DEVELOPMENT OF AN AUTOMATIC SYSTEM FOR HELICOPTER APPROACH TO A MOVING VESSEL

Przemysław Bibik, pbibik@meil.pw.edu.pl, Warsaw University of Technology (Poland)

Sebastian Topczewski, stopczewski@meil.pw.edu.pl, Warsaw University of Technology (Poland)

Marcin Żugaj, zugaj@meil.pw.edu.pl, Warsaw University of Technology (Poland)

Abstract

The paper presents part of the results obtained in the HELIMARIS project (”Modification of an optionally piloted helicopter for maritime mission performance”) led by PZL Swidnik in cooperation with Warsaw University of Technology and CTO. In the paper, development of control algorithms for automated approach of a light single rotor helicopter to the moving vessel is presented. For the purpose of the approach task a Linear Quadratic Regulator (LQR) is used. The model of a helicopter is developed and evaluated in FLIGHTLAB software using flight test data for validation. Developed solutions and cases for approach of the helicopter to the vessel are presented and discussed.

1. INTRODUCTION

Helicopter maritime operations differ from land-based operations. Factors which strongly influence such operations are:

- environmental conditions
  - operation during day or night
  - visual limitations
  - wind influence
  - gusts and turbulence
  - level of sea state
  - sea sprays
- vessel conditions
  - obstacles close to the landing area
  - size of the landing area
  - motion of the vessel
- helicopter limitations
  - navigation equipment onboard
  - power available
  - current mass of the helicopter

From the control point of view the unique phases of flight are especially approach to the moving vessel and landing on it in the presence of the turbulence caused by the ship superstructure[1].

Typically, several military and civil approach methods (procedures) are used. Those methods are designed for manned flights taking into account average pilot skills. What is more, there is no international standard or regulation establishing ship-helicopter operational limits and typical ship-deck equipment to support pilots tasks[2,3,7].

In the paper authors focused on implementation of a dedicated control algorithm for automated approach of a light single rotor helicopter to the moving vessel. The selected algorithm is a Linear Quadratic Regulator (LQR). It is a feedback optimal regulator which defines the Linear Quadratic (LQ) problem[4]. Analyzed system is described by a set of linear differential equations and a quadratic cost function. The cost function is defined as measured deviations of current state values from the desired state values of the system. By definition, LQR calculates an optimal gain for actual system state in actual moment, holding the system in equilibrium point (setpoint of work) - also with disturbances acting on the system. In the presented work it is assumed, that the control system has full and accurate information about the state of both – the helicopter and the vessel.

In the development process of the control system an accurate nonlinear model of the object is used. The object of the control and stabilization in HELIMARIS project is a single engine helicopter in classical configuration. The model of the helicopter is developed and evaluated in FLIGHTLAB software using flight test data for validation. The control inputs include three main rotor controls and the tail rotor collective pitch angle control.

Presented theory of automatic control is applied to the developed helicopter model and tested based on specified requirements and use case.

2. APPROACH AND LANDING PROCEDURES

The level of complexity of maritime operations requires use of established approach / descent and landing / takeoff procedures.

Procedures used by British and Dutch Navies are divided into three typical:

- for/aft or forward facing procedure

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- relative wind or into wind procedure
- cross-deck procedure

and three additional (rarely used) ones[6]:

- aft/fore or facing astern procedure
- astern procedure
- oblique procedure

For the purpose of test of the control algorithm typical (for/aft or forward facing) procedure was selected (Figure 2).

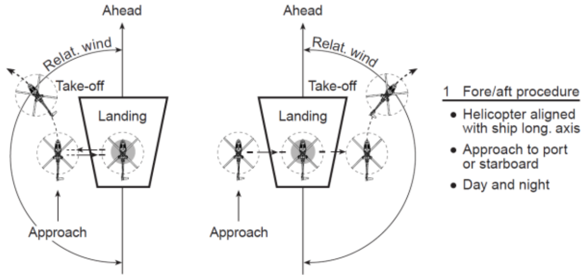

Figure 1 for/aft or forward facing procedure [6]

In this procedure approach / landing maneuver should be performed in below steps:

1. Approach of the helicopter to a hover position alongside the vessel.
2. Alignment of the helicopter with the vessel's center-line.
3. Sidewards flight and then hover above the landing area.
4. Vertical landing.

The developed control algorithm was adapted to control the helicopter using mentioned procedure.

3. WEATHER CONDITIONS

Factors which strongly influence helicopter maritime operations are weather conditions. The main one is the wind with its velocity and direction. Connected factors are wind gusts and air turbulence mainly caused by vessel's superstructure.

Next factor which highly influence pilot's workload is visual limitation which can be caused by fog, rain, sea sprays and smoke produced by vessel's exhaust.

Landing phase is mainly affected by sea state level causing vessel's attitude changes.

For proper control system design both the helicopter and the ship models should cover effects of turbulent air surrounding the ship deck and variable ship deck motion.

4. CONTROL METHOD

In this paper authors focused on the specific part of Automatic Flight Control System (AFCS) – automatic control algorithms. For the purpose of control of the helicopter in maritime tasks, Linear Quadratic Regulator (LQR) was selected. It is a linear regulator operating in feedback loop (Figure 2). Selected algorithm is adapted to perform specific AFCS functionalities, necessary to realize approach and landing procedure described in chapter 2 such as:

- pitch, roll, and yaw rates stability augmentation,
- body coordinate system speed hold,
- altitude hold,
- navigation mode (control of the helicopter via preselected route),

and (in the future tests) to fulfill requirements specified according to weather limitations presented in chapter 3.

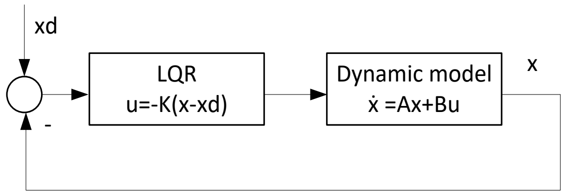

Figure 2 LQR feedback loop

Basically, this regulator is used to determine the optimal gain, using current state variables as an input. Using these gains LQR is keeping the system in control set point. This regulator needs information about full state vector.

Using values of cost function (difference between current state values and desired ones) LQR keeps it minimized by calculating desired values of control inputs. Control response characteristics (response speed, overshoot) are the result of the weighting matrices selection. Values of these matrices determine desired work of the regulator (including constraints and limitations).

Way of selection the weighting matrices values are often performed using iterative method with expert knowledge about type of considered systems responses. Values are changed till moment when system response is satisfactory. Balance between system response and control efforts depends on values of Q and R matrices[5].

As mentioned previously, LQR is a regulator – but can also be adapted to work as a controller. In this paper LQR is implemented to act with infinite horizon and continuous time.

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Before control algorithm definition specific assumptions must be made:

- linear model of the system is known,
- system is in equilibrium point,
- full state model variables are known for the regulator in each moment of work (including initial conditions),
- pair of A (state matrix) and B (control matrix) are stabilizable.

Based on these assumptions LQR can be defined. For the linear continuous state-space model:

(1) $\dot{x} = Ax + Bu$

where A is a state matrix with n x n dimensions and B is a control matrix with n x m dimensions, where:

- n is the number of states,
- m is the number of control inputs,

with cost function defined as:

(2) $J = \int_0^\infty (x^T Q x + U^T R u) dt$

Q is a symmetrical, positively semi-defined matrix with n x n dimensions and R is a symmetrical, positively defined matrix with m x m dimensions, regulation in feedback which minimizes the cost function is defined as:

(3) $u = -K(x - x_{DES})$

where x_{des} vector of desired values of state variables values and K is the feedback gain with m x n dimensions which minimizes the cost function J, described as:

(4) $K = R^{-1} B^T P$

where P is the Riccati's equation matrix solution with n x n dimensions for the continuous time defined as:

(5) $A^T P + PA - PBR^{-1} B^T P + Q = 0$

In most cases matrix Q and R have diagonal character.

5. HELICOPTER DYNAMIC MODEL

The helicopter model is developed in Flightlab software. All elements of the helicopter, except the undercarriage, are modeled as rigid. The main and tail rotors are modeled in a similar way, using blade element approach with flapping dynamics included. The aerodynamic model selected is quasi-steady with stall delay, and Peters-He 6 state induced velocity model. The interaction between rotors and fuselage are also modeled. The airframe model includes fuselage, empennage, sensors and landing gear. The aerodynamic loads of the fuselage and empennage are modeled using empirical look-up tables. The engine model is based on Flightlab turboshaft engine model with detailed model of its dynamics and control systems.

The selected helicopter model control system does not include any stability augmentation system – there are only hydraulic boosters placed in the control lines between pilot sticks and the swashplate.

The helicopter numerical model is validated using flight test data delivered by the helicopters' manufacturer. The validation covers both steady flight and dynamic response cases.

Helicopter body coordinate systems are presented in Figure 3. As typical three, Cartesian, right handed systems of coordinates were used:

- inertial, stationary system of coordinates $O_n x_n y_n z_n$, with the origin O_n located at an arbitrary point on the earth surface, the direction of the $O_n z_n$ axis is coincident with the orientation and sense of the earth acceleration vector, the $O_n x_n y_n$ plane is tangent to the earth surface, the $O_n x_n$ axis is directed towards the North with the $O_n y_n$ axis completing the right-hand system directed East,
- gravitational coordinate system $O_g x_g y_g z_g$ is fix to the vehicle, with the system's origin O_g located at the helicopter arbitrary point. This coordinate system is translated in parallel, relative to the $O_n x_n y_n z_n$ inertial system, and senses of both systems' axes are matching,
- body coordinate $O_b x_b y_b z_b$ system is associated with the aircraft; origin of the system O_b matches the origin of the gravitational system O_g, with the $O_b x_b$ axis lying in the aircraft's plane of symmetry $O_b x_b z_b$ and is directed towards the front of the aircraft's fuselage; the $O_b z_b$ axis is directed "down", with positive sense towards the aircraft's landing gear, and the $O_b y_b$ axis completes the right-handed system and is directed towards the right side of the fuselage.

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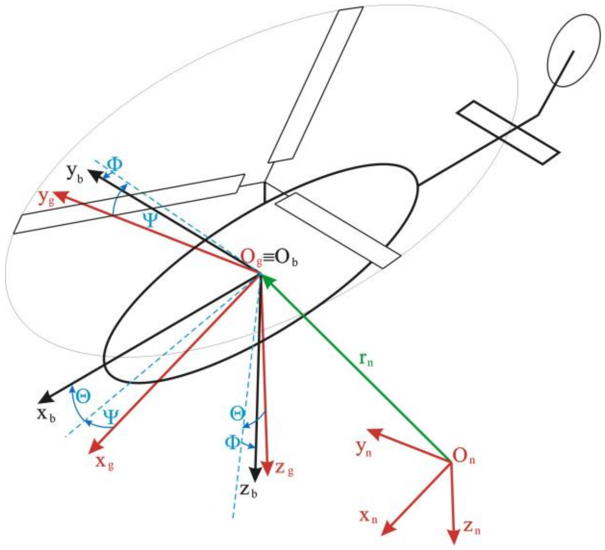

Figure 3 Helicopter model coordinates systems

Based on described nonlinear model, linear model was developed and used to establish LQR gains.

6. VESSEL MODEL

Numerical model of the vessel is developed in Flightlab software too. The ship fuselage is modeled as rigid 6-dof body. Its motion is modeled using several harmonics describing all 6 dofs of the ship motion. The wind model over ship deck includes a look-up table of steady winds for given sea-state, ship speed and azimuth, and turbulent, stochastic components. Parameters of ship dynamic and aerodynamic models are based on the work performed by CTO.

7. TEST CASE

To verify the control method performance, test case was applied.

In the test, forward facing procedure (described in chapter 2) is used in case of approach to the moving vessel without final landing phase with preselected boundary conditions:

- start of the helicopter movement (from hover position) 1000 feet from the center of the vessel landing area in O_nx_n direction (to stern) and 300 feet from the center point of landing area in O_ny_n direction (to port), movement of the vessel along the O_nx_n direction with constant forward speed of 25 feet/s,
- approach towards the vessel landing area along the O_nx_n direction with constant forward speed (in helicopter body coordinate system) of 75 feet/s and constant altitude of 100 feet,
- sidewards flight to the position over the center point of landing area with constant side speed (in helicopter body coordinate system) of 25 feet/s and constant altitude of 100 feet.

At current stage of the research no wind aspects are included in the test.

Results of the performed test and reference route are presented in Figure 4 (actual X-Y trajectory, helicopter – black line and vessel – red line) and **Błąd! Nie można odnaleźć źródła odwołania.** (complete results of the test where helicopter twelve state variables are presented).

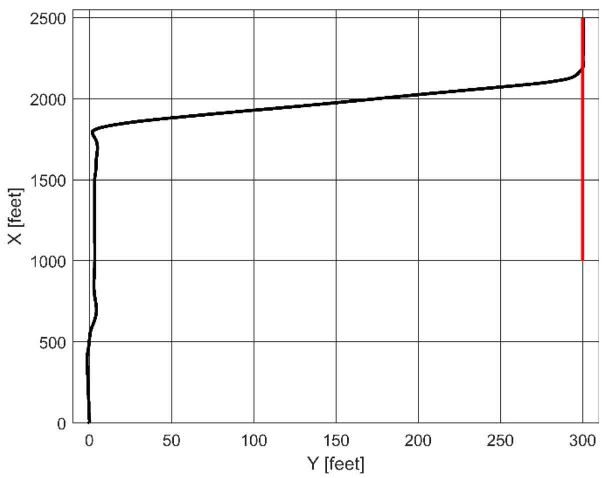

Figure 4 Actual trajectory

Control algorithm managed to acceptably stabilize desired parameters.

In the first phase of the approach helicopter starts from hover in point X,Y,Z (0,0,-100) in $O_nx_ny_nz_n$ coordinate system and accelerates to reach desired value of forward speed and after small overshoot it stabilize it at the value of 75 feet/s.

After deceleration to the forward speed of 25 feet/s and reaching the vessel level in O_nx_n direction, helicopter accelerates to reach desired value of side speed and after small overshoot it stabilize it at the value of 25 feet/s. Finally, after deceleration and reaching the vessel level in O_ny_n direction helicopter follows the vessel landing area with constant forward speed of 25 feet/s.

Duration of the whole maneuver is about 50 seconds.

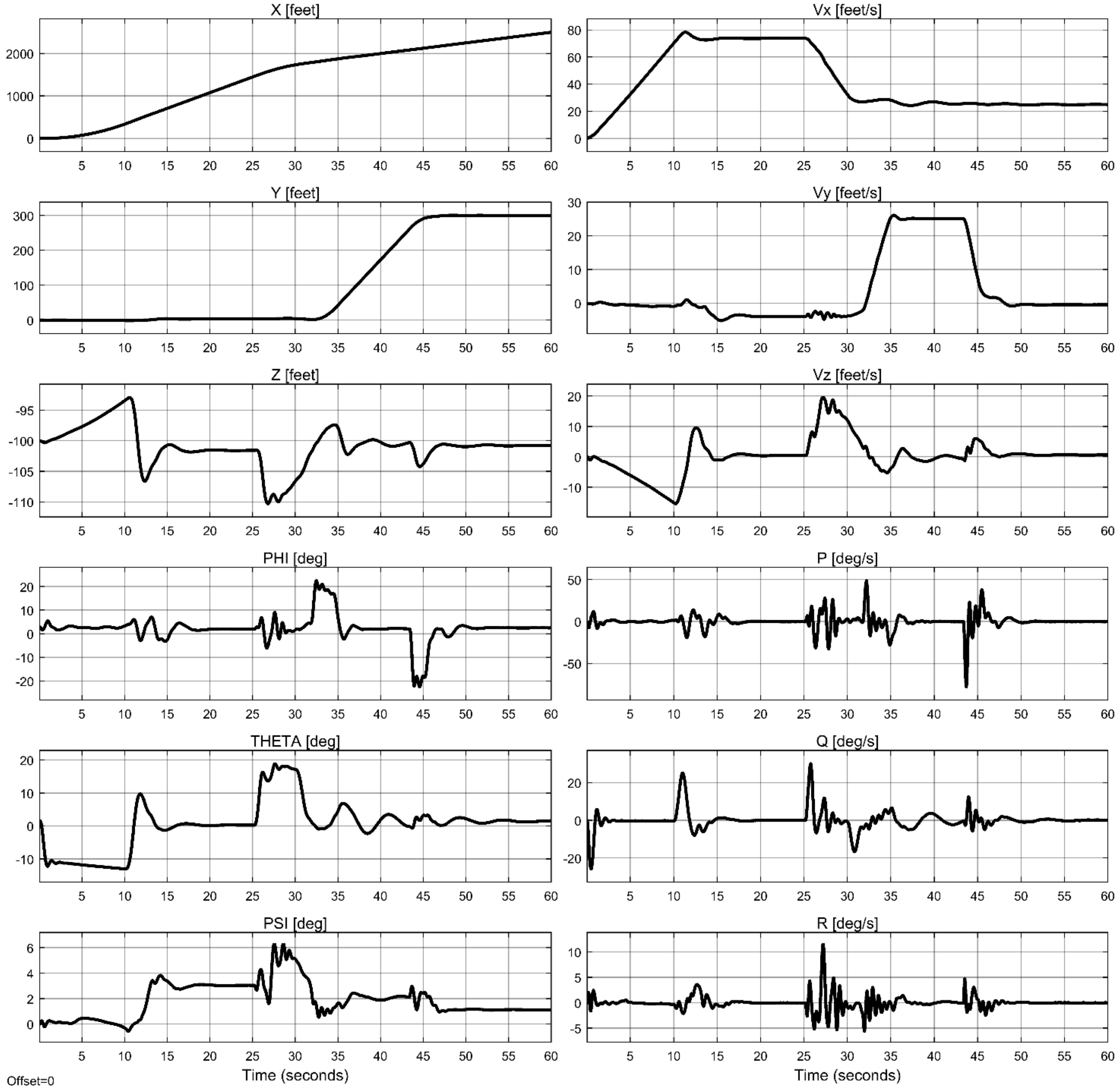

Figure 5 Complete results of the test – helicopter state variables

8. CONCLUSIONS

In the paper, methodology of helicopter automatic control in case of approach to the moving vessel is presented. Authors presented typical approach and landing procedures from which one is used for the evaluation of developed control algorithm. Control algorithm is based on Linear Quadratic Regulator (LQR) methodology which is described here. For the proper design of the control algorithm, dynamic model of the helicopter is used. As an approach and landing of the helicopter on the vessel is challenging task, possible weather conditions and limitations are mentioned.

Current stage of the research is in the middle phase; therefore, no wind aspects are included in the test case and no final landing step (helicopter touchdown on the vessel) is modelled. In further research it is essential to check the wind influence on the developed control algorithms. It is also necessary to establish (using developed vessel model) optimal strategies for the selection of the touchdown moments.

9. ACKNOWLEDGMENTS

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