Control System Design for An Autonomous Helicopter Model in Hovering Using Pole Placement Method

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Abstract: This paper present the results of attitude, velocity, heave and yaw controller design for UTM autonomous model scaled helicopter using identified model of vehicle dynamic from parameterized state-space model proposed by Mettler (2000) with quasi-steady attitude dynamic approximation (6 DOF model). Multivariable state-space control methodology such as pole placement was used to design the linear state-space feedback for the stabilization of helicopter because of its simple controller architecture. The design specification for controller design was selected according to Military Handling Qualities Specification ADS-33C. Results indicate that acceptable controller can be designed using pole placement method with quasi-steady attitude approximation and it has been shown that the controller design was complianced with design criteria of hover requirement in ADS-33C.
Keywords: Pole Placement, Model Scaled Helicopter.

1. Introduction.

The helicopter was known to be inherently unstable, complicated and nonlinear dynamics under the significant influence of disturbances and parameter perturbations. The system has to be stabilized by using a feedback controller. The stabilizing controller may be designed by the model-based mathematical approach or by heuristic control algorithms. Due to the complexity of the helicopter dynamics, there have been efforts to apply non-model-based approaches such as fuzzy-logic control, neural network control, or a combination of these. Several researchers have proposed PID control (classical control theory) for the autonomous helicopter application [1, 3 and 8]. The classical control approach used by these researchers was used as a low-level vehicle stabilization controller for purpose of attitude, heading and thrust control.

The main goal in this research is to provide a working autopilot system for the helicopter model. Therefore, a linear control theory was used because of its consistent performance, well-defined theoretical background and effectiveness proven by many practitioners. In this research, multivariable state-space control theory such as pole placement method has been applied to design the linear state feedback for the stabilization of the helicopter in hover mode. We have chosen the pole placement method because of it simple controller architecture and were suitable for nonlinear system and multiple input multiple output (MIMO) system. Its computational also provided a powerful alternative to classical control theory which eliminated tedious trial and error gain tuning.

2. Air Vehicle Description.

The basis of UTM autonomous UAV Helicopter platform is a conventional remote control (RC) model helicopter, the Raptor 60 class RC Helicopter manufactured by Thunder Tiger Corporation, Taiwan. It has a rotor diameter of 1.55m and is equipped with a high performance Thunder Tiger's MAX-91SX-HRING C SPEC PS (90 cu in) two-stroke petrol engine which produce power about 15kW. The engine is equipped with pump and muffler which pressurized the fuel system to ensure that the engine has stable fuel supply during flight at any altitude and fuel level in tank. Raptor 60 class helicopter has an empty weight about 4.7 kg and capable to carry about 3 kg payloads and an operation time of 15 minutes. General physical characteristics of Raptor 60 class are provided in Fig. 1.

Most model scaled helicopters use two bladed rotors and like most of RC helicopter model, Raptor 60 class helicopter uses an unhinged teetering head with harder elastometric restraints, resulting in a stiffer rotor head design. The rotor head designs of model scaled helicopters are relatively more rigid than those in full scaled helicopters, allowing for large rotor

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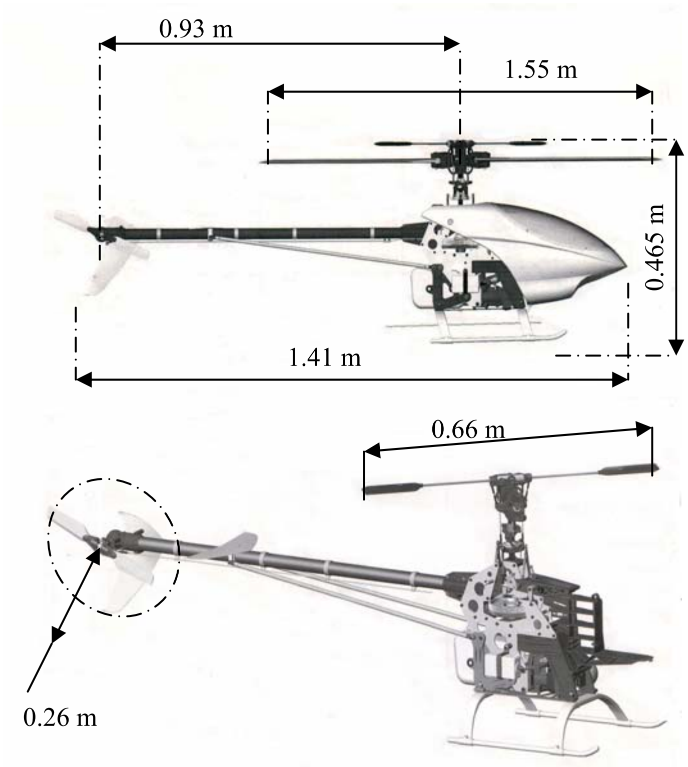
control moments and more agile maneuvering capabilities. Since the rotors can exert large thrusts and torques relative to vehicle inertia, Raptor 60 class helicopter rotor head design features stabilizer bar for the ease of handling.

Model scaled helicopters are often equipped with mechanical Bell-Hiller stabilizer bar. Invented by Hiller around 1943, the basic principle of operation of the rotor control is to give the main rotor a following rate which compatible with normal pilot responses [4]. The following rate is the rate at which the tip path plane of main rotor follows the control stick movements made by the pilot or realigns itself with the mast after an aerodynamics disturbance. According to [7], the stabilizer bars receives the same cyclic pitch and roll input from the swash plate but no collective input and has a slower response than main blades. The stabilizer bar is also less sensitive to airspeed and wind gusts due to smaller blade Lock number, γ (ratio between the aerodynamic and internal forces acting on the blade).



Dimensions	See Figure
Rotor speed	168 rad/s
Tip speed	130 m/s
Empty weight	4.7 kg
Full payload capacity	7.7 kg
Engine type	2 stroke, single cylinder
Flight autonomy	15 minutes

Figure 1 Raptor 60 class RC helicopter physical characteristics.

3. Dynamics of Model Scaled Raptor 60 Class Helicopter.

Helicopter dynamics obey the Newton-Euler equation for rigid body in translational and rotational motion. The helicopter dynamic can be studied by employing lumped parameter approach which indicates that helicopter as the composition of following component; main rotor, tail rotor, fuselage, horizontal bar and vertical bar. The parameterized state-space model can be described with the following state (refer Fig. 2 for coordinate axis) and control input vector consisting 4 components of lateral cyclic, longitudinal cyclic, tail rotor collective and main rotor collective [6].

$$x=\begin{bmatrix} u & v & p & q & \phi & \theta & a & b & w & r & r_{fb} & c & d \end{bmatrix}^T \quad (1)$$

$$u = [\delta lat \quad \delta lon \quad \delta ped \quad \delta col] \tag{2}$$

where *u, v, w* are the velocities in the fuselage coordinates, *p, q, r* are the roll, pitch and yaw angular rate, ϕ, θ are the roll and pitch attitude angles about the principal fuselage axis, *a, b,* (*c, d*) represent the longitudinal and lateral main rotor (stabilizer bar) flapping angles for a first order tip path plane model and r_{fb} is an additional state used to account for the active yaw damping system.

In order to reduce the state space model to rigid body form (6 DOF with 8 states), the dynamic rotor and stabilizer bar states can be replaced by their steady-state values and then substitute the resulting expressions into the angular rate equation of motion. Taking roll channel as example, the lateral rotor and stabilizer bar flapping derivatives are set to zero ($\dot{b} = \dot{d} = 0$) and obtain the steady-state expressions. Note that the longitudinal channel can be treated similarly and the resulting parameterized state-space matrices with quasi-steady approximation are shown in Eq. 3.

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{q} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{w} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} X_u & 0 & 0 & 0 & 0 & -g & 0 & 0 \\ 0 & Y_v & 0 & 0 & g & 0 & 0 & 0 \\ L_u & L_v & -L_b(\tau_f - B_d\tau_s) & 0 & 0 & 0 & L_w & 0 \\ M_u & M_v & 0 & -M_a(\tau_f + A_c\tau_s) & 0 & 0 & M_w & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & Z_w & Z_r \\ 0 & N_v & N_p & 0 & 0 & 0 & N_w & N_r \end{bmatrix} \begin{bmatrix} u \\ v \\ p \\ q \\ \phi \\ \theta \\ w \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & Y_{ped} & 0 \\ L_b(B_{lat} + B_d D_{lat}) & L_b B_{lon} & 0 & 0 \\ M_a A_{lat} & M_a(A_{lon} + A_c C_{lon}) & 0 & M_{col} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & Z_{col} \\ 0 & 0 & N_{ped} & N_{col} \end{bmatrix} \begin{bmatrix} \delta lat \\ \delta lon \\ \delta ped \\ \delta col \end{bmatrix} \tag{3}$$

where τ_s and τ_f is stabilizer bar and main rotor time constant, A_{lon}, B_{lon}, A_{lat} and B_{lat} is the rotor longitudinal and lateral flapping input derivatives, C_{lon} and D_{lat} is the stabilizer bar's longitudinal and lateral cyclic pitch sensitivity. It can be shown that the stabilizer bar can be coupled through derivative A_c and B_d while the external aerodynamic and gravitational forces and moments are presented in terms of stability derivatives [6]. The general aerodynamic effects are expressed by speed derivatives such as X_u, Y_v, L_u, L_v, M_u and the rotor forces are expressed through the rotor derivatives X_a, Y_b and the rotor moments through the flapping spring derivatives L_b, M_a. The matrices can be determined using formulation outlined in [5, 6, 10 and 11].

The model has simple block structure and the dynamic of model scaled helicopter can be sufficiently decoupled to allow an analysis of lateral/longitudinal dynamics separately from yaw/heave dynamics in hover condition. The standard rotorcraft handling qualities matrices outline in [10] can be used to analysis rotorcraft dynamic.

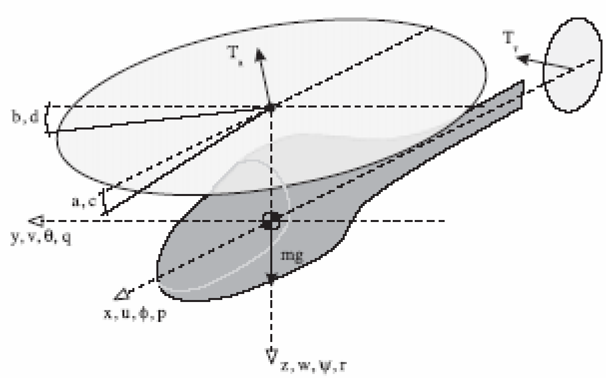


Figure 2 Helicopter variables with fuselage coordinate system and rotor/stabilizer bar states [6].

4. State Space Controller Design.

A typical feedback control system in Fig. 3 can be represented in state space system as Eq. 4 and 5 where the light lines are scalars and the heavy line are vectors.

$$\dot{x} = Ax + Bu \tag{4}$$

$$y = Cx \tag{5}$$

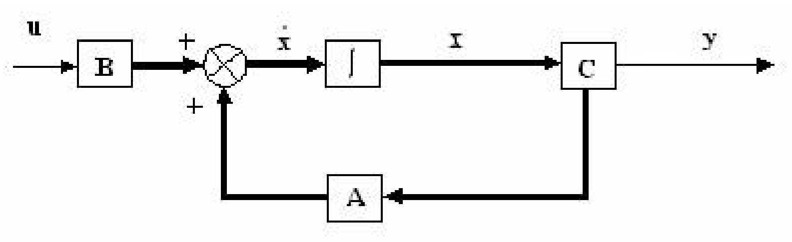


Figure 3 A typical state space representation of a plant.

In the typical feedback control system, the output (y) is fed back to the summing junction. In linear state feedback design, each state variable is fed back to the control, u , through a gain, k_i to yield the required closed-loop pole values. The feedback through the gains k_i is represented in Fig. 4 by the feedback vector **–K**.

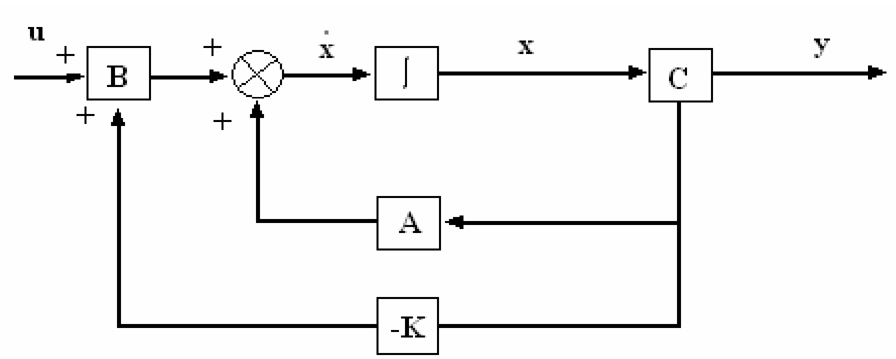


Figure 4 A state space representation of a plant [9].

The state equation for close loop system of Fig. 4 can be written by inspection as

$$\dot{x} = Ax + Bu = Ax + B(-Kx + r) = (A - BK)x + Br \tag{5}$$

$$y = Cx \tag{6}$$

The design of state variable feedback for closed loop pole placement consists of equating the characteristic equation of a closed loop system to a desired characteristic equation and then finding the values of feedback gains, k_i . The gain, k_i value can be solved using Matlab using function *'acker'* for SISO system and *'place'* for MIMO system.

5. Results and Discussion.

Eq. 3 can be analyzed separately in longitudinal and lateral stability augmentation, heave and yaw dynamic mode. All state variables in the Eq. 3 were also assumed to be measurable while designing controller using pole placement method.

1) Attitude Controller Design.

The attitude dynamics indicates the behavior when the translational motion in *x* and *y* is constrained. For the design of attitude feedback design, the dynamic model was extracted by fixing the state variables of translational velocities in *x*, *y* and *z* direction and the yaw terms to zero.

The design specification for the controller design is selected according to Aeronautical Design Standard for military helicopter (ADS-33C). In Fig. 5, the damping ratio limits on pitch (roll) oscillations in hover and low speed is specified to be greater than 0.35 (OS% ≤ 30.9) and the settling time to be achieved less than 10 second. Therefore for the purpose of attitude controller design, the percentage of overshoot (OS) is set to be 10% and the settling time of 5 second should be achieved with no steady state error.

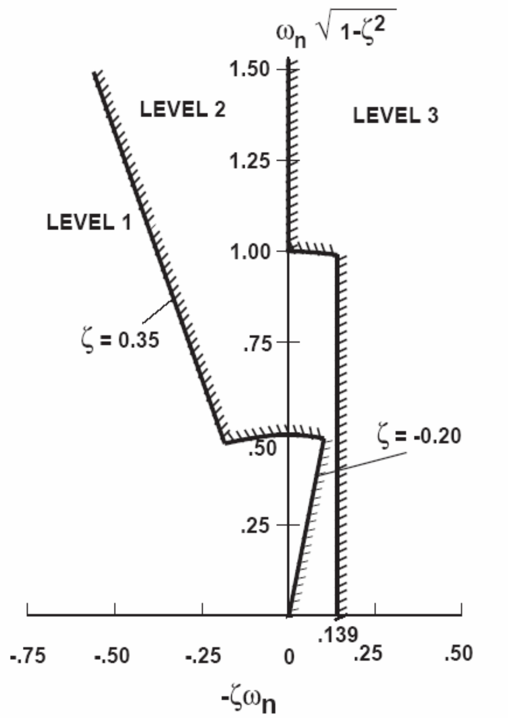


Figure 5 Limits on pitch (roll) oscillations – hover and low speed according to Aeronautical Design Standard for military helicopter (ADS-33C) [2].

Using the *'place'* and *'ltiview'* function in Matlab, the performance of attitude controller can be achieved according to design requirement for the both pitch and roll axis. In the pitch axis response, the poles are placed at p = -0.8 + 1.095i, -0.8 – 1.095i and -0.003917 in order to achieve 10% OS and 5 second settling time and the phase variable feedback gain is found to be $K_\theta = [0 \quad -0.4527 \quad 0.0136]$. In the roll axis response, the poles are placed at p = -0.8 + 1.095i, -0.8 – 1.095i and -0.5219 in order to achieve 10% OS and 5 second settling time and the phase variable feedback is found to be $K_\phi = [-0.0015 \quad -0.5508 \quad 0.0084]$. The time response and bode diagram plot for both axes are shown in Fig. 6(a) and Fig. 6(b). In Fig. 7, both controller bandwidth and time delay have been shown to meet Level 1 requirement specify in Section 3.3.21 of the Military Handling Qualities Specification ADS-33C.

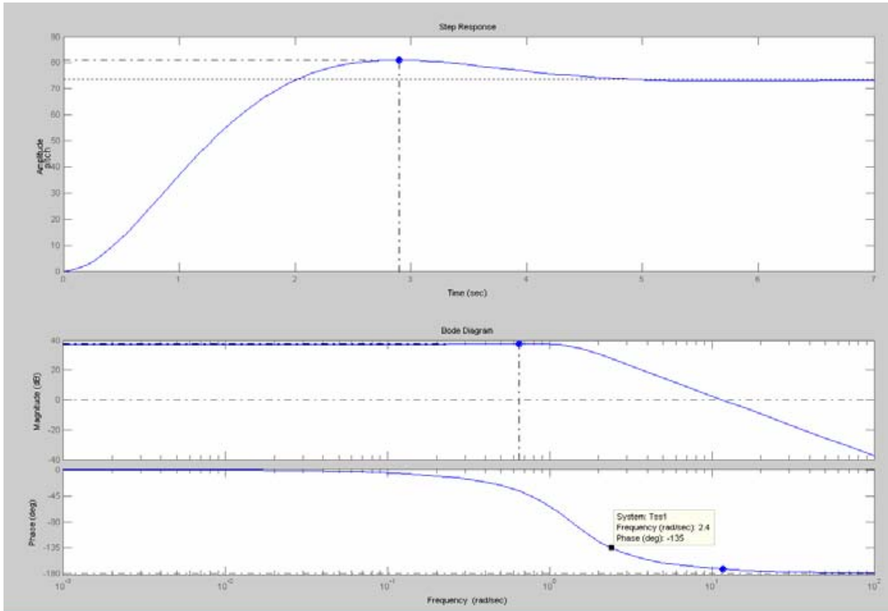


Figure 6(a) Attitude compensator design for pitch axis response. The phase variable feedback gain is found to be $K_\theta = [0 \quad -0.4527 \quad 0.0136]$. The bandwidth, ω_{BW_θ} is located at 2.40 rad/s and the phase delay, $\tau_{P_\theta} = 0$.

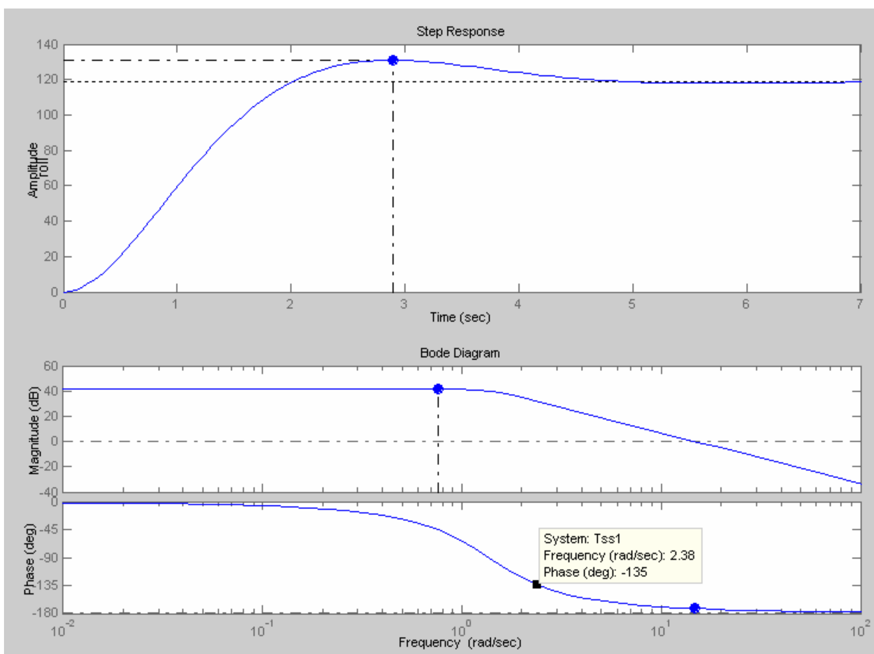


Figure 6(b) Attitude compensator design for roll axis response. The phase variable feedback gain is found to be $K_\phi = [-0.0015 \quad -0.5508 \quad 0.0084]$. The bandwidth, $\omega_{BW\phi}$ is located at 2.38 rad/s and the phase delay, $\tau_{P\phi} = 0$.

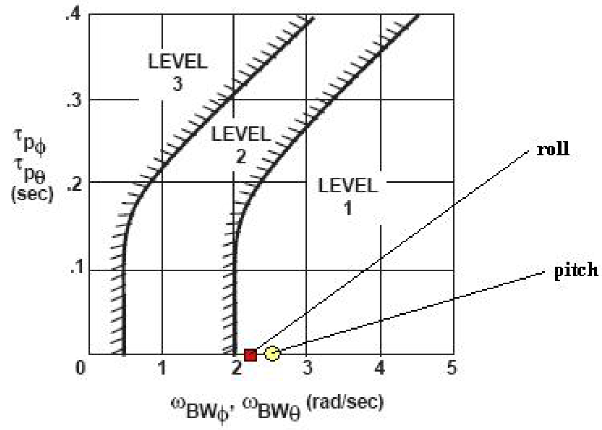


Figure 7 Compliance with small-amplitude pitch (roll) attitude changes in hover and low speed requirement specified in Section 3.3.2.1 of the Military Handling Qualities Specification ADS-33C.

2) Velocity Control.

Once the attitude dynamics are stabilized, the feedback gain for the velocity dynamic can be determined with similar approach. For velocity control, the design of the phase variable feedback gains should yield 10% overshoot and a settling time of 5 second. In longitudinal velocity mode, the poles was selected to be placed at p = -0.8 + 1.095i, -0.8 – 1.095i and -57.7 in order to achieve 10% OS and 5 second settling time and the suitable feedback gains were found to be $K_u = [-0.0797 \quad -0.0245 \quad 0.6905]$ for longitudinal velocity. In lateral velocity mode, the poles was selected to be placed at p = -0.8 + 1.095i, -0.8 – 1.095i and -4761.2 in order to achieve 10% OS and 5 second settling time and the suitable feedback gains were found to be $K_v = [2.7894 \quad 21.2979 \quad 24.2157]$ for lateral velocity. Fig. 8(a) and Fig. 8(b) shows the step response of the velocity dynamic in longitudinal and lateral modes.

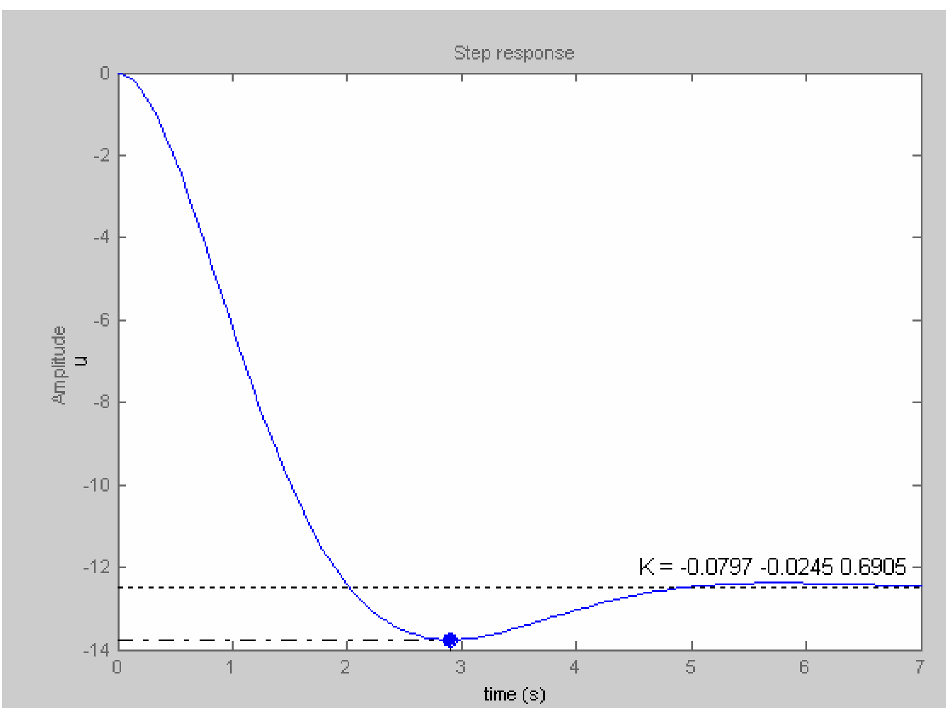


Figure 8(a) Velocity compensator design for longitudinal velocity mode.

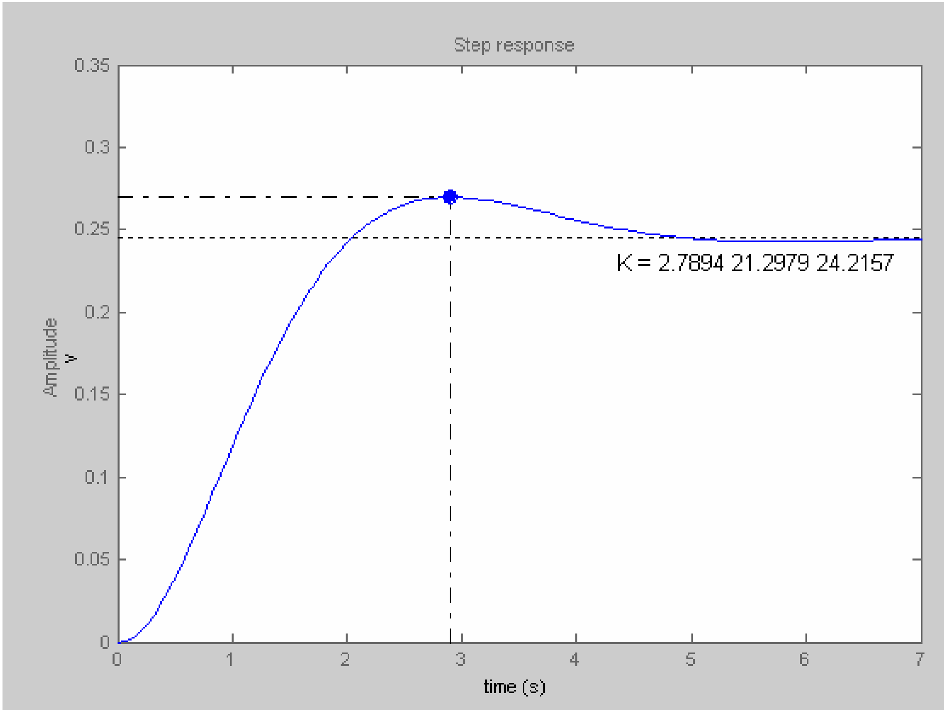


Figure 8(b) Velocity compensator design for lateral velocity mode.

3) Heave and Yaw Control.

The heave dynamics were represented as a first order system transfer function and further damping by velocity feedback improves the system response considerably. ADS-33C has listed a procedure for obtaining the equivalent time domain parameters for the height response to collective controller in Fig. 9. For Level 1 handling quality define in Cooper-Harper Handling Qualities Rating (HQR) Scale, the vertical rate response shall have a qualitative first order appearance for at least 5 second following a step collective input (See Table 1). In order to achieve this, the gains are chosen to be K_w = -2.12. The step response for the heave controller in shown in Fig. 10.

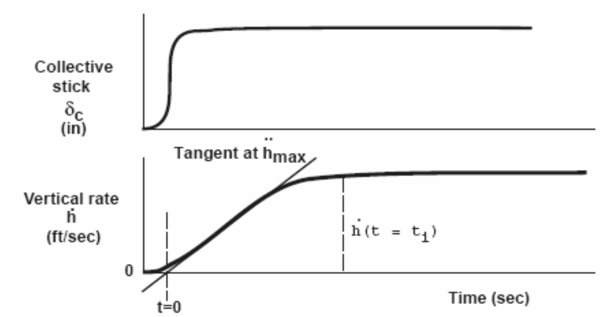


Figure 9 Procedure for obtaining equivalent time domain parameters for height response to collective controller according to Aeronautical Design Standard for military helicopter (ADS-33C) [2].

Table 1 Maximum values for height response parameters-hover and low speed according to Aeronautical Design Standard for military helicopter (ADS-33C) [2].

Level	$T_{\dot{h}_{eq}}$ (sec)	$\tau_{\dot{h}_{eq}}$ (sec)
1	5.0	0.20
2	∞	0.30

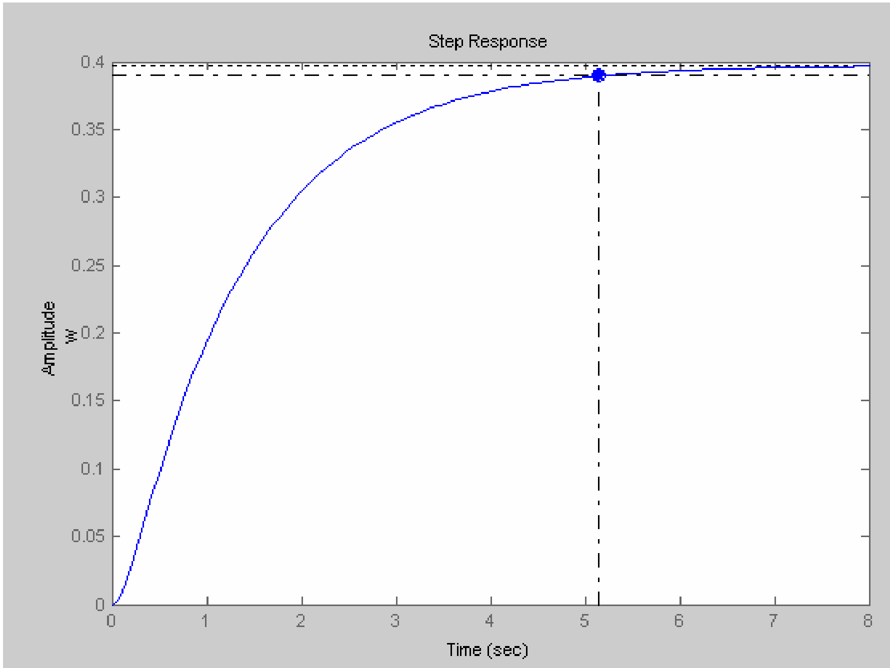


Figure 10 Heave dynamics compensator design.

The yaw controller can be design in similar way to heave controller. For yaw response to lateral controller, the design of the phase variable feedback gains should yield 10% overshoot and a settling time of 10 second and the poles were placed at p = -0.4 + 0.5458i, -0.4 - 0.5458i and -3.203 in order to achieve the design requirement. Based on the step response of the velocity dynamic shown in Fig. 11, the suitable feedback gains were found to be $K_{\psi} = [-\ 0.0696 \quad 7.1105 \quad -\ 2.3611]$. In Fig. 12, yaw controller bandwidth and time delay have been shown to meet Level 1 requirement specify in Section 3.3.21 of the Military Handling Qualities Specification ADS-33C.

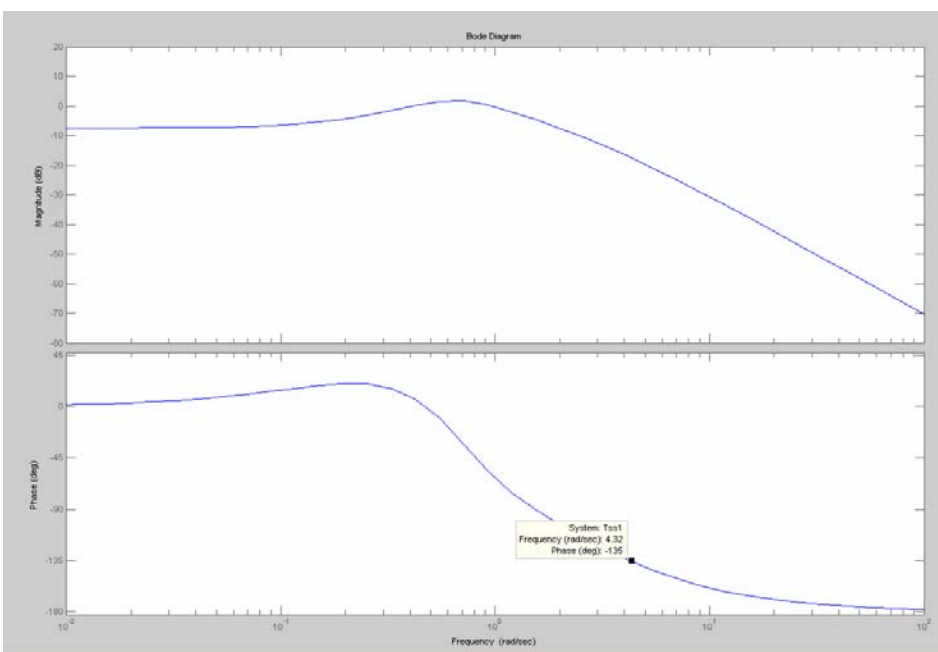


Figure 11 Yaw dynamics compensator design. The phase variable feedback gain is found to be $K_{\psi} = [-\ 0.0696 \quad 7.1105 \quad -\ 2.3611]$.

The bandwidth, $a_{BW\phi}$ is located at 4.32 rad/s and the phase delay, $\tau_{P\phi} = 0$.

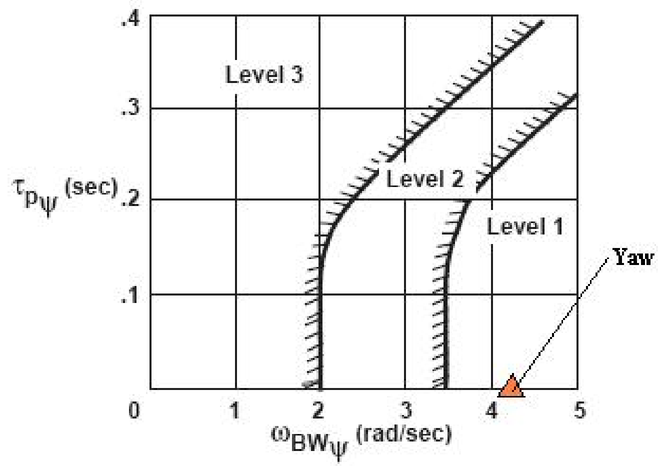


Figure 12 Compliance with small-amplitude heading changes in hover and low speed requirement specified in Section 3.3.5.1 of the Military Handling Qualities Specification ADS-33C.

6. Conclusion.

The paper has shown results of using state feedback method in designing attitude, velocity, heave and yaw controller for UTM autonomous helicopter model. Parameterized state space model was reduced to rigid body form with quasi-steady attitude approximation and can be decoupled to allow an analysis of lateral/longitudinal dynamics separately from yaw/heave dynamics in hover condition. The phase variable feedback gains were calculated for each helicopter dynamics in hover condition to satisfy the requirements contained in the ADS-33C.

7. Acknowledgements.

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8. References.

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