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Model of Stabilization of Helicopter in Hover Mode over a Given Point Object under Destabilizing Action of Weather Conditions

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Abstract The design problem of the high precision stabilizer for hovering of the helicopter about the point object as a part of the automatic control system (ACS) is considered. Here we substantiate method and models for hover mode of helicopter as well as measurements of parameters of this flight mode that requires smaller volume of calculation and preserves high speed and accuracy of stabilization. Also we investigate reduction of number of state vectors and volume of calculation via usage of extended Kalman filter (EKF) and standard sensors.

Keywords: *control, control system, helicopter, filter, perturbation, stabilization*

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1. Introduction

Due to the increased usage of helicopters to perform works over the point objects: discharge of cargos into the holes of pipelines (for example, in nuclear power stations), the mounting of sections of the television and radio towers and their antennas, rescue operations, landing on a limited area etc, there is a need to stabilize the helicopter with precision accuracy in the hover mode over a point object under the negative impact of environmental factors (Figure 1) [1,2,3].

It's difficult for the crew to solve this problem. The 1st reason is fast change of conditions in the system "helicopter-point object- weather". Second reason is slow response of the system "helicopter-point object- weather" comparing with speed of the variations of perturbations. That's why it is necessary to create stabilizer as part of ACS with high speed of reaction and precision accuracy. Classic theory of control used for mentioned issue can't provide necessary accuracy and speed-of-response. LQG theory is the most popular now. Information, which is necessary for the LQG theory application for solution of the stabilization problems, could be achieved in two ways:

- usage of the additional sensors and essential improvement of their accuracy. This way is not reasonable because of increasing of the weight, seizes and cost of equipment;
- usage of standard navigation equipment and improved program product. Second way is chosen for this work.

The design of the stabilizer with precision accuracy for the hover mode of the helicopter as part of ACS requires development of the model of stabilization of the system "helicopter-point object- weather" and also the model of measurement of parameters of helicopter hovering above point objects.

Figure 1. Example of precision stabilization of the helicopter

2. Methodology

2.1. Model of System with Zero Acceleration Relatively to a Point Object

The aggressive action of weather conditions on the helicopter in flight, and especially in hovering mode, causes a violation of stabilization conditions relatively to the trajectory and this is the most important reason of organization of the precision stabilization relatively to the center of the given point object. (Figure 2, point O). Random character of inputs: internal and external perturbations, that affect helicopter in the hover mode, requires the implementation of the management strategy based on probabilistic characteristics of the measured parameters [4]:

$$z(t_k) = z\left[x(t_k), u(t_k), g(t_k), \phi(t_k), k\right],$$

where $z(t_k)$ - vector of measured reactions; $x(t_k)$ - variables of the state; $u(t_k)$ - variable input of managing actions; $g(t_k), \phi(t_k)$ - measurable and not measurable internal and external perturbations respectively. So to determine the appropriate control action $u_r(t_k)$, that would ensure the satisfaction of the conditions of steady following the actual parameter values of the helicopter hovering $X_r(t_k)$ in the changing of predetermined parameters $X_p(t_k)$ [5]:

$$\lim_{t\to\infty} X_r(t_k) = \lim_{t\to\infty} X_p(t_k). \qquad (1)$$

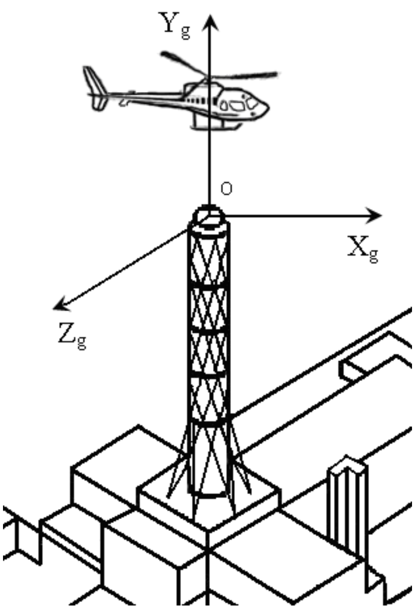

Figure 2. Stabilization of helicopter's hovering over a point object

The performance of control process and in flight helicopter stabilization is determined by the error that is caused by the mismatch $r(t_k)$ between given $x_p(t_k)$ and current $x_r(t_k)$ values of the controlled/stabilized value:

$$r(t_{k+1}) = x_p(t_k) - x_r(t_{k+1}). \qquad (2)$$

Under the influence of perturbations stabilization parameters would deteriorate and mismatches (2) would not have zero value and the helicopter would be shifted from the point O (Figure 2)

$$r(t_{k+1}) = x_p(t_k) - x_r(t_{k+1}) \neq 0. \qquad (3)$$

The process of observation of the requirements violation (1) can be formalized as following:

$$\overline{x}(t_{k+1}) = A\hat{x}(t_k) + Bu(t_k); \qquad (4)$$

$$\hat{x}(t_{k+1}) = \overline{x}(t_{k+1}) - Kr(t_{k+1}); \qquad (5)$$

$$r(t_{k+1}) = z(t_{k+1}) - C\overline{x}(t_{k+1}), \qquad (6)$$

where $\overline{x}(t_{k+1})$ - estimated evaluation $x(t_{k+1})$ before measuring at time t_{k+1}; $\hat{x}(t_{k+1})$ - evaluation of "helicopter-ACS-point object" system state parameters, that includes measurement at time t_{k+1}; $r(t_{k+1})$ - mismatch; K - matrix of Kalman coefficients filter.

The error of the "Helicopter-ACS-Point object" system response on perturbations has also random nature and it is defined as the difference between the system state at time t_k and its change at time t_{k+1}

$$\overline{\xi}(t_k) = x(t_k) - \overline{x}(t_k); \qquad (7)$$

$$\hat{\xi}(t_k) = x(t_k) - \hat{x}(t_k). \qquad (8)$$

After subtracting from the system state equation (4) another equation that includes external factors and internal processes destabilizing action

$$x(t_{k+1}) = Ax(t_k) + Bu(t_k) + B\Delta u(t_k), \qquad (9)$$

we obtain:

$$\overline{\xi}(t_{k+1}) = A\xi(t_k) + B\Delta u(t_k). \qquad (10)$$

After combining measurements equations:

$$z(t_k) = Cx(t_k) \qquad (11)$$

with equations (5), (6), (7) we obtain:

$$\hat{x}(t_{k+1}) = \overline{x}(t_{k+1}) + KC\overline{\xi}(t_{k+1}). \qquad (12)$$

Let us represent the equation (12) in the form of an error

$$\hat{\xi}(t_{k+1}) = \xi(t_{k+1}) - KC\overline{\xi}(t_{k+1}). \qquad (13)$$

Taking into account that "helicopter-ACS-point object" measurement of reaction of system error (13) is random and has normal distribution law, it can be characterized by mean square error. The optimality condition of such system can be defined as follows [6]:

$$\eta\left[\hat{\xi}(t_{k+1})\right] = M\left[r^2(t_{k+1})\right] = \min, \qquad (14)$$

and for hovering mode

$$\eta\left[\hat{\xi}(t_{k+1})\right] = M\left[r^2(t_{k+1})\right] = 0. \qquad (15)$$

The value of $\eta\left[\hat{\xi}(t_{k+1})\right]$, as the initial covariance of "helicopter-ACS-point object" system error of $\hat{\xi}(t_{k+1})$ (Figure 2) can be defined through the expected error and error variance. Generalized criterion (14) is the criterion of some function of mathematical expectation and error variance (13):

$$f\left[M(\hat{\xi}(t_{k+1})), D(\hat{\xi}(t_{k+1}))\right] = \text{extremum}. \quad (16)$$

If helicopter deviation from point O (Figure 2) in hovering mode is considered as an error, then stabilization system task is to ensure the minimum of the function (16), i.e.

$$f\left[M(\hat{\xi}(t_{k+1})), D(\hat{\xi}(t_{k+1}))\right] = 0. \quad (17)$$

Requirements (17) represent the offset of the adjustable parameter under mathematical expectation

$$\varepsilon_{\mathrm{M}}(t_k) = M_p(t_{k+1}) - M_r(t_{k+1}) \to 0 \quad (18)$$

and variance

$$\varepsilon_{\mathrm{D}}(t_k) = D_p(t_{k+1}) - D_r(t_{k+1}) \to 0, \quad (19)$$

that are written with consideration (13) and should tend to the minimal allowable values, for our task it is zero.

If there is a possibility to evaluate the performance of stabilization on the value of deviation of mathematical expectation $\varepsilon_{\mathrm{M}}(t_k)$ and variance $\varepsilon_{\mathrm{D}}(t_k)$, that provide reaching given performance parameters of the stabilization process, we will minimize the corresponding functional [7]:

$$J_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_M^2 + \varepsilon_D\right) \to 0. \quad (20)$$

Performance criterion (20) gives an opportunity to carry out structural synthesis of stabilization and control system, with which you can implement automatic stabilization of the helicopter, including hovering mode, in the random weather conditions. Let's define the task of the structural synthesis of automatic control system (ACS) as follows: for the helicopter, given by an appropriate mathematical model, it is necessary to determine control

$$u(t_k) = f\left(x(t_k), g(t_k), \phi(t_k), V, t\right), \quad (21)$$

as a function of specified arguments that provides satisfying of condition (20). In function (21) V – is the measurement error.

Control actions (21) are formed by two parallel channels (Figure 3), one of which is a quick-action channel based on the accelerations vector $\bar{J}$, and the second – inertial channel based on the speed vector $\bar{V}$. Moreover, the signal of the inertial channel is subtracted from the quick-action channel signal.

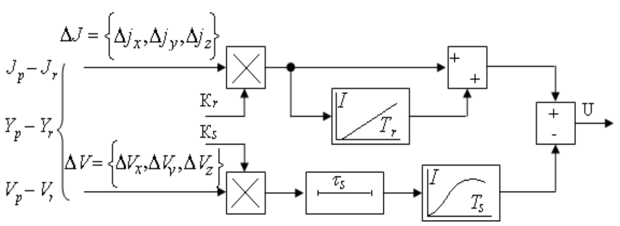

Figure 3. Block diagram of control actions formation.

The developed stabilizer (Figure 3), which is a part of ACS, solves the problem of simultaneous performance and storage stability of the automatic control system that is impossible to implement in standard schemes, where there is a contradiction, namely the growth of amplification coefficient, causes a decrease the stability margin of the automatic stabilization and control.

Acceleration sensors j_x, j_y, j_z, that characterize short-period oscillations of the helicopter center of masses, are first to react on the violations of conditions (20). The second sensors are the sensors of the displacement rate of the helicopter center of masses O (Figure 2) $\dot{H}, \dot{X}, \dot{Z}$, which characterize long-period of the helicopter center of mass oscillations. Therefore, to solve the task of helicopter on given point object O (Figure 2) point hovering stabilization, you need to make a model of the system with zero accelerations relative to the centre of the point object. It should be noted, that in case of using of such model the system (9) state vector, and therefore a vector of measurements (11), taking into account that accelerations vector is the first derivative of the speed and the second from the distance, are significantly reduced (up to 6 parameters). In view of this the differential equation of "helicopter-point object" system takes the form [8]:

$$\begin{aligned}
&\Delta\dot{S}(t_k) = \Delta V(t_k),\ \Delta S = \{\Delta X, \Delta Y, \Delta Z\},\\
&\Delta V = \{\Delta V_x, \Delta V_y, \Delta V_z\};\\
&\Delta\dot{V}(t_k) = -J_h(t_k) + \dot{W}_h,\ J_h = \{j_x, j_y, j_z\},\\
&\dot{W}_h = \{\dot{W}_x, \dot{W}_y, \dot{W}_z\},
\end{aligned} \quad (22)$$

where $J_h = \{j_x, j_y, j_z\}$ - the accelerations vector, $\dot{W}_h = \{\dot{W}_x, \dot{W}_y, \dot{W}_z\}$ - the perturbation accelerations vector.

1st Results

Therefore, "helicopter-point object" system model condition evaluation using extended Kalman EKF filter acquires following form:

$$\begin{aligned}
\begin{bmatrix}\Delta\dot{S}(t_k)\\ ----\\ \Delta\dot{V}(t_k)\end{bmatrix}_{6\times1} &= \begin{bmatrix}0 & | & \mathrm{I}\\ - & - & -\\ 0 & | & 0\end{bmatrix}_{6\times6}\begin{bmatrix}\Delta S(t_k)\\ ----\\ \Delta V(t_k)\end{bmatrix}_{6\times1} +\\
&+\begin{bmatrix}0 & | & 0\\ - & - & -\\ 0 & | & \mathrm{I}\end{bmatrix}_{6\times6}\begin{bmatrix}0\\ ----\\ -J_h(t_k)\end{bmatrix}_{6\times1} + \begin{bmatrix}0\\ ----\\ W_h(t_k)\end{bmatrix}_{6\times1}.
\end{aligned} \quad (23)$$

If "helicopter-point object" system model is given by the relation of type (22), then you can make the state transition matrix for it as follows [5]:

$$\Phi(t_k, t_{k+1}) = \begin{bmatrix}\mathrm{I} & | & \Delta t\mathrm{I}\\ - & - & -\\ 0 & | & \mathrm{I}\end{bmatrix} \quad (24)$$

Thus, using the information from acceleration sensors, that are the part of inertial navigation system of the helicopter, you can significantly reduce the state vector without loss of accuracy helicopter's hovering stabilization.

2.2. Measuring Model of Helicopter Hovering Stabilization Parameters with Respect of the Point Objects

To organize the functioning of the linear-quadratic Gauss (LQG) stabilizer (Figure 3) based on the extended Kalman filter EKF (23), it can be used the measurement model consisting of two measurements: speed $V(t_k)$ and acceleration $J(t_k)$ in the inertial frame. Taking into account that helicopter speed $\dot{S}(t_k)$ has nature of long-period oscillations, and the rate of this speed changes (acceleration), which incidentally is a derivative of speed $dV(t_k)/dt_k$, has nature of the short-period oscillations, they can be divided and considered as a case of nested models of measurements $J_h(t_k)$ and $\dot{S}(t_k)$, i.e. $J_h(t_k)$ is a nesting in $\dot{S}(t_k)$, or that is the same $J_h(t_k)$ is a subset of a set $\dot{S}(t_k)$. It is proposed to form an identification of helicopter acceleration changes $J_h(t_k)$ via usage of the errors prediction of the parameters measurement $V(t_k)$, which is obtained from the inertial navigation system (INS), GPS receiver or Doppler radar for measuring velocity and drift angle (DMVD), as the data for evaluation procedure. The procedure proposed has two stages: measured data with error prediction method is displayed by the model in $\dot{S}(t_k)$ space, in turn $\dot{S}(t_k)$ is displayed in space $J_h(t_k)$ [9].

Therefore, the way of evaluation based on the use of parametric vector $J_h(t_k)$ and parametric vector $V(t_k)$ error prediction method $\bar{\xi}_J$ can be set as follows:

$$\hat{\xi}_J = \arg\min_{\xi_J} \sum_{t=1}^{N} \varepsilon_1^2(t_k, \bar{\xi}_J); \qquad \hat{\xi}_\nu = \arg\min_{\xi_\nu} \sum_{t=1}^{N} \varepsilon_2^2(t_k, \bar{\xi}_\nu), \tag{25}$$

where N is the number of measurements (data recording points); $\varepsilon_1(t_k, \bar{\xi}_J)$ – error of the prediction.

$$\varepsilon_1(t_k, \bar{\xi}_J) = j(t_k) - \hat{j}(t_k / t_{k-1}, \bar{\xi}_J)$$

in the model of prediction $J_h(t_k)$.

In a further we enter two assumptions regarding the structures of the models $J_h(t_k)$, $V(t_k)$ and data [8]:

1. Structures $J_h(t_k)$ and $V(t_k)$ are attached

$$J_h(t_k) \subset V(t_k), \tag{26}$$

so that there is a smooth displaying

$$\xi_\nu(\bar{\xi}_J): S_1 \to S_2; S_1 \subset R^{\dim \xi_J}, \ S_2 \subset R^{\dim \xi_\nu}, \tag{27}$$

so that

$$\varepsilon_2(t_k, \xi_\nu(\bar{\xi}_J)) = \varepsilon_1(t_k, \bar{\xi}_J), \tag{28}$$

where S_1, S_2 - nonzero sets; $\varepsilon_1(t_k, \xi_J)$ is the stationary process for any $\xi_J \in S_1$; $\frac{\partial \xi_\nu(\bar{\xi}_J)}{\partial \xi_J} = \max$ on S_1.

2. Structures $J_h(t_k)$ and $V(t_k)$ allow to identify the parameters that confirms the existence of single "real" vectors of parameters ξ_ν^* and ξ_J^* such that:

$$\varepsilon_1(t_k, \xi_J^*) = \varepsilon_2(t_k, \xi_\nu^*)$$

-white noise with mean zero and σ^2-dispersion.

Taking into account the assumptions one and conditions (28) we can record a conclusion [9]:

$$\xi_\nu^* = \xi_\nu(\xi_J^*). \tag{29}$$

The first assumption is a general condition for attached models J_h and $\dot{S}$. In turn the model $\dot{S}(t_k)$, in addition to the above, includes also the characteristics of the data. In view of the fact that $J_h(t_k)$, represents an attached into $\dot{S}(t_k)$ subset, i. e. the model of more simplified structure, it should provide a clear identification model than $\dot{S}(t_k)$. Indeed, in view of the fact that $\ddot{S}(t_k) = \{\ddot{S}_x(t_k), \ddot{S}_y(t_k), \ddot{S}_z(t_k)\}$, measured with sensors of linear accelerations SLA_x, SLA_y, SLA_z, their signals create the measurement model of more simplified structure with clearer information. In addition, the implementation of such model is more affordable to construct, because these sensors are the part of the regular inertial navigation system.

In the practical implementation there are cases where $\hat{J}_h$ evaluation is more difficult to calculate than $\hat{\xi}_\nu = \arg\min_{\xi_\nu} \sum_{t=1}^{N} \varepsilon_2^2(t_k, \bar{\xi}_\nu)$ evaluation, so it is advisable to determine $\hat{\xi}_\nu$ and on these evaluations to determine the evaluations $\hat{J}$. If S_2 set in not confluent (not zero) in space $R^{\dim \xi_\nu}$, then for $N \to \infty$, one could argue that under $\xi_\nu^* \in S_2$, $\hat{\xi}_\nu$ it also belongs to the S_2 and enables to calculate $\bar{J}_h$ under the ratio:

$$\bar{J}_h = J_h(\hat{\xi}_\nu), \tag{30}$$

where $J_h(\hat{\xi}_\nu)$ is the inverse function

$$J_h(\xi_\nu): S_2 \to S_1.$$

For our case, we can accept that $\bar{J}_h = \hat{J}_h$. Under the assumption that $\hat{\xi}_\nu \in S_2$ can be shown as [9]:

$$\sum_{t=1}^{N} \varepsilon_1^2(t_k, J_h) = \sum_{t=1}^{N} \varepsilon_2^2(t_k, \bar{\xi}_\nu(J_h)) \geq \sum_{t=1}^{N} \varepsilon_2^2(t_k, \hat{\xi}_\nu) = \\ = \sum_{t=1}^{N} \varepsilon_1^2(t_k, J_h), \ J_h \in S_1. \tag{31}$$

Condition (31) requires the implementation of equality $\bar{J}_h = \hat{J}_h$ and that the dimension J_h was lower than dimension ξ_ν, which is not always done. If these conditions are not met, i.e. $\hat{\xi}_\nu \notin S_2$, condition (30) is not met too. So, in the future during evaluation of predicting errors that condition cannot be used. In such cases, the vector $\bar{J}_h$ can be defined as a solution of an optimization task [9].

$$\bar{J}_h = \arg\min_{J_h} G(J_h),$$

$$G(J_h) = 0,5\left[\hat{\xi}_\nu - \xi_\nu\left(J_h\right)\right]^T \mathrm{Q}_{\xi_\nu}^{-1}\left[\hat{\xi}_\nu - \xi_\nu(J_h)\right], \quad (32)$$

where $\hat{\mathrm{Q}}_{\xi_\nu}$ - reasoned evaluation

$$\mathrm{Q}_{\xi_\nu} = \left\{ E\left(\frac{\partial \varepsilon_2(t_k, \xi_\nu)}{\partial \xi_\nu}\bigg|_{\bar{\xi}_\nu = \xi_\nu{}^*} \right)^T \frac{\partial \varepsilon_2(t_k, \xi_\nu)}{\partial \xi_\nu}\bigg|_{\bar{\xi}_\nu = \xi_\nu{}^*} \right\}^{-1}. \quad (33)$$

Natural evaluation Q_{ξ_ν} may be determined by the ratio:

$$\hat{\mathrm{Q}}_{\xi_\nu} = \left\{ \frac{1}{N}\sum_{t=1}^{N}\left(\frac{\partial \varepsilon_2(t_k, \xi_\nu)}{\partial \xi_\nu}\bigg|_{\bar{\xi}_\nu = \hat{\xi}_\nu} \right)^T \times \right. \quad (34)$$
$$\left. \times \frac{\partial \varepsilon_2(t_k, \xi_\nu)}{\partial \xi_\nu}\bigg|_{\bar{\xi}_\nu = \hat{\xi}_\nu} \right\}^{-1}$$

Optimization task (32) can be formed by the following rule:

$$\begin{cases} \tilde{\xi}_\nu = \arg\min_{\alpha \in S_2}(\hat{\xi}_\nu - \xi_\nu)^T \mathrm{Q}_2^{-1}(\hat{\xi}_\nu - \xi_\nu); \\ \overline{J}_h = J_h(\tilde{\xi}_\nu). \end{cases} \quad (35)$$

Regarding the challenge of stabilization of helicopter in hover mode over a point object with a limited area, a geometric representation can be provided. While hovering, the helicopter is influenced by destabilizing the random external weather conditions and internal processes, so the condition of the system "helicopter-point object" (Figure 2) is not determined. Under these conditions, to provide precision accuracy of helicopter stabilization, it is necessary to know the error of the prediction of evaluation of parameter vector $\overline{J}_h(t_k)$ of the enclosed model and parametric vector in model $V(t_k)$.

2nd Results

The error of the prediction of evaluation of helicopter accelerations in hovering mode j_x, j_y, j_z, that appear under false weather conditions, will greatly depend on the amount and quality of information about its speed $V(t_k)$, which comes from the inertial navigation system, satellite navigation system and Doppler velocity meter and drift angle, so on the errors arising from the violation of the conditions of precision accuracy of hovering

$$\Delta V_x = \frac{dS}{dt} \neq 0,\ \Delta V_y = \frac{dH}{dt} \neq 0,\ \Delta V_z = \frac{dz}{dt} \neq 0, \quad (36)$$

$$\Delta j_x = \frac{d^2S}{dt^2} \neq 0,\ \Delta j_y = \frac{d^2H}{dt^2} \neq 0,\ \Delta j_z = \frac{d^2z}{dt^2} \neq 0. \quad (37)$$

3. Conclusions

Using the information from the accelerations sensors, which are part of the inertial navigation system of the helicopter, you can essentially reduce the state vector $x(t_k)$ without perturbation of the requirements for accuracy of stabilization of helicopter in hover mode over a point object. Besides, changes under the external influences of helicopter accelerations $J(t_k)$ are characterized by short-period oscillations (requirement 32) of the helicopter centre of mass and significantly ahead in time changes in its velocity vector $V(t_k)$, which are characterized by long-period oscillations of the helicopter in space relatively to the given point O (Figure 2) of the limited area object (requirement 30). Therefore completing the prediction for the given method of inaccuracies, arising from the perturbation of the requirements (31), we can identify the state of the «helicopter-point object» system, in another words the degree of fulfillment of the requirements (25). The degree of the requirements (36) and (37) perturbations can serve as a signal for the functioning of the stabilization system for a helicopter in the hovering mode.

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