AUTOMATIC FLIGHT CONTROL SYSTEM FOR THE SMALL-SCALE COMPOUND HELICOPTER

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ABSTRACT

The paper presents results obtained in the project named “Automatic Control of a Compound Helicopter” led by Warsaw University of Technology and sponsored by the BOEING Company. In the paper, the system for automatic control of the ARCHER01 unmanned compound helicopter is described. For the purpose of controlling the helicopter with additional pusher rotor a Linear Quadratic Regulator (LQR) is integrated with a proportional controller. The model of the helicopter is developed and evaluated in FLIGHTLAB software. Developed control system is presented. Simulation results for four configurations of the system are shown and discussed.

1. INTRODUCTION

Nowadays, the growing interest in compound helicopters is primarily due to their main advantage, which is the ability to reach higher flight speed than are achievable for classical configuration helicopters. However, considered rotorcraft are highly nonlinear systems and therefore feature complex control systems [1][2]. Especially the need to provide executable control in transient mode (mode with medium speed between hover, low speed flight and with high speed in aircraft flight mode), results in a significant complication of the flight control system design process [3]. Hence, despite the wide range of compound helicopter capabilities, the technology is still underdeveloped in the aerospace industry [4]. Thus, issues related to compound helicopter development pose an encouraging area for carrying out research on modern and innovative solutions.

The main objective of the research was to propose an automatic flight control system for a small-scale, unmanned, compound helicopter fitted with an additional pusher propeller. For the purpose of this research, the nonlinear compound helicopter model was developed in the FLIGHTLAB environment. This software allows linear models for given, specific flight conditions to be derived quickly and efficiently from non-linear models. For this reason, it was decided to use the LQR approach to design the automatic control system for a classical configuration part of the helicopter and integrate it with additional control of the pusher propeller using the proportional controller.

In order to check the correct performance of the developed control system, it was applied to the nonlinear numerical helicopter model and tested using four different control options.

2. DESCRIPTION OF COMPOUND HELICOPTERS

Compared to classical single rotor configuration, the advantage of compound helicopters is the possibility to reach higher speeds in forward flight due to off-loading of the main rotor [5]. Additional propellers provide the propulsive force, while integrated wings may participate in generating the lift force [6]. The overall effect of the above-mentioned components allows, first of all, to reduce main rotor losses due to occurrence of stall region and subsonic flow regions at higher speeds and to decrease the fuselage pitch angles, which simultaneously contribute to elimination of the parasite drag [7]. Use of compound helicopters may also result in increased range or reduced vibration levels [8].

However, the disadvantages that are associated with the configuration also should be noted. These include greater complexity, increased weight, interference of airflow between the main rotor, tail rotor and additional propellers or lifting surfaces and higher energy requirements compared to conventional helicopters.

3. DESCRIPTION OF STUDIED HELICOPTER

The model used in the study was developed in FLIGHTLAB software and it is based on the real ARCHER01 helicopter, which is one of the variants developed in the ARCHER (Autonomous Reconfigurable Compound Helicopter for Education and Research) project at the Warsaw University of Technology [9] (Fig. 1). The aim of the project was to develop a universal test-bed platform on which it would be possible to attach additional elements to the rotorcraft (additional propellers, wings, stabilators), obtaining different variants of the helicopter in a compound configuration.

Figure 1   ARCHER helicopter in flight

The ARCHER helicopter is a small, unmanned helicopter with electric propulsion. In configuration ‘01’ an additional pusher propeller is fitted at the end of the tail boom (Fig. 2).

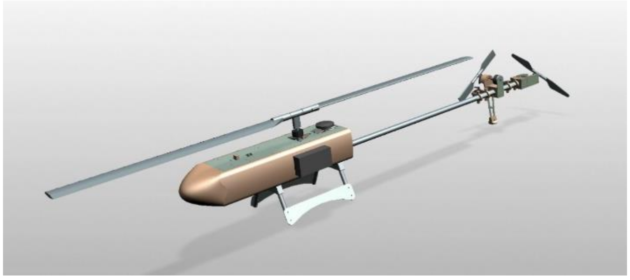

Figure 2   CAD model of the ARCHER01 helicopter

The propeller has variable angular velocity and blades collective pitch angle which enables a variety of control schemes. In ARCHER01 all rotors are powered by individual electric motors which allows wide variations of the angular rates and makes measurements of powers required quite simple. All the rotorhubs of the helicopter are rigid, without any flapping allowed. The helicopter is controlled manually by a pilot or with the use of an Arduino autopilot running on the Cube Orange hardware. During the flight a wide set of parameters (e.g. powers, angular rates of motors, swashplates angles, accelerations, body angular rates, positions and speeds) is recorded using additional measurement system developed for the helicopter. Basic ARCHER helicopter data is given in Table 1.

Table 1   Basic ARCHER01 characteristics

Characteristic	Metric
Main rotor diameter	1.78 m
No. of main rotor blades	2
Main rotor RPM	1’500 - 2’000
Tail rotor diameter	0.158 m
No. of tail rotor blades	2
Tail rotor RPM	7’200
Pusher propeller RPM	0-9’000
Main rotor & tail rotor rotorhubs	rigid, no flapping
Take-off Weight	8 kg
Main rotor blades airfoil	NACA0015mod
Tail rotor blades airfoil	NACA23012
Propulsion	electric

4. HELICOPTER SIMULATION MODEL

The simulation model of the ARCHER01 unmanned helicopter was developed in FLIGHTLAB software. The model reflects all mass, geometric and aerodynamic parameters of the real helicopter. The main rotor was modeled using blade element method with quasi-steady aerodynamic loads and Peters-He Six state inflow. Aerodynamic coefficients of the main rotor were validated using flight test data of ARCHER00 helicopter. The tail and pusher rotors have been modeled as discs in order to make calculations efficient for the FCS development. The fuselage is modeled as a 6 DOF rigid body with aerodynamic characteristics calculated with a CFD model. For the purpose of current project, the propulsion is modeled as an ideal one providing enough power for any requirement.

The control system of the simulation model allows independent control of all elements – i.e. three angular rates of the rotors and propellers and respective pitch angles. The actual settings of all control variables are the output of the Flight Control System running in the MATLAB/SIMULINK environment containing the developed control laws (Fig. 3).

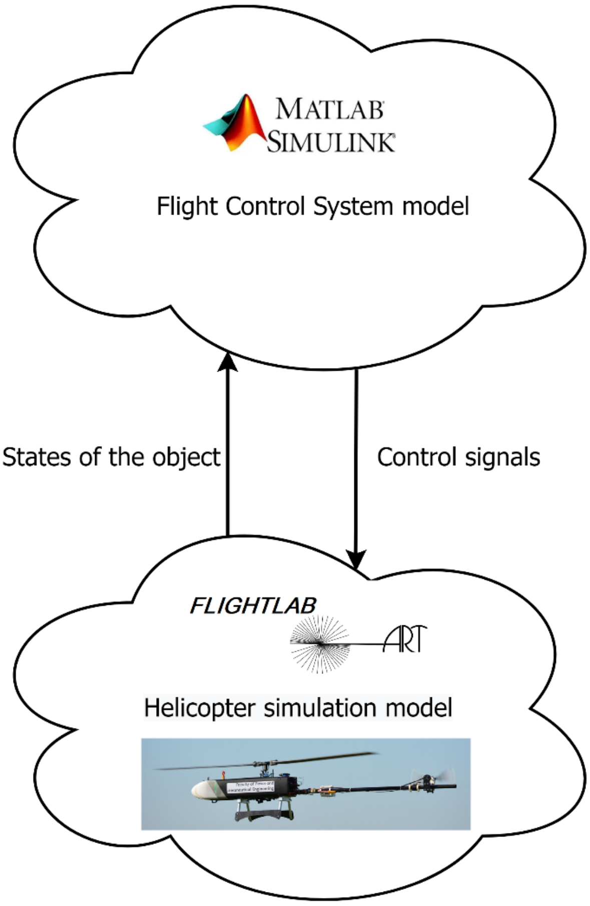

Figure 3 MATLAB/SIMULINK – FLIGHTLAB connection scheme

5. CONTROL SYSTEM

The ARCHER01 helicopter is controlled by changing the main rotor collective and two cyclic (longitudinal and lateral) pitch angles, the tail rotor collective pitch angle and by changing angular velocity and blade pitch angle of the pusher propeller.

In this study, the control system combines both LQR and proportional controller to control the ARCHER01 helicopter model. Information flow in the control system is shown in Fig. 4, where:

- x is a state variable vector; $x = [x, y, z, \varphi, \theta, \psi, v_x, v_y, v_z, p, q, r]$, where $x,\ y,\ z$ are the coordinates of the helicopter's position in the inertial, stationary coordinate system, $\varphi,\ \theta,\ \psi$ are attitude angles, $v_x,\ v_y,\ v_z$ are linear velocities in body coordinate system and $p,\ q,\ r$ are angular velocities in body coordinate system,
- u and u' are control input vectors; $u = [x_b, x_a, x_c, x_p]$, where $x_b,\ x_a,\ x_c,\ x_p$ are percentage positions of the main rotor longitudinal cyclic stick, main rotor lateral cyclic stick, main rotor collective stick and tail rotor collective stick, respectively, $u' = [x_\Theta, x_\Omega]$, where $x_\Theta,\ x_\Omega$ are pusher propeller blade pitch angle in degrees and angular velocity in RPM, respectively.

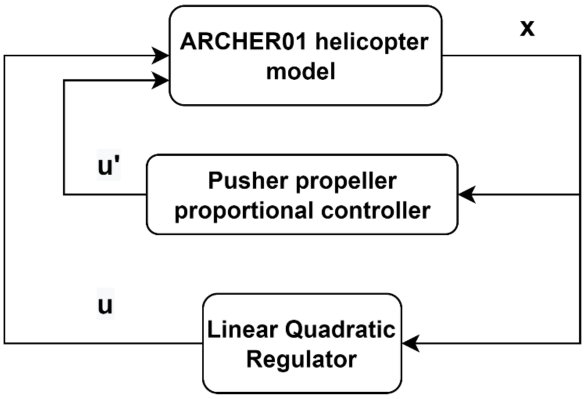

Figure 4 Control system diagram

It is assumed that all of the measurable state variables are controllable by the LQR. Additionally, the proportional controller can control the longitudinal velocity (in the body coordinate system) of the helicopter.

The proposed LQR is using the classical configuration control variables to control the helicopter – the main rotor collective and two cyclic (longitudinal and lateral) pitch angles and the tail rotor collective pitch angle. To design the LQR controller the linear model of the controlled object and information about all controlled state variables are required. The LQR gains are established based on the reduced helicopter dynamic linear model which was derived from the created nonlinear model in the FLIGHTLAB software described in Chapter 4 and then used in the full nonlinear model. The LQR works in a feedback loop, using differences between actual and desired helicopter state variables. The main issue related with the designing of LQR comes down to the selection of the weighting matrices values (Q – state weight matrix, R – control weight matrix). In this study, the selection of these values was made using an iterative expert method till the answers of the helicopter model were satisfactory. More specific theoretical basis of the LQR are presented in [10][11][12][13].

In parallel to the LQR, a proportional controller is added to control blade pitch angle and angular velocity of the pusher propeller. This controller works in a feedback loop using differences between actual and desired helicopter longitudinal velocity in the body coordinate system.

One of the reasons for integrating the proportional controller in the system was the inability to generate the linear model of the compound helicopter which apart from the classic configuration control variables would include the influence of the pusher propeller control variables on the helicopter state variables and from which the LQR using all control variables could be developed.

6. TEST CASES

The purpose of the test cases, in addition to showing the performance of the control system, was to demonstrate the effect of control using different flight control system options on the helicopter state variables.

The mission task was to accelerate the helicopter in the longitudinal direction from hover to a forward linear velocity in body coordinate system of $V_x = 80\frac{ft}{s}$, keeping a constant flight altitude and a zero lateral deviation. To accomplish the goal, the following control system options, which simultaneously served as test cases, were used:

- 1 – no forward linear velocity control by the LQR, the velocity controlled by the P controller of the pusher propeller – constant angular velocity of the pusher propeller, pitch control of the pusher propeller,
- 2 – no forward linear velocity control by the LQR, the velocity controlled by the P controller of the pusher propeller – constant pitch of the pusher propeller, angular velocity control of the pusher propeller,
- 3 – forward linear velocity control by the LQR and the P controller of the pusher propeller – constant angular velocity of the pusher propeller, pitch control of the pusher propeller,
- 4 – forward linear velocity control by the LQR and the P controller of the pusher propeller – constant pitch of the pusher propeller, angular velocity control of the pusher propeller.

7. RESULTS

To verify the control system performance, the simulations of the test cases described in chapter 6 were conducted. Results of the test cases are presented in Fig. 5 – Fig. 8, where X, Y, Z are the coordinates of the helicopter’s current position in the inertial, stationary coordinate system, Phi, Theta, Psi are attitude angles, Vx, Vy, Vz are linear velocities in body coordinate system, P, Q, R are angular velocities in body coordinate system and ‘MR. longitudinal stick pos.’, ‘MR. lateral stick pos.’, ‘MR. collective stick pos.’, ‘TR. collective stick pos.’ are percentage positions of the main rotor longitudinal cyclic stick, main rotor lateral cyclic stick, main rotor collective stick and tail rotor collective stick.

Based on the figures presenting values of the state variables and input signals, it was noted that all four proposed control systems fulfilled the main task of achieving the desired forward linear velocity $V_x = 80\frac{ft}{s}$.

The analysis of the obtained results for all test cases is presented below.

7.1 Test Case 1

The rise time required to achieve the desired linear velocity is 8 seconds. Model maintains a straight flight, the maximum deviation in terms of altitude is less than 1 ft and maximum lateral deviation is approximately equal to 2.2 ft. Angular velocities, apart from the moment of transition from hovering to horizontal acceleration, are equal to zero around all three axes. The value of rotorcraft pitch despite of the initial transition period tends to maintain value close to zero.

7.2 Test Case 2

By controlling the angular velocity of the pusher propeller, rise time of Vx compared to the first case decreased to 6 seconds. Referring to the values of angular velocities and attitude angles, no significant difference was observed with respect to the first case. Rotorcraft maintains a straight flight and lateral and vertical deviations are approximately identical to those for the first case. It seems that this system behaves similarly to the test case 1 but has a shorter Vx rise time which makes it more effective compared to the first analyzed case.

7.3 Test Case 3

The use of LQR in parallel with the linear controller to control the Vx velocity manages to reach the set value in a shorter time, in this case, the rise time is 4 seconds. The shorter time rise is achieved by additional pitching of the model to reach faster the preset velocity. Such a solution, however, has the disadvantage of increased deviation in the z-axis, which reached 25.5 ft maximum from the preset reference altitude. For this reason, a flight at a safe, high altitude of 657 ft was assumed. In the future project iterations, attempts will be made to compensate the altitude deviation. The model’s return to the preset altitude was achieved after 11 seconds. In terms of preserving the set course, the model behaved identically to the other cases already discussed.

7.4 Test Case 4

Similar to the comparison of the case studies 1 and 2, it can be noted that Vx rise time for the case in which algorithm controls the angular velocity of the pusher propeller, the rise time is shorter and equal to 3 seconds, which is one second shorter than for third case study. In terms of other parameters, no differences were found compared to the third control system. It seems that Vx control by pusher propeller angular velocity in conjunction with the LQR seems to be the most effective. It should be noted that this type of control involves a deviation in altitude similar to the test case 3.

The list of selected parameters for all test cases is presented in Table 2.

Table 2 comparison of basic parameters for the analyzed cases

	Test case 1	Test case 2	Test case 3	Test case 4
Vx rise time [s]	8.0	6.0	4.0	3.0
max Y deviat. [ft]	2.2	2.2	1.6	1.6
max Z deviat. [ft]	0.8	0.8	25.5	25.5
max Vz [ft/s]	0.8	0.8	5.2	5.2
max Theta [deg]	-2.2	-2.2	-40.1	-40.1

For better visualization, a comparison of the selected helicopter state variables is shown in Fig. 9, which are: Vx, Vz, Theta, Q, X, Z.

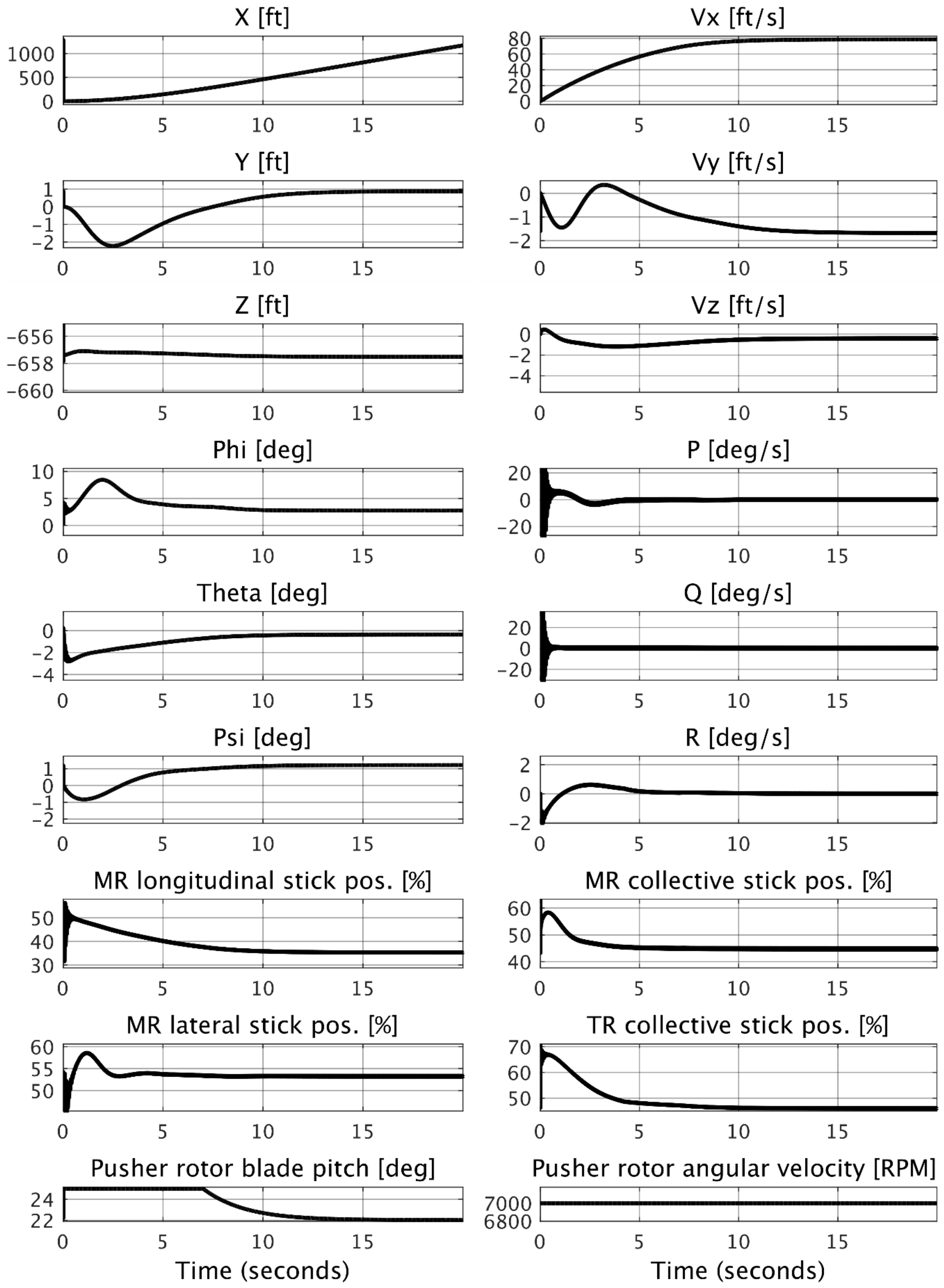

Figure 5 Results of the test case 1 - no longitudinal velocity control in the LQR, constant angular velocity of the pusher propeller, pitch control of the pusher propeller

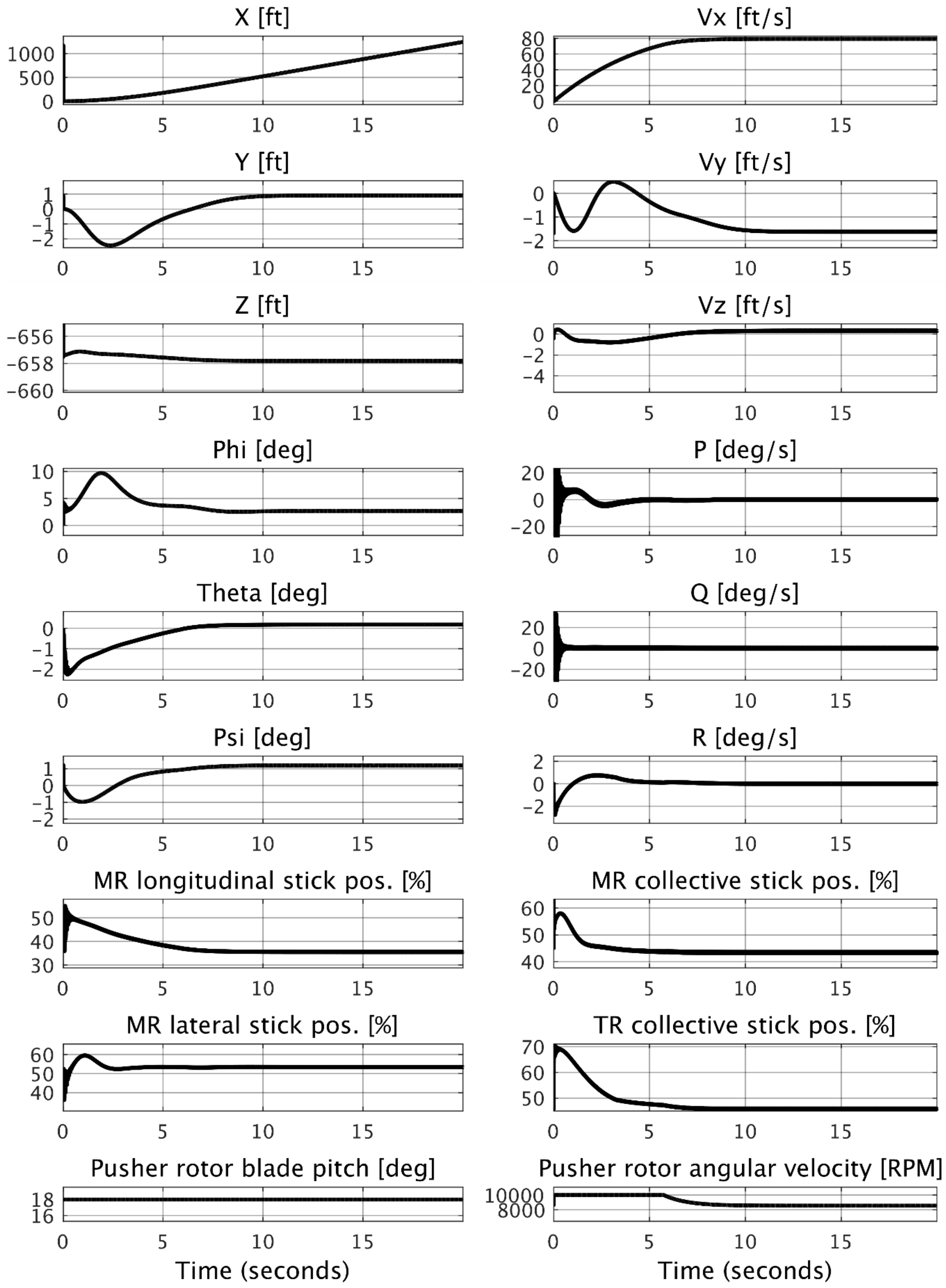

Figure 6   Results of the test case 2 - no longitudinal velocity control in the LQR, constant pitch of the pusher propeller, angular velocity control of the pusher propeller

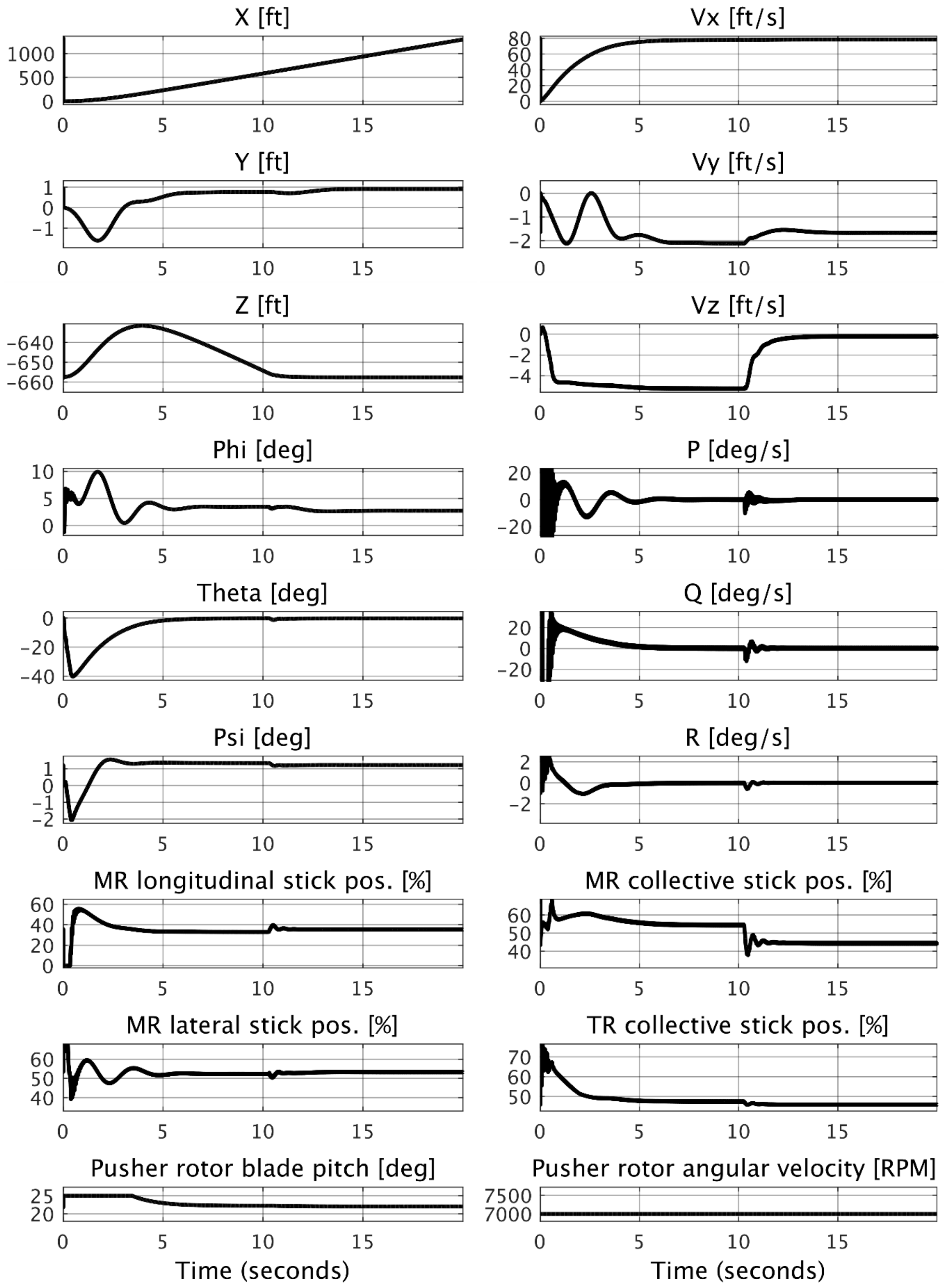

Figure 7 Results of the test case 3 - longitudinal velocity control in the LQR, constant angular velocity of the pusher propeller, pitch control of the pusher propeller

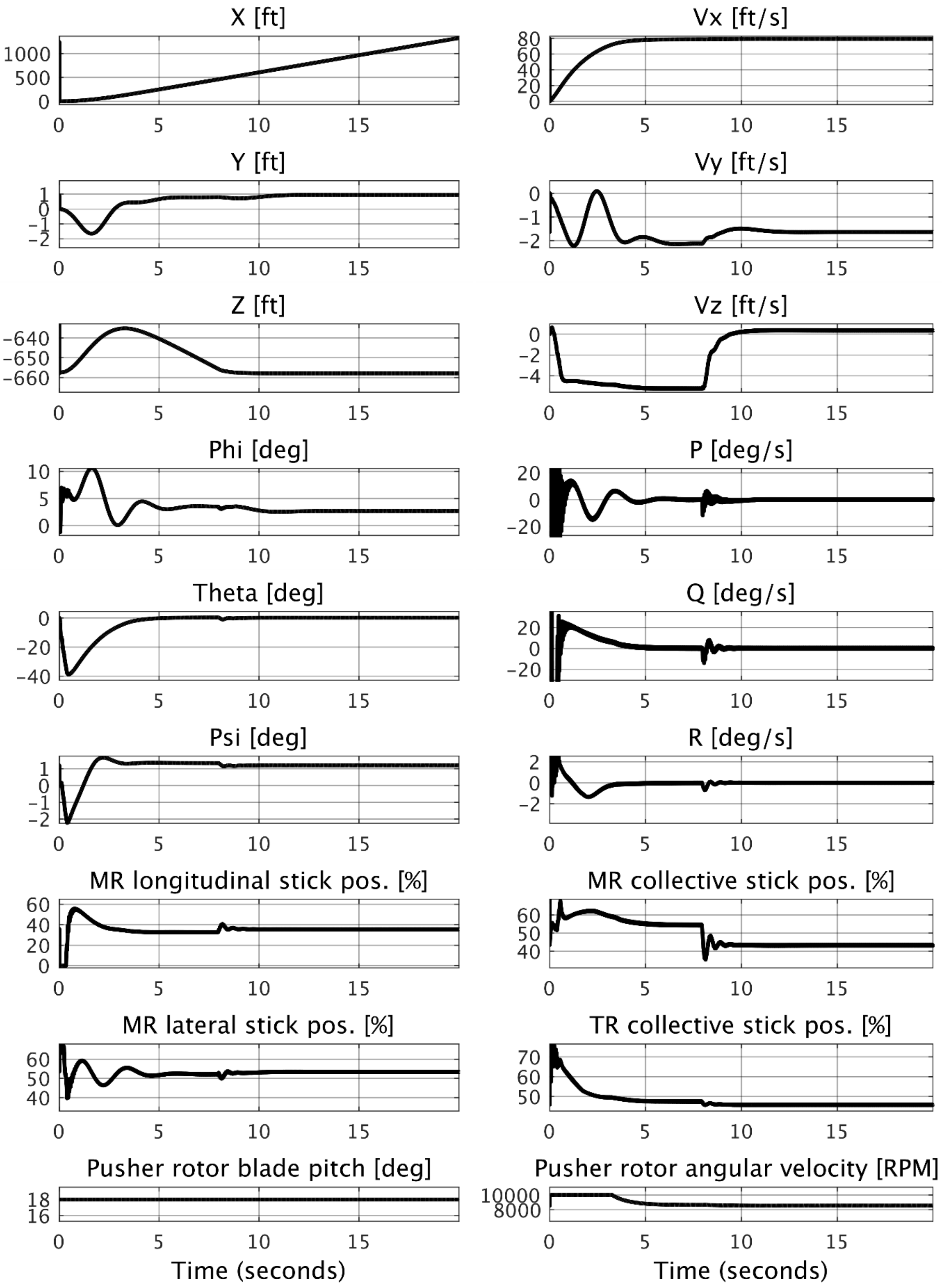

Figure 8 Results of the test case 4 - longitudinal velocity control in the LQR, constant pitch of the pusher propeller, angular velocity control of the pusher propeller

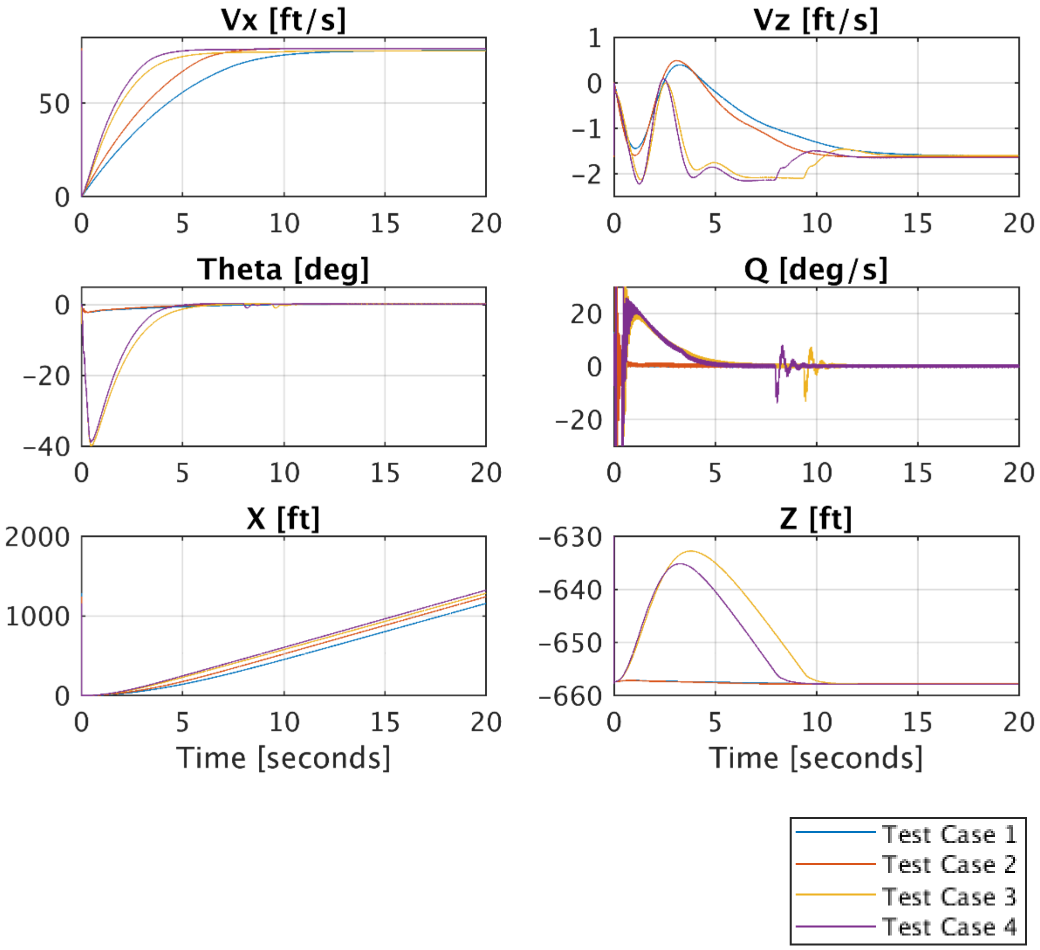

Figure 9 Comparison of the selected helicopter state variables

8. CONCLUSIONS

The paper addresses the problem of designing automatic flight control system for the small compound helicopter. The system was developed for the classical configuration helicopter with additional pusher propeller located behind the tail rotor. The control system integrates two controllers – Linear Quadratic Regulator and proportional controller. LQR is adapted and used to control all observable state variables of the helicopter by using the classic configuration control variables, additionally P controller can control the longitudinal velocity (in the body coordinate system) of the helicopter by changing angular velocity and pitch angle of the pusher propeller. The system was applied to the full nonlinear helicopter model developed in FLIGHTLAB software. The model was validated using flight test data.

Four different configurations of the developed system were analyzed, where both LQR and P controller performances were checked. Test case objectives were fulfilled, proving that the chosen control system design strategy is correct.

The study investigated the system performance while accelerating and performing low-speed mission profile. As part of further research, the system will be analyzed and tuned for high-speed mission profiles.

9. ACKNOWLEDGEMENTS

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