Impact of actuators backlash on the helicopter control during landing on the moving vessel deck

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Abstract

Purpose – The purpose of this paper is to test the performance of the control system developed for the helicopter automatic approach and landing on the moving vessel deck, when different values of backlashes are applied to the four control actuators.

Design/methodology/approach – The system consists of automatic control algorithm based on the linear quadratic regulator and the vessel motion prediction algorithm based on autoregressive method with parameters calculated using Burg's method. Necessary navigation data is provided by on-board inertial navigation system/Global Positioning System. Calculated control commands are executed by four electromechanical actuators. Performance of the mission, which is based on selected procedure of approach and landing of the helicopter on the moving vessel deck, is analyzed taking into account different values of backlashes applied to the actuators.

Findings – In this paper, a description of the control system dedicated for automatic approach and landing of the helicopter on the moving vessel deck is shown. Necessary information about helicopter dynamic model, control system and vessel motion model is included. Tests showing influence of actuator backlashes on the mission performance are presented.

Practical implications – The developed control methodology can be adapted for selected helicopter and used in prospective development of an automatic flight control system (AFCS) or in a simulator. The system can be used to define in which conditions helicopter can perform safe and successful automatic approach and landing on a moving vessel deck.

Originality/value – In this paper, an integrated control system is presented; influence of the control actuator backlashes on the mission performance is analyzed.

Keywords Automatic flight control system, Linear quadratic regulator, Helicopter landing on a vessel deck, Vessel motion prediction, Burg's method, Actuator backlashes, Helicopter dynamic model

Paper type Research paper

Introduction

In this paper, an aspect of the performance of the control system developed for the helicopter automatic approach and landing on the moving vessel deck, when different values of backlashes are applied to the four control actuators is shown.

For the automatic approach and landing of the helicopter on the moving vessel deck, an integrated control system is used. A linear quadratic regulator, which is an autopilot (AP), is combined with the vessel motion prediction algorithm, which is based on autoregressive method with parameter's calculated using Burg's method. The developed control system is applied to the Leonardo PZL SW-4 helicopter dynamic model, developed in FLIGHTLAB environment and validated using manufacturer flight test data and by two test pilots. Tests of the developed control system performance during approach and landing on the moving vessel deck are performed using the selected procedure at selected environmental conditions with different values of backlashes applied to four control actuators.

This paper is a further development of Topczewski *et al.* (2020).

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Helicopter model

Comprehensiveness of modeling the helicopter dynamics depends of the purpose to which the model will be used (Padfield, 2008). In this research, a reliable helicopter model is

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necessary to apply automatic control laws to control the helicopter in approach and landing on the moving vessel.

Here, the helicopter model is reflecting a single rotor PZL SW-4 helicopter powered by one turboshaft engine with a three-bladed articulated main rotor and two-bladed see-saw tail rotor (Figure 1) and is developed in FLIGHTLAB software, which is a well-established rotorcraft modelling software (Du Val and He, 2017). FLIGHTLAB is based on the multi-body dynamics methodology. In the modeling process, the vehicle is divided into several subsystems (e.g. main rotor, tail rotor, fuselage, empennage, propulsion system). Connections between the subsystems are defined, and later, the subsystems are further divided into elements (e.g. main rotor is divided to main rotor hub and blades, blades are divided into blades elements). For each element, equations of generalized forces are formulated. Systems of dynamics equations are assembled via partial differentiation and solved using nonlinear solvers. Such an approach allows great flexibility of the FLIGHTLAB software and allows modeling of various flying types of vehicles, not only rotorcraft. Unfortunately such technique of system modeling makes it impossible to present the final equations of motion of the modeled object.

For the purpose of helicopter dynamics modeling, the helicopter has been divided to six subsystems – fuselage, main rotor, tail rotor, empennage, skids and engine. The main rotor rotates clockwise (looking from above), and the tail rotor rotates clockwise looking from the left side (the lower blade is advancing). It is assumed that main rotor blades are non-deformable 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 non-deformable. All elements of the helicopter, except the skids, are modeled as rigid.

Loads acting on the helicopter come from aerodynamic, gravity and inertia forces. The main and tail rotors are modeled using the blade element theory, including flapping dynamics. 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 also taken into account. The aerodynamic loads of the fuselage and empennage are modeled using empirical lookup tables. The engine model is based on FLIGHTLAB turboshaft engine model with detailed model of its dynamics and control systems.

Figure 1 Leonardo PZL SW-4 helicopter

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

Besides the manual control system, which includes hydraulic boosters placed in the control lines between pilot sticks and the swashplate, there are four electromechanical actuators, which are part of the automatic control system. Basic parameters of the actuators are: slide out range ($\pm$30 mm), slide out speed ($\pm$20 mm/s), time to maximum slide out (1.57 *s*). Backlashes of the actuators implicate a change in the output caused by a change in the input, except when the input changes direction. In the case when the input changes direction, there is no effect on the output when the initial change in the input occurs. The amount of side-to-side play in the system is referred to as the deadband (centered about the output), which can be defined.

Control methodology

According to Anonymous (2003a, 2003b) and Arora *et al.* (2013), helicopter landing on a moving vessel deck may be considered as composed of three stages: approach to a moving vessel, hover over a landing deck and final landing phase with touchdown.

Here, during approach, the helicopter performs movement toward the hover position over the landing deck by passing preselected waypoints. From the beginning of this phase, vessel motion data is collected as an input to the vessel motion prediction system. The phase is finished when the helicopter reaches the position over the landing deck and starts hovering (hovering here means following the selected point over the moving vessel deck at safe height). Vessel motion prediction algorithm works online and estimates future vessel position and attitude at a specified lead time. It is analyzed whether the deck will not hit the helicopter during the descend (due to the vessel floating). It is also analyzed whether during the touchdown, predicted relative vertical velocity (sum of the vertical velocities of the helicopter and the vessel) and pitch and roll angles of the vessel will not exceed allowable values. When analysis of compliance of these parameters is positive (all of the described predicted parameters do not exceed allowable values at prediction time horizon), the final landing maneuver is performed at a specified lead time.

In the methodology developed, all of the helicopter maneuvers (approach, hover, landing) are performed in automatic way, based on linear quadratic regulator (LQR) (Dul *et al.*, 2020). This methodology requires the linear model of the controlled object dynamics for the calculation of gain matrix. Here, the linear model of the helicopter was developed by global linearization of the full nonlinear FLGHTLAB model. This approach is often used in flight dynamics, as it allows to reduce costs when new designs, and system modifications are tested (Lichota *et al.*, 2017; Lichota, 2016). Efficient operation of the LQR controller in case of approach and landing on the moving vessel deck required iterative adjusting of the weighting matrices Q and R until responses of the helicopter during the mission were at the satisfactory level according to the mission objectives and limitations. In LQR, control feedback is defined as:

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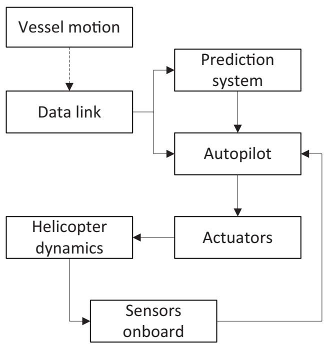
$$u = -K * (x - x_d) \tag{1}$$

where:
x = is a vector of state variables;
x_d = is a vector of the desired values of state variables; and
u = is a control vector, K is the feedback gain.

Figure 2 Information flow in the control system



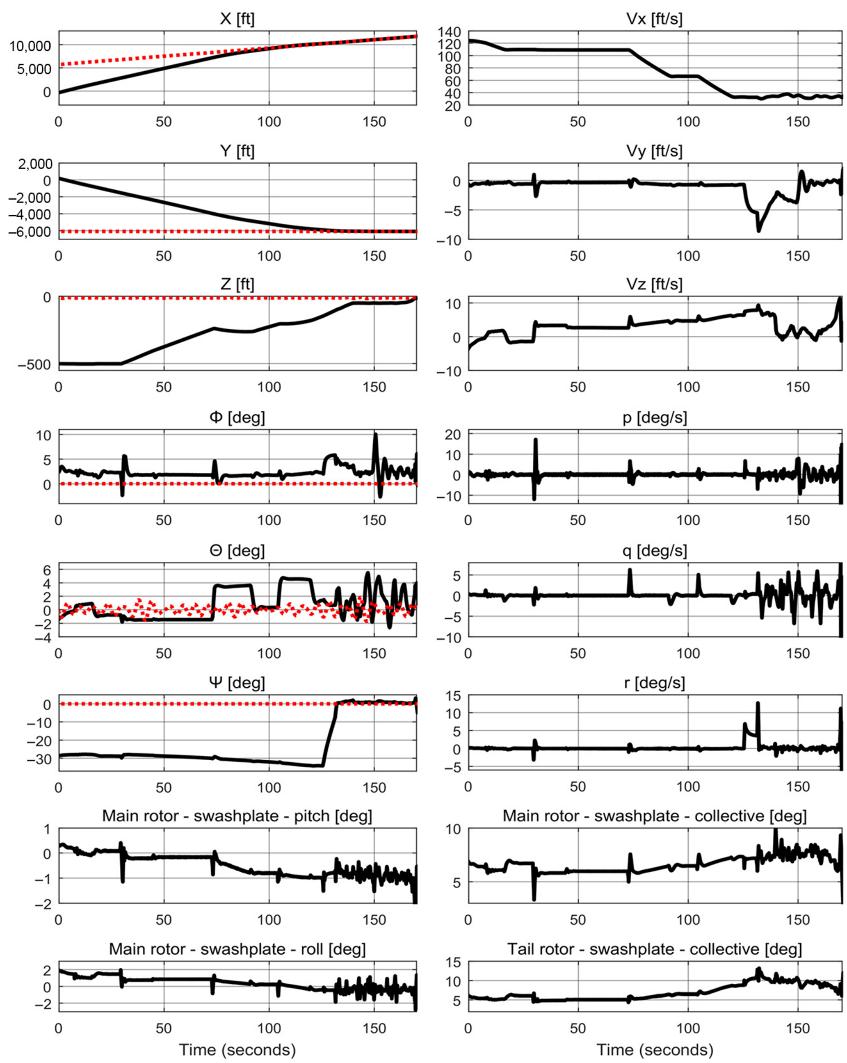
$$K = R^{-1}B^{T}P \tag{2}$$

where:
P = is the matrix solution of the Riccati's equation.

A broad description of the developed automatic flight control can be found in Topczewski *et al.* (2020).

Vessel position and attitude prediction system is used to estimate the future vessel deck movement. It is the element of the control system and is used to perform successful and safe landing on the vessel deck. When approaching to the vessel, the subsystem is collecting and analyzing the data. It collects specified number of data samples, and based on the autoregressive algorithm, predicts vessel deck position and attitude. The algorithm works online and in the loop: after the first set of data collection, it makes the first estimation, and each next second, it switches the data set window one sample ahead computing new estimation. Each of the time series parameters (components of the position and the attitude) is analyzed separately. For the purpose of prediction, the autoregressive method with model parameters calculated using Burg's method was selected (Collomb, 2009):

Figure 3 Case 1 – no actuator backlashes



$$x_{N+L} = -\sum_{i=1}^{N-1} a_i x_{N+L-i} \qquad (3)$$

where:

- N = is the number of the past measured samples;
- L = is the predicted sample current number;
- a_i = are the autoregressive model parameters calculated using Burg's method; and
- x_{N+L-i} = are samples, which are used as input to the autoregressive model from the last N samples.

The full description of the methodology applied can be found in Topczewski *et al.* (2020).

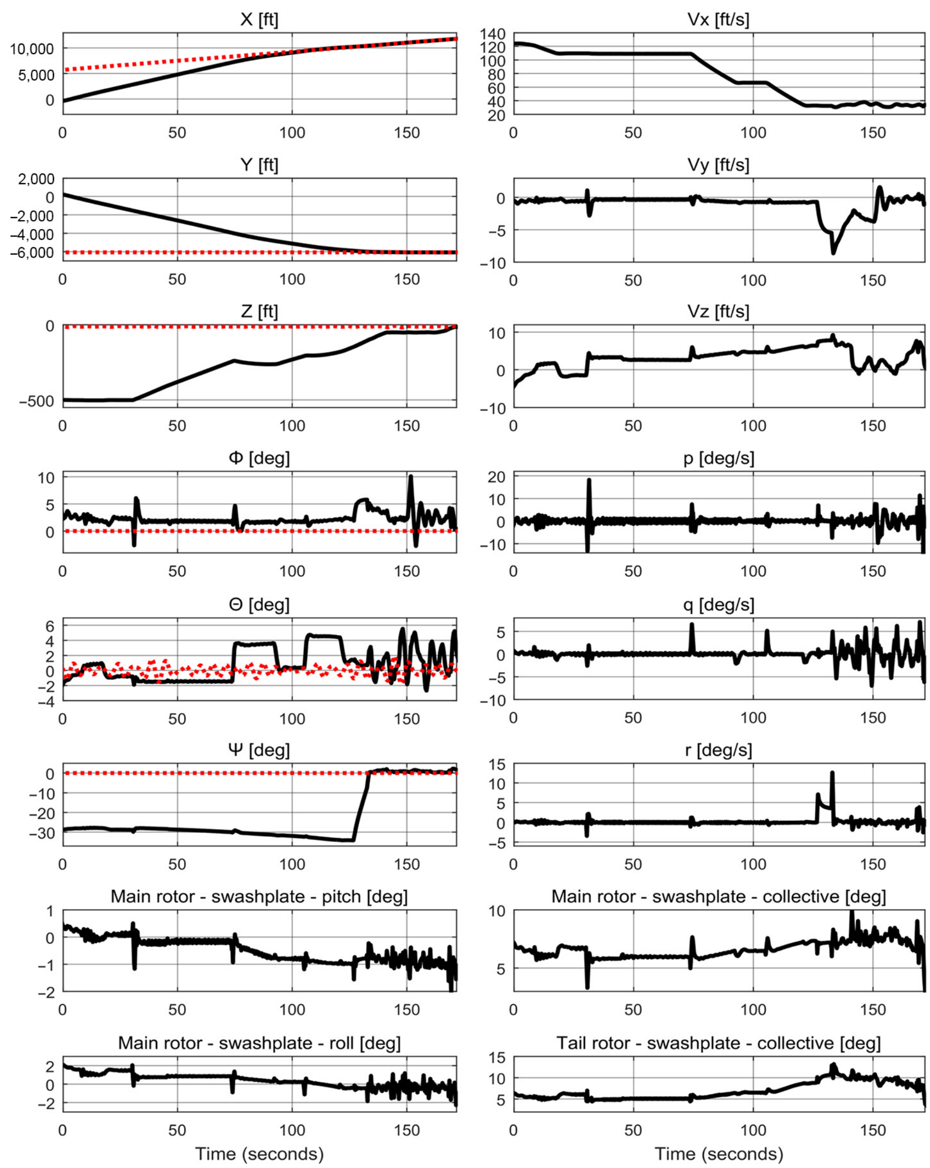
It is assumed that necessary information about helicopter and vessel state variables (position, linear velocities, attitude, angular velocities) is given by the integrated inertial navigation system/Global Positioning System (INS/GPS).

Developed integrated control system consists of the automatic flight control (AP), vessel motion prediction system, sensors and actuators. Information flow diagram in the system is shown in Figure 2.

Vessel motion model

A reliable model of vessel motion was used to test the efficiency of the control system developed. An analysis of the selected vessel (frigate) dynamics was made to obtain the response amplitudes of selected parameters (position and attitude), which are used by the prediction system and AP. The ship motion and aerodynamics modeling was performed by Ship Design and Research Centre S.A. The selected vessel was modeled and tested using ANSYS AQWA software, and the results were validated during towing tank tests, according to the procedures of International Towing Tank Conference (ITTC). The model of the vessel is based on harmonic functions and

Figure 4 Case 2 – 0.1 mm actuator backlashes applied



allows to obtain the position and attitude changes in time. It is used to estimate the vessel state using the prediction algorithm. All the calculations were made using response amplitude operators (RAO) (the idea of RAO-based seakeeping prediction is presented, e.g. by Bielicki *et al.* (2017)) describing vessel response to regular wave excitations:

$$RAO(\omega) = \frac{U_A(\omega)}{\xi_A} \tag{4}$$

where:

$U_A(\omega)$ = is the amplitude of vessel position or attitude to regular wave of ω frequency; and

ξ_A = is the regular wave amplitude.

Test cases

In this section, test cases are performed to:

- prove the efficiency of the control system developed during approach and landing on the moving vessel using prescribed procedure; and
- check the influence of the actuators backlashes on the mission performance.

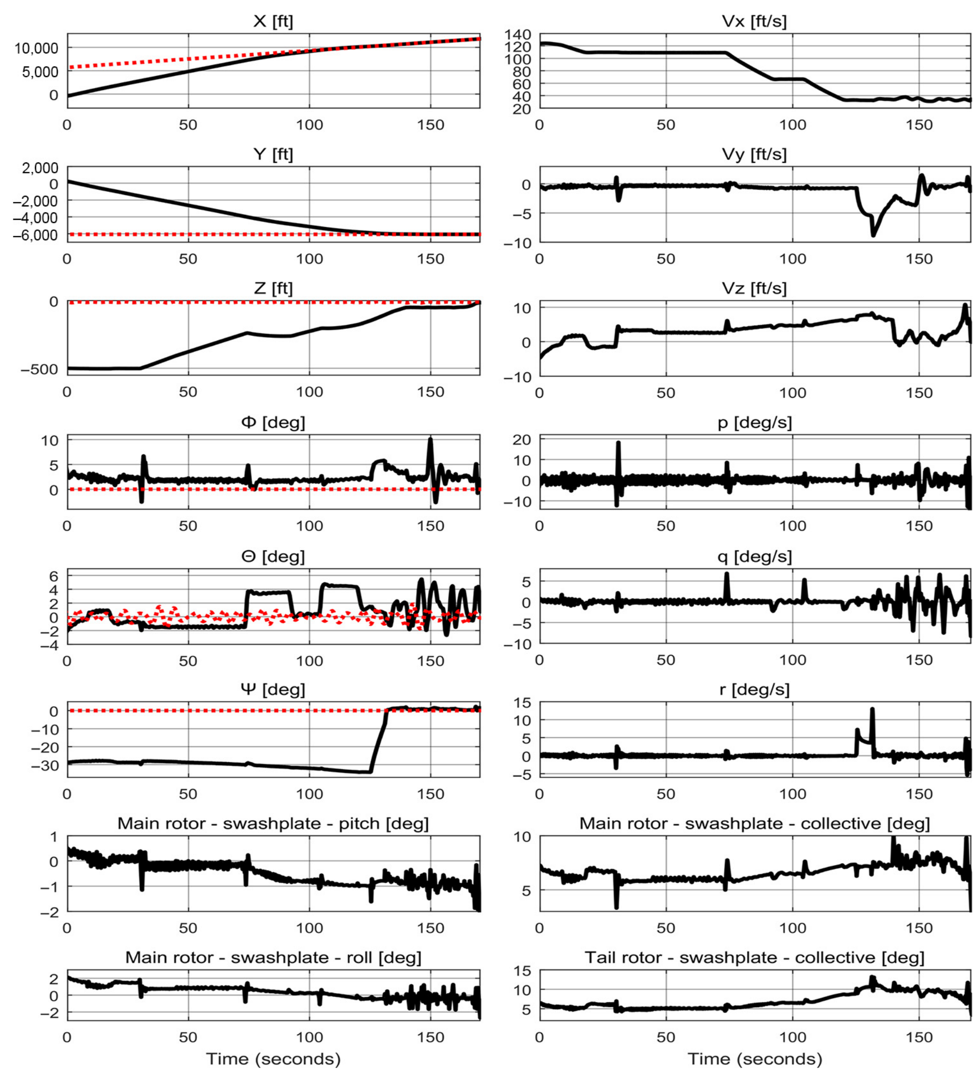
Here, the adapted oblique procedure (Anonymous, 2003a, 2003b) is selected to perform automatic approach and landing on the moving vessel. In the adapted procedure approach is performed over port, starting 2 NM from the vessel, at height of 500 ft over the sea. Helicopter yaw angle is fixed with the vessel's centerline under an angle of 30°. After direct flight, 1.5 NM from the vessel, the helicopter starts to descend. Next, the helicopter hovers at height of 50 ft over the landing zone. The last step is vertical landing.

The simulations were performed for specified conditions:

- forward velocity of the vessel – 20 knots (33.75 feet/s);
- azimuth of the vessel – 0°;
- sea state 3 (in Douglas sea scale – average wave height 2.87 ft, peak period 6.3 *s*);
- wave heading – 180° (head waves – incoming to the bow); and
- no wind speed.

Four test cases are performed with different values of actuators backlashes (same value for every of four actuators) applied:

Figure 5 Case 3 – 0.2 mm actuator backlashes applied



- Case 1 – no actuators backlashes applied (reference case);
- Case 2 – 0.1 mm backlash applied to every actuator;
- Case 3 – 0.2 mm backlash applied to every actuator; and
- Case 4 – 0.4 mm backlash applied to every actuator.

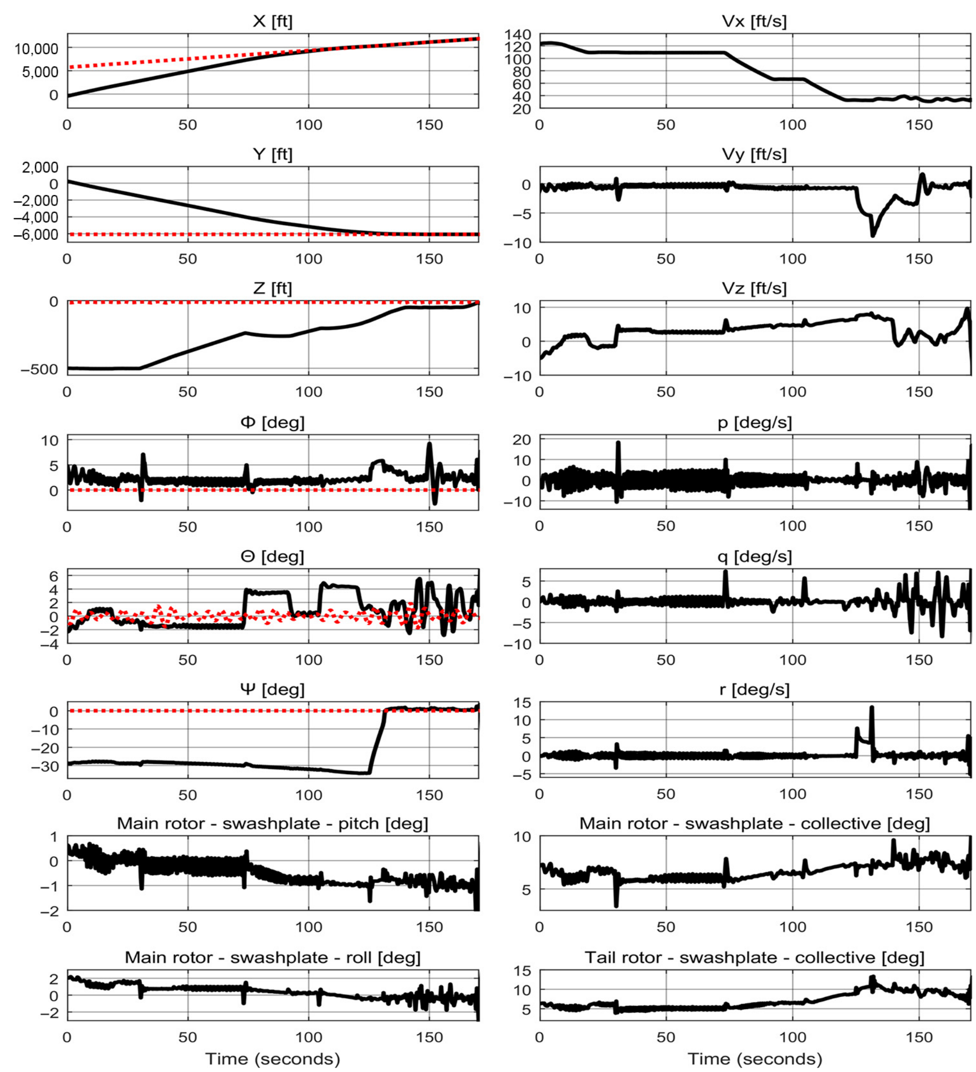
The simulation results are plotted in Figures 3–6, where the helicopter responses are marked black, and the responses of the vessel – dotted red.

Responses of the helicopter include position (X, Y, Z in the inertial coordinate system), attitude (Φ, θ, Ψ in the gravitational coordinate system), linear velocities (Vx, Vy, Vz in the body coordinate system), angular velocities (p, q, r in the body coordinate system) and values of control variables. Responses of the vessel include position (X, Y, Z in the inertial coordinate system) and attitude (Φ, θ, Ψ in the gravitational coordinate system).

In every case, starting 2 NM behind the vessel with Vx velocity of 125 ft/s, the helicopter began the approach maneuver at the height of 500 ft above sea level. 1.5 NM behind the vessel helicopter started to descend, and decrease the forward velocity to 110 ft/s. After interception of the vessel position, the helicopter hovered at safe height of 50 ft above sea level tracking vessel forward velocity waiting for command from prediction subsystem to begin the landing maneuver. After the command appeared, the helicopter landed in demanded period of time – 10 *s*, i.e. in the time horizon of the prediction.

In every case, the designed system led the helicopter to the successful approach and landing on the moving vessel deck in time of ~170 s. The approach phase is successful in every case because the helicopter was successfully led by AP to the relative hover position over the landing deck (position of the deck was varying in time), compensating the influence of the actuators backlashes. The landing phase was also successful because the final landing maneuver with touchdown was made in assumed period of time (10 s here). Values of attitude angles while touchdown were small (not more than 6°), touchdown was always performed within the limitations of landing zone. However, disturbances can be seen. Because of the backlashes applied, control commands calculated by the system are less precisely executed by the actuators. Therefore, oscillations and higher amplitudes

Figure 6 Case 4 – 0.4 mm actuator backlashes applied



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of the control commands values, and consequently, oscillations and higher amplitudes of helicopter parameters can be observed (the higher ones, the higher values of backlashes are applied), which can be seen in Figure 7 where short time period of 20 s of helicopter responses (without vessel responses) is presented for the better perception of the parameters (two extreme cases are presented – no actuator backlashes case is marked black, and 0.4 mm actuator backlashes case is marked dotted blue). Reaction on the actuators backlashes impact can be seen for all of the helicopter parameters; however, roll angular rate (and consequently roll angle) seems to be the most impacted parameter – that is correct as the helicopter rolling moment of inertia is the smallest one and any rocking occurs in this axis first. Impact on the velocities can be clearly seen on the Vy what implicates higher deviations on Y position. Lack of precision when executing calculated control commands by the actuators led to small, acceptable degradation of the mission performance in every phase (passing the waypoints in approach, hover over the selected point, landing at selected point).

Conclusion

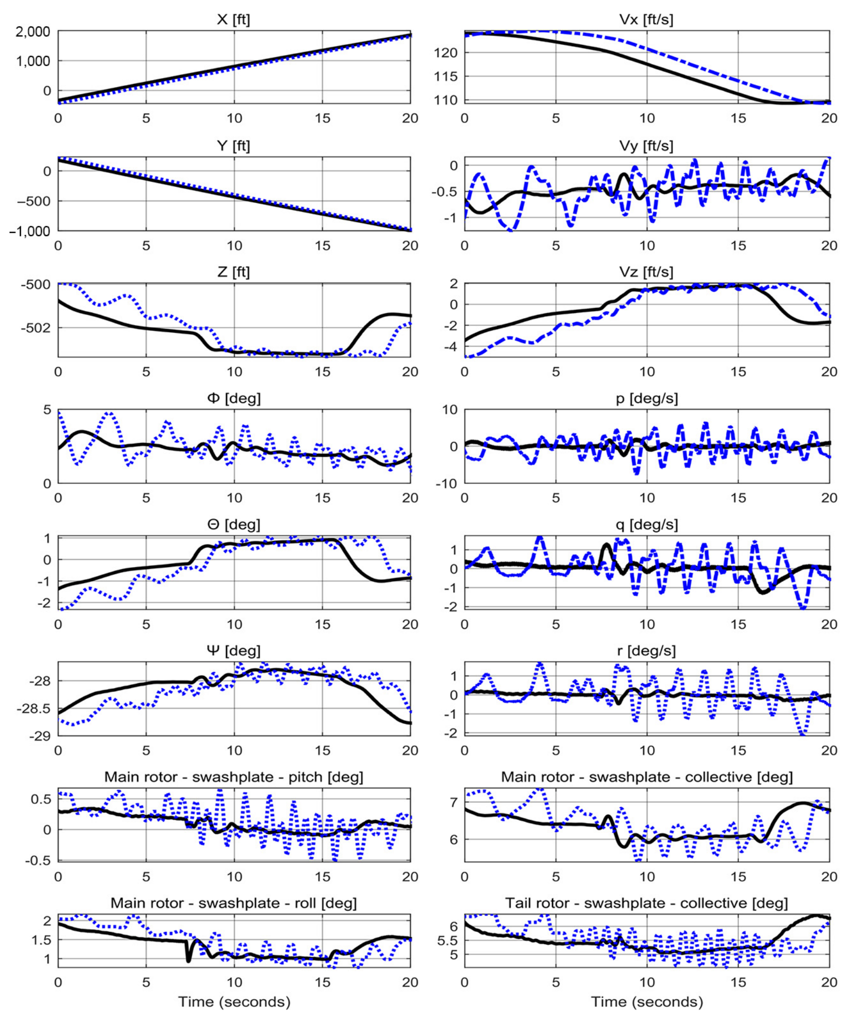
In this paper, the impact of actuator backlashes on the helicopter mission of approach and landing on the moving vessel deck is described.

In the first part of the research, the helicopter model (Leonardo PZL Swidnik SW-4) is described. A reliable model of the helicopter is necessary to test the effectiveness of the control system developed. The model was validated using flight test data from the manufacturer and by two test pilots.

An integrated control system is designed to allow an automatic approach and landing of the helicopter on the moving vessel. The system consists of the control algorithm (LQR), which is responsible for calculating control commands, prediction algorithm that estimates the future vessel deck motion and is used for precise and safe helicopter landing on the vessel, sensors (helicopter and vessel INS/GPS), which give information about the position, linear velocities, attitude and angular velocities and actuators, which perform calculated control commands.

In the next part, the vessel motion model is described. It is necessary to test the efficiency of the control system developed.

Figure 7 Comparison of Cases 1 (no backlashes) and 4 (0.4 mm backlashes)



Finally, test cases were performed to analyze the impact of actuators backlashes on the mission performance in the selected environmental conditions. Four different backlash values were applied to the actuators (same value for every actuator). Tests confirmed the ability of the designed control system to successfully approach and land on the moving vessel deck. However, small degradation in the mission performance in case of increasing the backlashes values was shown.

In the next step of the research, it is planned to analyze the sensitivity of the developed control system on the sensor data availability.

References

Anonymous (2003a), "Helicopter/ship qualification testing", *RTO AGARDograph 300 Flight Test Techniques Series*, Vol. 22.

Anonymous (2003b), *NAVAIR 00-80T-122 – Helicopter Operating Procedures for Air-Capable Ships Natops Manual*, Anonymous.

Arora, S., Jain, S., Scherer, S., Nuske, S., Chamberlain, L. and Singh, S. (2013), "Infrastructure-free shipdeck tracking for autonomous landing", *2013 IEEE International Conference on Robotics and Automation (ICRA)*, Germany.

Bielicki, S., Bednarek, A. and Kraskowski, M. (2017), "Evaluation of response amplitude operator of ship roll motions based on the experiments in white noise waves", *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*, Ocean Engineering, Trondheim, Vol. 7B.

Collomb, C. (2009), *Burg's Method*, Algorithm and Recursion.

Du Val, R. and He, C. (2017), "FLIGHTLAB^{TM} modeling for real-time simulation applications", *International Journal of Modeling, Simulation, and Scientific Computing*, Vol. 8 No. 4.

Dul, F., Lichota, P. and Rusowicz, A. (2020), "Generalized linear quadratic control for full tracking problem in aviation", *Sensors*, Vol. 20 No. 10, doi: 10.3390/s20102955.

Lichota, P. (2016), "Inclusion of the D-optimality in multisine manoeuvre design for aircraft parameter estimation", *Journal of Theoretical and Applied Mechanics*, Vol. 54 No. 1, pp. 87-98, doi: 10.15632/jtam-pl.54.1.87.

Lichota, P., Szulczyk, J., Agudelo, D. and Vallejo Monsalve, F.A. (2017), "Power spectrum optimization in the design of multisine manoeuvre for identification purposes", *Journal of Theoretical and Applied Mechanics*, Vol. 55 No. 4, pp. 1193-1203, doi: 10.15632/jtam-pl.55.4.1193.

Padfield, G. (2008), *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling*, Blackwell Publishing.

Topczewski, S., Narkiewicz, J. and Bibik, P. (2020), "Helicopter control during landing on a moving confined platform", *IEEE Access*, Vol. 8, pp. 107315-107325, doi: 10.1109/ACCESS.2020.3000294.

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