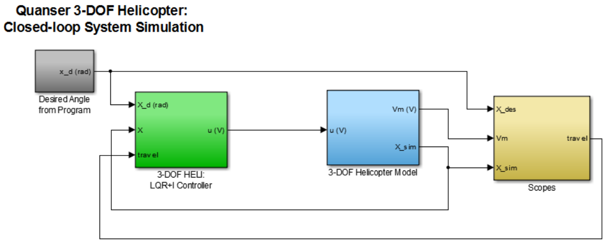

Fig. 3 Simulink block diagram of 3-DOF helicopter system

B. PID Controller Designed by Quanser

The existing controller used for Quanser bench-top helicopter is PID controller where the gains of proportional, integral and derivatives are tuned by LQR. The main Simulink block diagram is shown in Fig. 3. The user or aircraft engineer can change the desired angle according to the direction and view the responds of the helicopter from the scopes. The efficiency of the controller is evaluated from percentage of overshoot, settling time and steady state error properties.

The existing PID controller with LQR tuning provided by Quanser is shown in Fig. 4. The simulation results of this original controller are shown in Section III (Results and

Discussions). These results are set as the benchmark performance of the proposed adaptive PID controller.

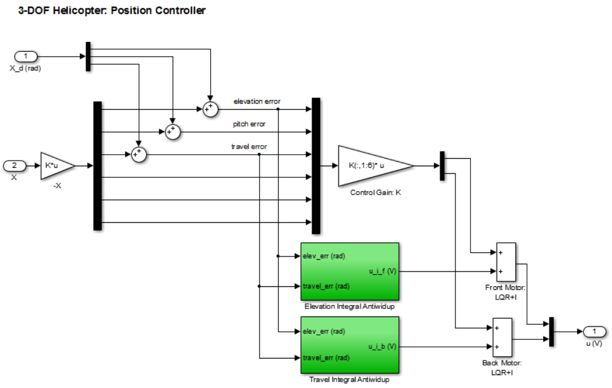

Fig. 4 PID (LQR) controller used by Quanser

C. Adaptive PID Controller Design

The design architecture of the proposed adaptive PID controller is shown in Fig. 5. Self-tuning method of adaptive controller has been chosen. The concept of Self-tuning Controller (STC) is that the controller self-tunes its parameter to obtain the desired properties in the closed-loop system. It is assumed that the structure of the controller is specified, in this case is deadbeat or pole-placement controller and the parameters of the model are estimated online (recursive). This is done by the block “Recursive Identification”. The block “Controller Parameters Computation” computes the controller’s parameter with a specified method and few design parameters that fulfil the specification are selected. The “Deadbeat or pole-placement Controller” parameters are obtained from the previous block. This controller can be replaced by any control methods that could obtain optimal control of the system.

During the design implementation, Self-tuning Toolbox which works on Matlab& Simulink environment has been used to work with the original PID controller [10]. Self-tuning Toolbox is open source software where the user has full of freedom to modify the algorithm to suit their needs.

Pole-placement design works based on the selected damping factor and natural frequency of second order system. The pole-placement controller used in this research is in the form of second order transfer function shown in (3).

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \qquad (3)$$

where a_1,a_2 , b_1 and b_2 are the identification parameters.

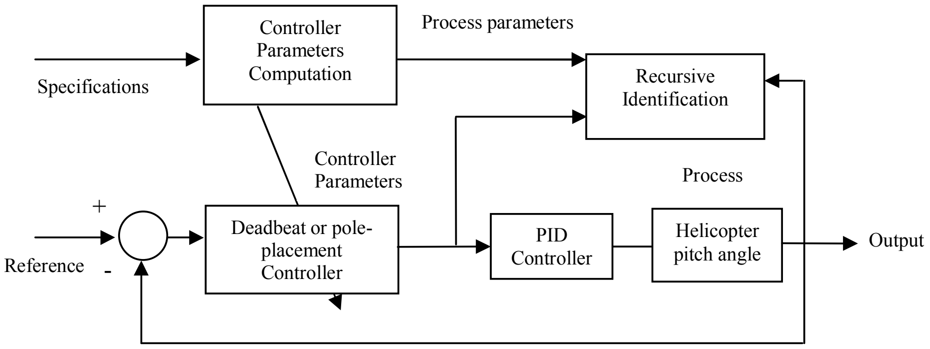

Fig. 5 Self-tuning controller using deadbeat or pole-placement algorithm for travel angle control of bench-top helicopter

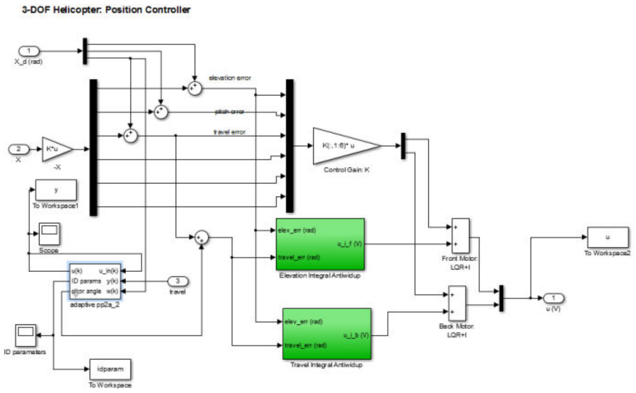

Fig. 6 Proposed adaptive PID (pole-placement)

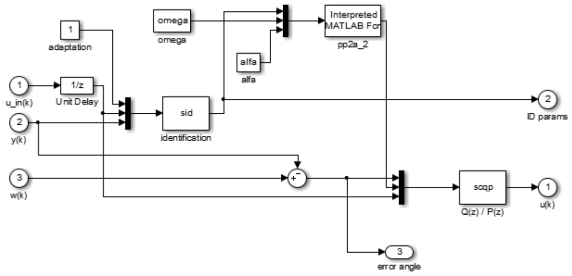

Fig. 7 Pole-placement subsystems provided by STC Toolbox [10]

The dynamic behavior of the closed-loop is depends on the location of its poles. In general, adaptive pole-placement controller is shown in Figs. 6 and 7. The block labeled “sid” is the discrete model identification function. The method available in STC Toolbox for identification are recursive least square method, least square method with exponential forgetting and least square method adaptive directional forgetting and in this project, the last method has been chosen.

The control law for adaptive pole-placement used is written in (4).

$$u(k) = q_0 e(k) + q_1 e(k-1) + q_2 e(k-2) + (1-\gamma)u(k-1) + \gamma U(k-2) \quad (4)$$

Detail information on pole-placement can be found in [10].

The discrete transfer function of adaptive deadbeat controller is similar to pole-placement since both of them are second order type controller, mentioned in (3).

For a second order control system, the control law of deadbeat controller is given by [10]:

$$u_k = r_0 w_k - q_0 y_k - q_1 y_{k-1} - p_1 u_{k-1} \quad (5)$$

where$u$ is the controller output, w is the reference value, y is the process output and k is the step number. The constants values of r_0, q_0, q_1, and p_1 are calculated from the identification initial plant parameter estimation.

III. Results and Discussions

A. Standard PID Controller Test

Test of the proposed controllers have been conducted in Matlab& Simulink environment. First, a test was conducted on the original PID controller for benchmarking performance. A step response of 10° was applied to the travel angle of desired angle block in Fig. 3 shown earlier. The desired angle subsystem is shown in Fig. 8. The other two angles, pitch and elevation angles were made zero as travel angle is the only angle of interest.

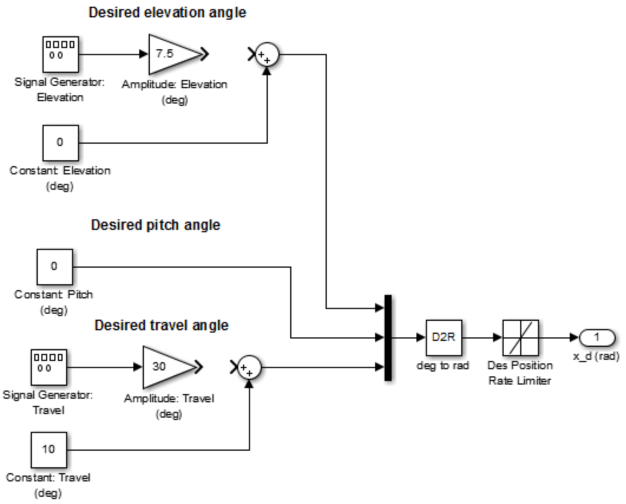

Fig. 8 Desired angle subsystems of Matlab/Simulink programme

Figs. 9-11 show the responses of original PID controller tuned by LQR. It was shown that, when desired angle was set to 10°, the PID controller reached the set point in around 30s with 15% overshoot. As the desired angle increase to 20° and 30°, there is slight increase in the settling time and percentage of overshoot due to larger effort for larger desired angle produced by fixed PID controller.

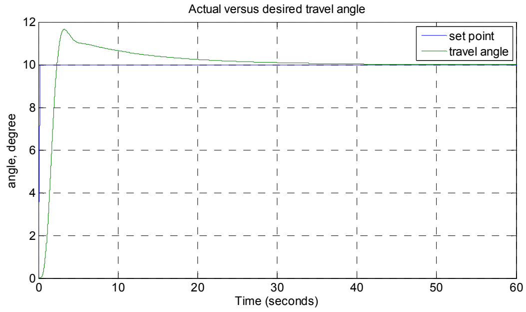

Fig. 9 Response of PID controller for 10° set point

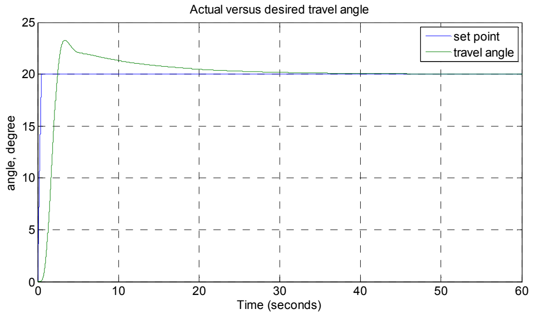

Fig. 10 Response of PID controller for 20° set point

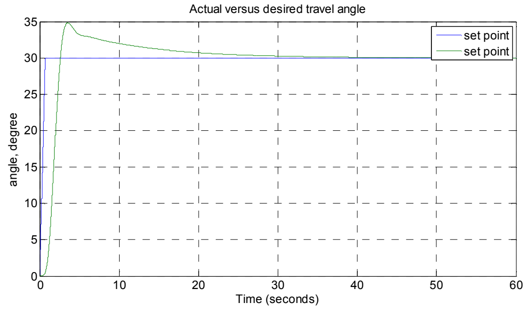

Fig. 11 Response of PID controller for 30° set point

B. Adaptive (Pole-Placement) PID Controller Test

As mentioned in the methodology section, two types of algorithms those are deadbeat and pole-placement have been proposed as the method to find optimal parameter for the adaptive controller. Fig. 12 shows the pole-placement controller responds towards step change from 0° to 10°. The response has 25s settling time which is shorter than standard PID controller. However, the percentage of overshoot is higher than standard PID controller which is 25%. For step change from 0° to 20° and 30°, the test results are shown in Figs. 13 and 14. The settling time is maintained at around 20s and there is not much variation on the percentage of overshoot. In all cases, the steady-state error is zero.

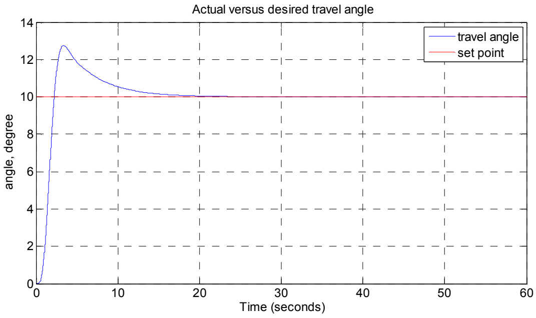

Fig. 12 Response of adaptive pole-placement PID controller for 10° set point

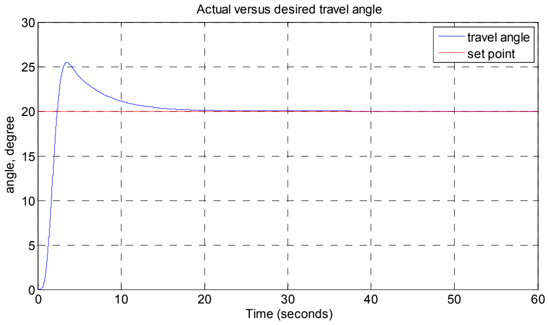

Fig. 13 Response of adaptive pole-placement PID controller for 20° set point

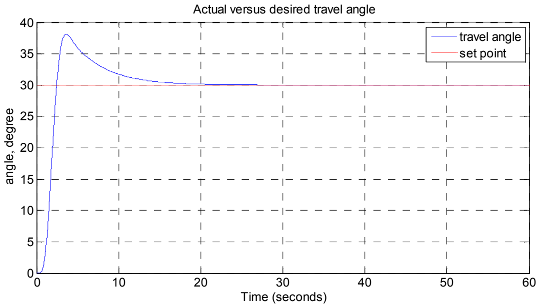

Fig. 14 Response of adaptive pole-placement PID controller for 30° set point

C. Adaptive (Deadbeat) PID Controller Test

Deadbeat algorithm has also been tested on the adaptive PID controller. The results are presented in Figs. 15-17. The deadbeat PID controller has successfully produced small percentage of overshoot and settling time (5% and 5s respectively) for step change of 10°. As the desired angle being increased to 20° and 30°, the adaptive deadbeat controller worked very well and adapts the variation in a very minimal step size. The percentage of overshoot for 20° variation is 6% whereas for 30° variation is 7.5%. Settling time is remained at 5s. The responses also produced zero steady state-error.

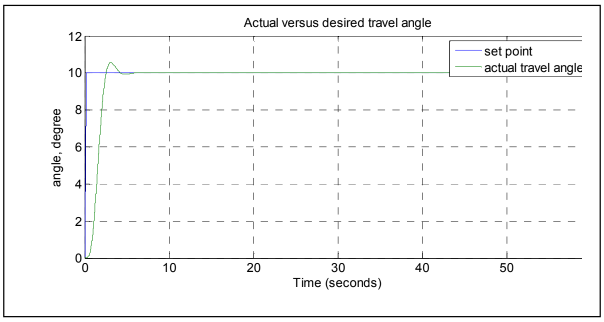

Fig. 15 Response of adaptive deadbeat PID controller for 10° set point

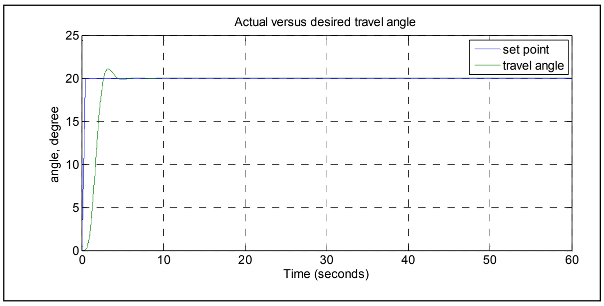

Fig. 16 Response of adaptive deadbeat PID controller for 20° set point

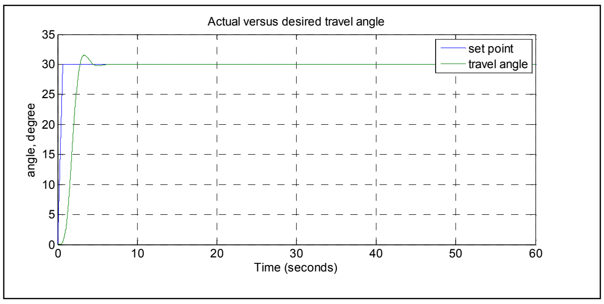

Fig. 17 Response of adaptive deadbeat PID controller for 30° set point

From the observation from all tests conducted via simulation for travel angle control of bench-top helicopter, the proposed adaptive (dead-beat and pole-placement) PID have improved the performance of the standard PID controller especially in the online tuning capability. Adaptive (dead-beat) controller has shown the best performance in terms of providing the shortest settling time for tracking the set-point and relatively small percentage of overshoot. Adaptive (pole-placement) has higher percentage of overshoot and longer settling time probably due to the choice of adaptive parameters those affect adaptive activities. Although the settling time produced by standard PID controller is quite long, the responds produced have no steady state error and relatively small percentage of overshoot.

IV. CONCLUSION

All three types of controllers which are standard PID tuned by LQR, adaptive (pole-placement) PID and adaptive (dead-beat) PID have been designed, tested and analysed. The objective of this research which is to compare the performances of standard PID controller tuned by LQR and adaptive PID has been achieved. From the simulation results obtained, it can be conclude that for a travel angle of Quanser bench-top helicopter, adaptive (dead-beat) PID has shown superior performance compared to adaptive (pole-placement) and standard PID controllers.

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