LQR and LQG control of the helicopter during landing on the ship deck

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Abstract

Purpose – The purpose of this study is to test the performance of the designed automatic control system based on the Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG) algorithms during landing of the helicopter on the ship deck. This paper is a further development of the series based on Topczewski *et al.* (2020).

Design/methodology/approach – The system consists of two automatic control algorithms based on LQR and the LQG. It is integrated with the ship motion prediction system based on autoregressive algorithm with parameters calculated using Burg's method. It is assumed that the source of necessary navigation data is integrated Inertial Navigation System with Global Positioning System. Landing of the helicopter on the ship deck is performed in automatic way, based on the preselected procedure. Performance of the control system is analyzed when all necessary navigation data is available for the system and in case when one of the parameters is unavailable during performing the procedure.

Findings – In this paper, description of the designed control system developed for performing the approach and landing of the helicopter using selected procedure is presented. Helicopter dynamic model is validated using the manufacturer data and by test pilots, overview is presented. Necessary information about ship motion model is also included. Tests showing mission performance while using LQR and LQG algorithms applied to the control system are presented and analyzed, taking into account both situations when full navigation data is available/unavailable for the control system.

Practical implications – Results of the system performance analyses can be used for selection of the proper control methodology for prospective helicopters autopilots. Furthermore, the system can be used to analyze the mission safety when information about one of the navigation parameters is identified by the navigation system as unavailable or incorrect and therefore unavailable during landing on the ship deck.

Originality/value – In this paper, control system dedicated for the automatic landing of the helicopter on the ship deck, based on two different control algorithms is presented. Influence of lack of information about one of the navigation parameters on the mission performance is analyzed.

Keywords Helicopter landing on a ship deck, Autopilot, Linear quadratic regulator, Linear quadratic Gaussian, Ship motion prediction, Burg's method, Helicopter dynamic model

Paper type Research paper

Nomenclature

Symbols

- P = error covariance matrix;
- k = index of the moment of time t_k;
- K = Kalman gain matrix;
- R = observation error covariance matrix;
- H = observation matrix;
- z = observation vector;
- Q = process error covariance matrix;
- φ = state matrix;
- x = state vector;
- w = state vector disturbances; and
- v = vector of observation vector disturbances.

Definitions, acronyms and abbreviations

- GPS = Global Positioning System;
- INS = Inertial Navigation System;
- LQG = Linear Quadratic Gaussian; and
- LQR = Linear Quadratic Regulator.

Introduction

In the paper, an aspect of the performance of the control system based on two different control algorithms integrated with ship motion prediction algorithm, designed for the helicopter automatic approach and landing on the ship deck is presented.

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The control system is composed of the autopilot based on Linear Quadratic Regulator (LQR)/Linear Quadratic Gaussian (LQG) algorithms and integrated with the algorithm predicting the future ship movement based on autoregressive method with coefficients calculated using Burg's method. The system is applied and tested using validated helicopter model based on Leonardo PZL SW-4, developed in the FLIGHTLAB environment. The model is validated using manufacturer data and by two Leonardo test pilots.

Here, the control system is tested while performing approach and landing on the ship deck, using preselected procedure. Tests are performed for both LQR and LQG algorithms with and without full navigation data available. Results of the tests are compared and analyzed.

This paper is a further development of the series based on Topczewski *et al.* (2020) where very detailed information about the developed system (helicopter model, sensor data availability, approach and landing strategy and control method and ship motion model) can be found.

Helicopter model

Comprehensiveness of modeling the helicopter dynamics depends on the purpose to which the model will be used (Padfield, 2008). In the research, a validated helicopter model is necessary to check the performance of the designed control system.

The helicopter simulation model used in the research is based on a single rotor PZL SW-4 helicopter with one turboshaft engine (Figure 1) and is developed in the FLIGHTLAB environment which is a well-established rotorcraft modeling software (Du Val and He, 2017). The helicopter dynamic model has been divided into seven subsystems – fuselage, main rotor, tail rotor, empennage, skids, propulsion and control. The main rotor is a three-bladed articulated and rotates clockwise (looking from above). The tail rotor is two-bladed seesaw and rotates clockwise looking from the left side (the lower blade is advancing). It is assumed that main rotor blades are nondeformable and are mounted to the hub by three hinges – in order from the axis of the shaft – flap, lag and pitch. Tail rotor (teetering) blades are also nondeformable. All elements of the helicopter, except the skids, are modeled as rigid.

Figure 1 Leonardo PZL SW-4 helicopter

Source: Figure by authors

Loads acting on the helicopter include aerodynamic, gravity and inertia forces. To model the rotors, blade element theory with flapping dynamics included was used. The aerodynamic model is a nonlinear unsteady one with stall delay, and Peters-He 6 state induced velocity model with an empirical ground effect model. The interactions between rotors and fuselage are included. Look-up tables are used to model the aerodynamic loads of the fuselage and empennage. The engine model is based on FLIGHTLAB turboshaft engine model with detailed model of its dynamics and control systems.

The model is validated for both steady flight and dynamic response cases, using flight test data from the manufacturer (Leonardo PZL Swidnik) and by two test pilots.

For the execution of control commands, there are four electromechanical actuators which are part of the developed control system. Basic parameters of the actuators are slide out range (± 30 mm), slide out speed (± 20 mm/s) and time to maximum slide out (1.57 s). Here, no backlashes are applied to the actuators. Broad description of the developed helicopter model can be found in Topczewski *et al.* (2020). Influence of the actuators backlashes on the helicopter performance can be found in Topczewski *et al.* (2021).

Control methodology

Helicopter maritime operations, especially deck landings differ from land-based ones (Horn and Bridges, 2007; Grocholsky *et al.*, 2016; Frost *et al.*, 2021) and are performed according to the preselected procedures (Arora *et al.*, 2013). According to Anonymous (2003), six navy helicopter-ship operations can be distinguished: fore/aft procedure, relative wind or into wind procedure, cross-deck procedure, aft/fore or facing astern procedure, astern procedure and oblique procedure. Here, landing procedure of the helicopter on the moving, confined ship deck is composed of three stages. Starting from approach to the ship, next hover over the landing deck and final landing with touchdown. During approach, helicopter performs the flight toward the ship's deck using navigation waypoints. Next, helicopter decelerate and intercept hover position over the landing deck, keeping the ship's forward velocity and safe height. Last phase of the landing maneuver is performed using the ship motion prediction algorithm, which is a part of the integrated control system. It is based on autoregressive method with model parameters calculated using Burg's method. It estimates future position and attitude of the ship described in inertial, stationary system of coordinates at specified lead time, using the data about ship position and attitude from the past. It works online, starting from the beginning of the approach. Predicted navigation information about position and attitude of the ship is used to select the best moment to perform helicopter touchdown in preselected time interval. It is made taking into account whether the ship deck will not hit the helicopter while descend and whether the sum of the helicopter and ship vertical velocities (relative vertical velocity) and allowable pitch and roll angles will not exceed margin values. When all of the analyzed parameters are within safety margins, helicopter moves from hover to the calculated touchdown position. Broad description of the developed ship motion prediction algorithm can be found in Topczewski *et al.* (2020).

Here, the landing procedure is performed automatically based on the autopilot which is a part of the integrated control system. It is based on both LQR (Topczewski *et al.*, 2018) and LQG (György, 2019) algorithms to calculate control commands for performing all of the helicopter landing procedure phases. For estimating gains, both algorithms require linear model of the controlled object dynamics which was generated using global linearization of the helicopter nonlinear model developed in FLIGHTLAB software. Here, linear model with 21 significant state variables (helicopter position, linear velocities, roll, attitude angles, angular velocities, main rotor–induced velocities, each blade flap, each blade lag) and 4 control variables (main rotor lateral cyclic, longitudinal cyclic, collective and tail rotor collective) is applied. Here, it is assumed that online available helicopter state variables are position, attitude, linear velocities and angular velocities. The rest of the helicopter state variables are included in the linear model because they affect generating LQR and LQG gain matrices but they are not controlled. Effective performance of the LQR and LQG algorithms depends on proper selection of the values of the weighting matrices (Lichota *et al.*, 2020; Dul *et al.*, 2020). Here, selection of these values was made using iterative expert method to obtain satisfactory helicopter responses at all stages of the landing procedure. Broad description of the developed autopilot based on the LQR can be found in Topczewski *et al.* (2020).

The LQR methodology assumes that all of the state variables are continuously observable and available for the controller. The LQG methodology can be applied, when state variables are not completely measurable. It integrates LQR algorithm and Kalman filter which is used to estimate state variable values. Kalman filter can be defined for the process described as:

$$x_{k+1} = \Phi \quad x_k + w_k \tag{1}$$

$$z_k = Hx_k + v_k \tag{2}$$

where:

- x is a state vector;
- k is an index of the moment of time t_k;
- φ is a state matrix;
- w is a vector of state vector disturbances;
- z is an observation vector;
- H is an observation matrix; and
- v is a vector of observation vector disturbances.

Kalman gain matrix is defined as:

$$K_k = P_k^- H^T \left(H P_k^- H^T + R \right)^{-1} \tag{3}$$

where:

- K is a Kalman gain matrix;
- P is an error covariance matrix; and
- R is an observation error covariance matrix.

Update of the state variable estimate is defined as:

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \tag{4}$$

Update of the error covariance is defined as:

$$P_k = (I - K_k H)P_k^- \tag{5}$$

Predict:

$$\hat{x}_{k+1}^- = \Phi \quad \hat{x}_k \tag{6}$$

$$P_{k+1}^- = \Phi \quad P_k \Phi^T + Q \tag{7}$$

where:

Q = is a process error covariance matrix.

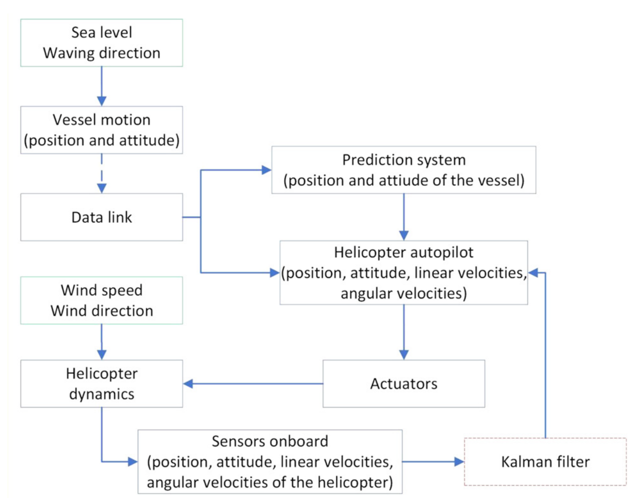
In the research, Kalman design process was based on the developed linear model of the system, selection of the process and observation error covariance matrices was made by performing analyses of the results of the state variables estimation process and adapted to ensure the control performance during the landing procedure.

Developed integrated control system consists of the autopilot, which use raw information about the ship position and attitude obtained from ship sensors and sent by the data link, used to intercept the ship and predicted information from the ship motion prediction system, used to perform the final touchdown maneuver. Calculated control commands are performed by the actuators. Helicopter state variables are measured by onboard sensors. It is assumed that state variables of the helicopter and the ship are measured by the integrated Inertial Navigation System/Global Positioning System (INS/GPS). The system information flow diagram is shown in the Figure 2. Basic system design is marked blue and its full description can be found in Topczewski *et al.* (2020). Here, Kalman filter is added (marked red) and integrated with the autopilot based on the LQR algorithm, working as LQG.

Ship motion model

In the research, to simulate the helicopter landing on the ship deck at different sea states, the ship motion model is used.

Figure 2 Information flow in the control system



Source: Figure by authors

The model has been developed by Ship Design and Research Centre S.A and it is based on measured ship (frigate) dynamics in waves to obtain ship's deck response amplitudes of positions and attitudes. Apart from simulation of the helicopter landing on the ship deck, the output information from the model (position and attitude) is used as an input to the ship motion prediction system. The analyses have been made with use of potential code (ANSYS AQWA) in frequency and next time domain. The results have been validated according to the procedures of International Towing Tank Conference, during towing tank tests. Broad description of the developed ship model can be found in Topczewski *et al.* (2020).

Test cases

In the research, test cases are conducted to check the autopilot performance based on LQR and LQG during the procedure of the helicopter landing on the ship deck. Tests include case in which full information about helicopter state variables is available and case in which information about one state variable (helicopter pitch angle) is not available for the control system.

For the purpose of the tests, oblique procedure (Anonymous, 2003) is adapted and applied to perform the mission. In the procedure, helicopter starts the approach phase 2 NM from the ship, over port, at height of 500 ft (sea level). The yaw angle of the helicopter is fixed under an angle of 30° with the ship's centerline. Helicopter starts to descend 1.5 NM from the ship. Next, helicopter hovers at height of 50 ft over the sea level. Last step is vertical landing on the ship deck.

Simulations are performed for the selected conditions:

- ship moving with the forward velocity of 20 knots (33.75 ft/s), with azimuth of 0°;
- sea state 0 (in Douglas sea scale, no waves, no wind);
- information from navigation system about (available) state variables is not affected by errors; and
- no actuator backlashes are applied.

Four test cases are performed:

1 Case 1 – autopilot based on LQR, information about helicopter state variables constantly available.
2 Case 2 – autopilot based on LQG, information about helicopter state variables constantly available.
3 Case 3 – autopilot based on LQR, lack of information about helicopter pitch angle value (constant zero value starting 15 s from the beginning of the procedure).
4 Case 4 – autopilot based on LQG, lack of information about helicopter pitch angle value (constant zero value starting 15 s from the beginning of the procedure).

The simulation results are shown in Figures 3–6. The helicopter responses are marked black and the responses of the ship are marked red.

In the figures, information about helicopter state variables include position (X, Y and Z in the inertial coordinate system), attitude (Φ, θ and Ψ in the gravitational coordinate system), linear velocities (Vx, Vy and Vz in the body coordinate system) and angular velocities (p, q and r in the body coordinate system). Control variables include main rotor swashplate pitch, roll and collective and tail rotor swashplate collective. Information about ship state variables include position (X, Y and Z in the inertial coordinate system) and attitude (Φ, θ and Ψ in the gravitational coordinate system).

Case 1 and Case 2 present results of the successful helicopter landing on the ship deck in time of 165 s. In both cases, helicopter starts the approach phase 2 NM behind the ship at the height of 500 ft and flies toward the ship with the Vx velocity of 110 ft/s, then starts to descend and after 85 s starts to decelerate. The helicopter intercepts the ship deck position and tracks it at the safe height of 50 ft. Finally, it performs successful automatic landing based on the information from the ship motion prediction system. Small oscillations of linear and angular velocities and attitude angles can be seen during the descent. During deceleration, helicopter height changes can be observed.

Case 3 and Case 4 present results of the control system performance in situation in which it has no navigation information (constant 0 value) about the pitch angle of the helicopter. This information is unavailable for the system starting 15 s from the beginning of the procedure.

Time of the flight when the helicopter manage to perform the mission tasks, for the control system based on LQR is approximately 60 s while for the LQG is approximately 80 s. Growing oscillations in the pitch angle can be seen in both cases from the beginning of the descent but for the LQG, because of the signal filtering, the autopilot is able to stabilize it for a longer period of time.

While descent, growing height oscillations can be observed due to the pitch angle changes.

For the LQR, yaw angle is stabilized till the 63 s when rapid changes in linear and angular velocities and attitude angles can be seen and the system is not able to control the helicopter. For the LQG, the control system stabilizes the yaw angle till the end of the maneuver.

Flight safety level seems to be higher for the LQG – there are no aggressive changes in parameters in short time intervals. Although, from 80 s, the control system is not able to realize the mission, but linear velocity *V*x is quite slowly decreasing. Pitch angle is high but does not exceed 19°, roll and yaw angles are stabilized.

For the LQR, at the end of the safe helicopter flight, parameters are rapidly changing, their amplitudes are very high.

Conclusion

In the paper, the integrated control system developed to perform automatic landing of the helicopter on the moving ship deck is presented. System consists of ship motion prediction system, navigation sensors, actuators and the autopilot which here is based on both LQR and LQG algorithms. The prediction system is based on autoregressive algorithm with parameters calculated using Burg's method. It is assumed that navigation data come from onboard INS/GPS systems.

Helicopter model which is used to check the performance of the developed control system is based on Leonardo PZL Swidnik SW-4. The model is developed in the FLIGHTLAB software, validated using flight test data from manufacturer and by test pilots.

Ship motion model is used to simulate the helicopter landing on the ship deck at different sea states. The model is developed by Ship Design and Research Centre S.A and it is based on measured ship (frigate) dynamics in waves.

Figure 3 Case 1 – autopilot based on LQR, information about helicopter state variables constantly available

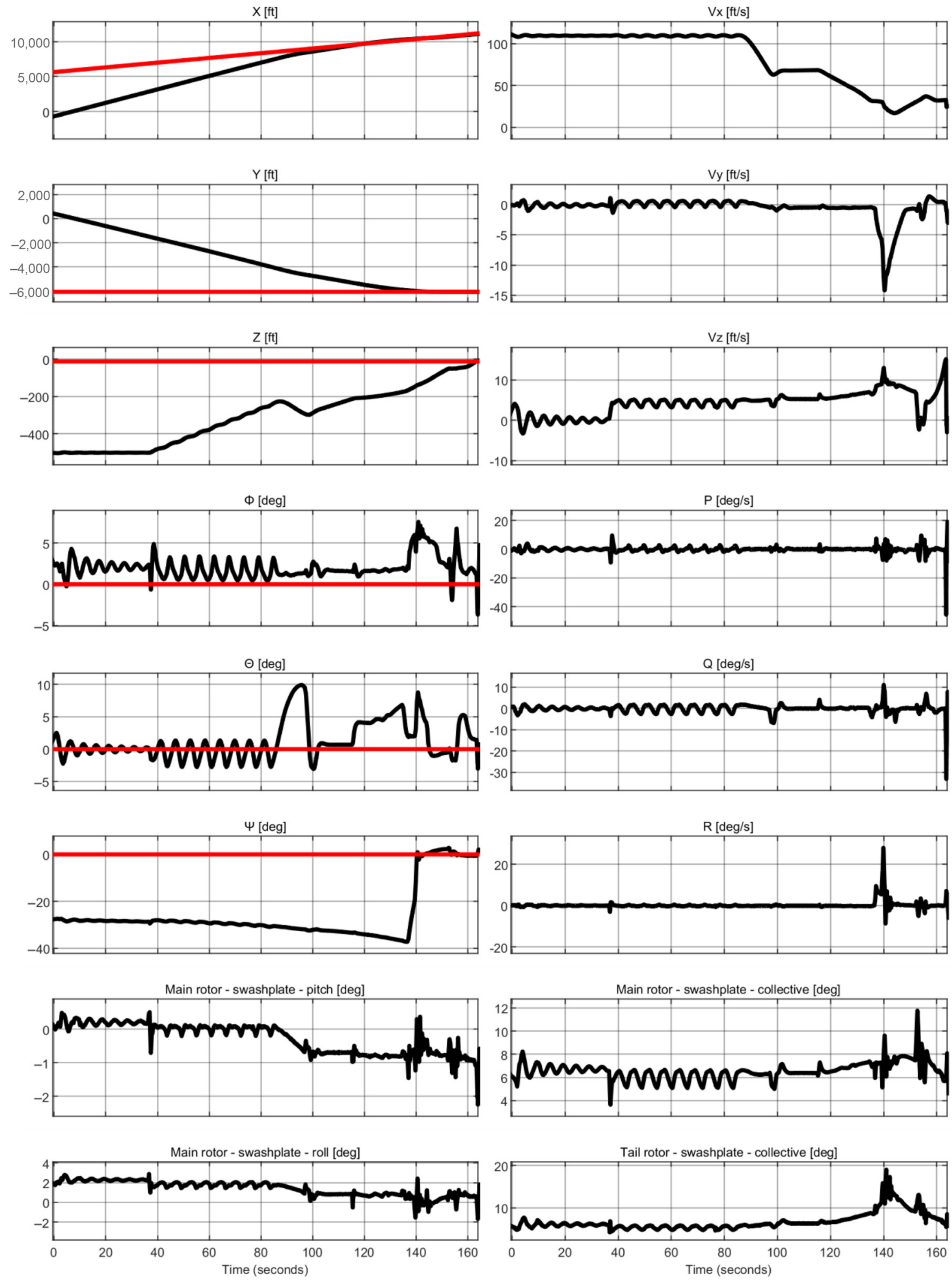


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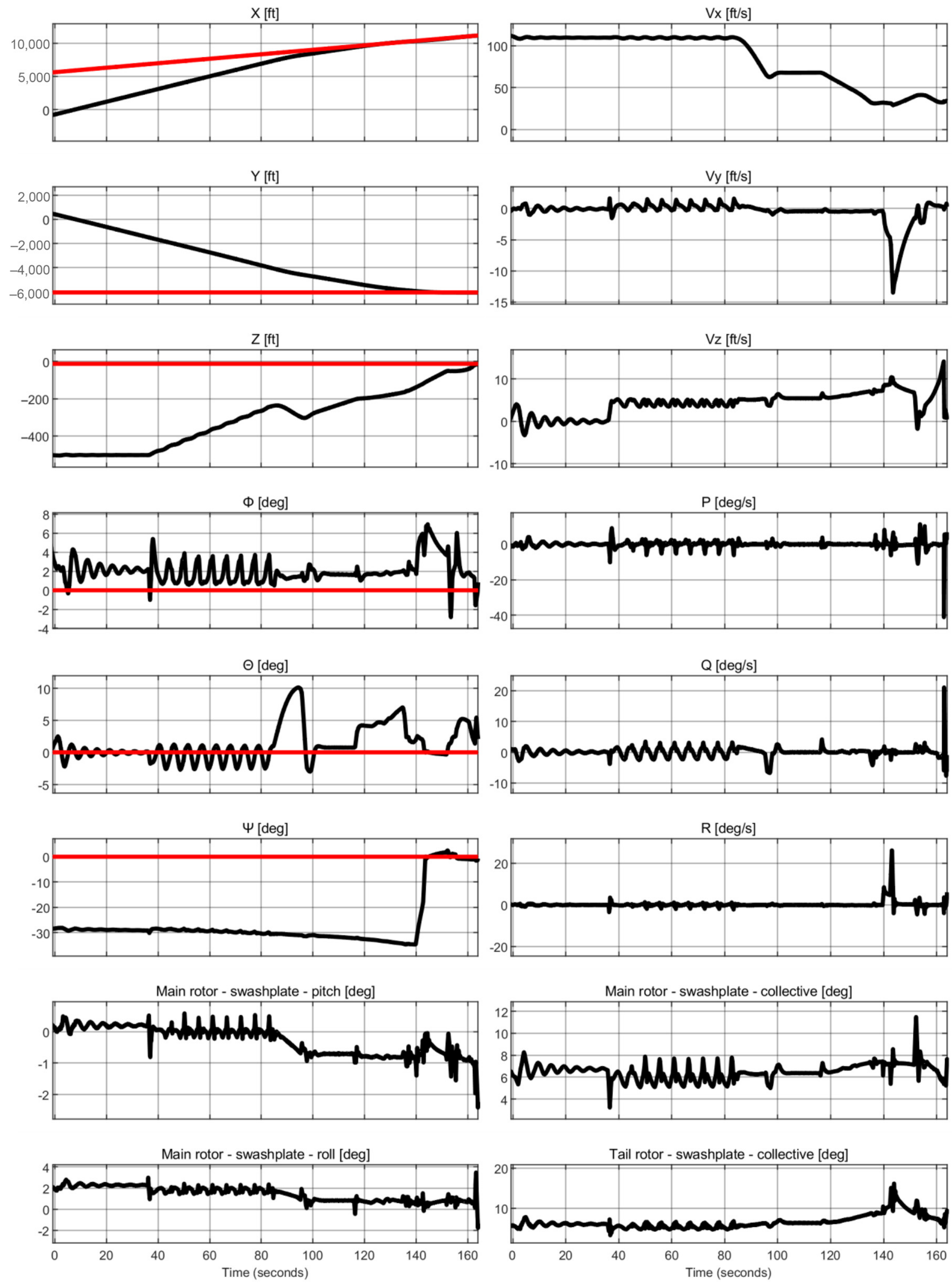
Figure 4 Case 2 – autopilot based on LQG, information about helicopter state variables constantly available



Source: Figure by authors

Figure 5 Case 3 – autopilot based on LQR, lack of information about pitch angle value

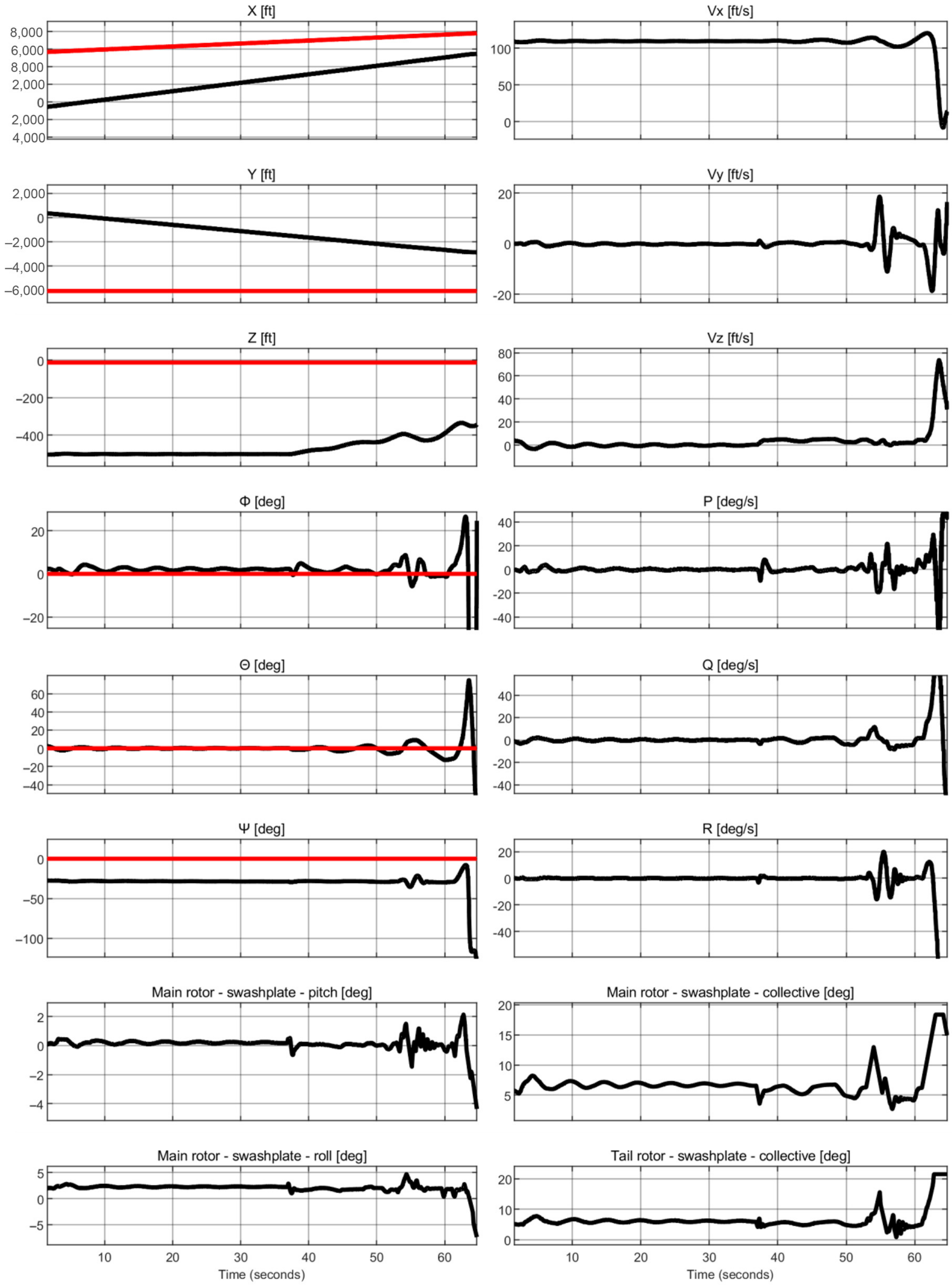


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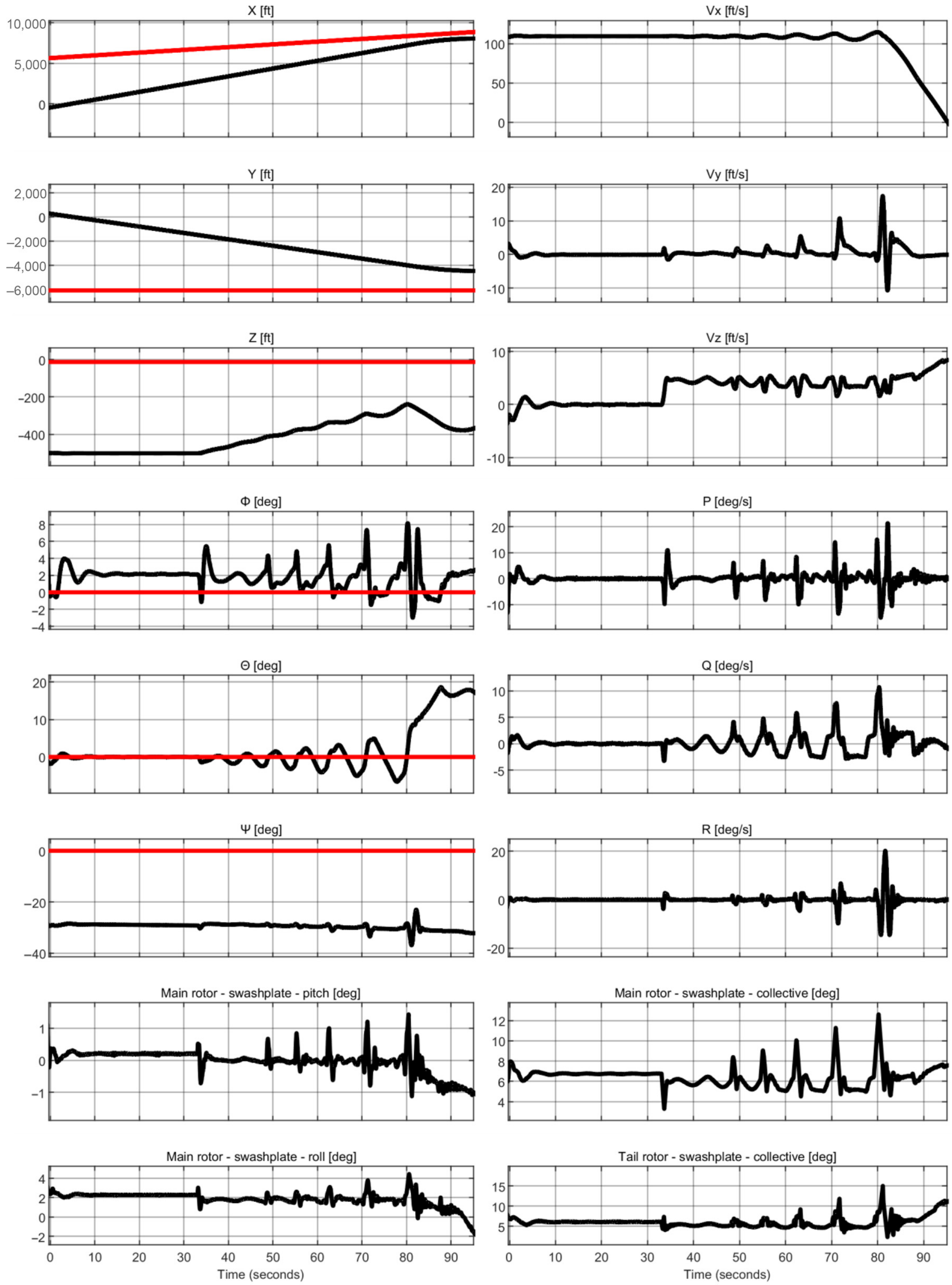
Figure 6 Case 4 – autopilot based on LQG, lack of information about pitch angle value



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Essential part of the research is included in the test cases section. The control system is evaluated while performing the procedure of helicopter landing on the moving ship deck. Four test cases are applied. In the first two, performance of the LQR and LQG algorithms is checked when full information about helicopter state variables is constantly available. The efficiency of the algorithms in these cases is similar and satisfactory, helicopter successfully lands on the moving ship deck. In the second two cases, performance of the LQR and LQG algorithms is checked when there is no information about pitch angle available. The efficiency of the algorithms in these cases is different. In both cases, helicopter is not able to realize the full mission but LQG algorithm is more effective, helicopter safety is assured for a longer period of time.

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