Consideration of aeroservoelasticity requirements in the development of highly maneuverable unmanned aerial vehicle

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Abstract. An approach to the joint design construction and stabilization system of the highly maneuverable unmanned aerial vehicle account with requirements of aeroservoelasticity, the most important of which is to prevent self-oscillations in the unmanned aerial vehicle stabilization loop. The approach includes three stages. The first stage is the preliminary choice of structure and basic parameters of the unmanned aerial vehicle stabilization loop account with aeroservoelasticity requirements. The second stage is the separate design of subsystems (airframe, stabilization system) by traditional methods in compliance with the requirements formulated at the first stage. The goals to be achieved at this stage are to obtain a rational (from the standpoint of mass and technological perfection) design of the unmanned aerial vehicle airframe, and a stabilization system that provides the required dynamics and the accuracy of execution of commands, as well as the minimum cost, dimensions and weight. The third stage is the coordination of the selected structure and design parameters of the airframe and stabilization system, aimed at meeting the aeroservoelasticity requirements (the authors use the model of the unmanned aerial vehicle stabilization loop stability study, reflecting the specifics of the classes of highly maneuverable aircraft). An example of the process of developing the highly maneuverable unmanned aerial vehicle account with aeroservoelasticity requirements is given.

1. Introduction

The most important requirement of aeroservoelasticity, which must be provided in the development of highly maneuverable unmanned aerial vehicle (UAV), is to prevent self-oscillations in the UAV stabilization loop. Self-oscillations lead to "clogging" of automatic control system (ACS) channels with high-frequency components of signals, which negatively affects the controllability of the UAV, disrupting the normal operation of on-Board equipment, and leads to a significant decrease in the quality of its functioning up to failure.

The problems associated with ensuring the stability of the UAV stabilization loop should be solved starting from the preliminary design stage. Detection of the presence of oscillations in the loop only at the final stages of design (during ground and flight tests) leads to significant additional costs for carrying out measures to eliminate them. The best results should be expected in the joint design of the UAV and stabilization system. Analysis of the state of the problem of ensuring aeroservoelasticity requirements of in the design of UAVS shows that to date, well-developed methods for studying the aeroelastic stability of UAVS with ACS, when the parameters of the latter are considered known [1-6]. However, the proposed approaches in the field of joint design of UAV and stabilization system [7-10] are still far from solving real full-size problems.

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2. Methodology

2.1. Statement and General scheme of the problem solution

The problem of joint design of the airframe structure and the stabilization system of highly maneuverable UAV, when as a limitation imposed by the joint functioning of subsystems (airframe design and stabilization system), is the requirement of stability stabilization loop of the elastic UAV has the following formulation. To be known: aeroballistic and mass-geometric parameters of the UAV; its internal layout; the stabilization system structural scheme; parameters of the calculated flight modes; requirements to the airframe design (strength, stability, etc.) and stabilization system (accuracy, speed, etc.); aeroservoelasticity requirements. It is required to obtain an agreed decision on the structure and parameters of the airframe design and UAV stabilization system, taking into account the complex requirements.

To solve the problem of joint design of the airframe and stabilization system, taking into account aeroservoelasticity requirements, an iterative approach was developed, including three stages (figure 1):

- choice of structure and main parameters of UAV stabilization loop;
- separate design of the airframe structure and the stabilization system;
- coordination of the selected parameters of the airframe and the stabilization system, aimed at fulfilling of the aeroservoelasticity requirements.

2.2. Choice of structure and main parameters of UAV stabilization loop

Let's consider an axisymmetric UAV of the cross-wing or wingless aerodynamic scheme with the aerodynamic control. Since the UAV is axisymmetric, it has identical pitch and course channels. We next consider the UAV motion on the pitch.

The initial equations of the axisymmetric UAV with the most common aerodynamic method of creating control forces and moments are the equation of forces and moments. The equations can be written by applying dynamic coefficients that are used to describe the aircraft trajectory in flight dynamics: the damping coefficient $a_1$, the static stability coefficient $a_2$, the efficiency coefficient of the aerodynamic rudders $a_3$, the coefficient of lift force created by the attack angle $a_4$ and the coefficient of lift force created by the aerodynamic rudders deflection $a_6$ ($a_6 = 0$).

The transfer functions of the rigid UAV as a control object in the pitch channel for angular velocity $\omega$ and linear acceleration $W$ (in the installation places of sensors) have the form:

$$W_\omega(p)\big|_{\text{AVS}} = \frac{\omega}{\delta} = \tau k_r \frac{1 + T_{tc} \delta}{1 + 2 \xi_r T_r \delta + T_r^2 \delta^2};$$

$$W_W(p)\big|_{\text{LAS}} = \frac{W}{\delta} = \tau V k_r \frac{1}{1 + 2 \xi_r T_r \delta + T_r^2 \delta^2};$$

$$k_r = \frac{a_4 a_4}{a_3 + a_4} ; \ T_{tc} = \frac{1}{a_4} ; \ \xi_r = \frac{a_4 + a_4}{2 \sqrt{a_3 + a_4}} ; \ T_r = \frac{1}{\sqrt{a_3 + a_4}} ;$$

$$a_1 = -\frac{m v_0 q S L}{V I_z} ; \ a_2 = \frac{c_y^a (\overline{\alpha_m} - \overline{\alpha_f}) q S L}{I_z} ; \ a_3 = \frac{c_y^e (\overline{\alpha_m} - \overline{\alpha_f}) q S L}{I_z} ; \ a_4 = \frac{c_y^a q S}{m v} + \frac{P}{m v} ;$$

$V, q$ – the speed and the dynamic pressure of the UAV; $m v_0^a$ – the derivative of coefficient of the moment of aerodynamic damping; $c_y^a, c_y^e$ – the derivative of lift coefficient of the UAV by angle of attack and rudder deflection; $P$ – the engine thrust; $\overline{\alpha_m}, \overline{\alpha_f}, \overline{\alpha_r}$ – coordinates of the center of mass, the center of pressure, and the axis of rotation of rudder, related to the length of the UAV L; $m, I_z, S$ – mass, moment of inertia and characteristic area of the UAV. In the expressions "minus" sign corresponds to the normal aerodynamic layout, "plus" sign – tail-first layout.
Figure 1. Enlarged scheme of solving the problem of joint design.

Transfer functions defined by the expressions (1), (2) is obtained under the conditions of neglecting the rudder lift force (because of its smallness in comparison with the lift force of the UAV) and the without Coriolis acceleration generated by the rotation of the UAV from the effects outflowing jet of the jet engine. Full UAV transfer functions include transfer functions of rigid and elastic UAV (the
latter, as a rule, are approximate and take into account only the elastic vibrations of the body on the 1st and 2nd tone).

On the highly manoeuvrable UAV, the most widely used stabilization system for the pitch and course channels with two feedbacks: angular velocity \( \omega \) (formed by the angular velocity sensor (AVS) with gain \( k_{\text{AVS}} \)) and linear acceleration \( W \) (formed by the linear acceleration sensor (LAS) with gain \( k_{\text{LAS}} \)). Feedbacks form two closed circuit: first circuit, with the angular velocity feedback, called the damping circuit, the second - with the linear acceleration, called the stabilization circuit.

Assuming the transfer functions of the drive and sensors of the ACS equal to one (which is acceptable at frequencies that characterize the trajectory of the UAV), we get an expression for the transfer function of a closed-loop of the stabilization system with two feedbacks.

At the frequencies that characterize the trajectory of the UAVs motion and determine its dynamic properties as the link of the control loop and the accuracy of targeting, the transfer function of the closed-loop of the stabilization system can be represented as an oscillatory link:

\[
p = \frac{k_{st}}{1 + 2\xi_{st}T_{st}p + T_{st}^2p^2};
\]

where \( k_{st} \) is the gain factor; \( \xi_{st} \) – the damping rate; \( T_{st} \) – the time constant; \( \omega_{st} \) – the natural frequency.

The parameters \( \omega_{st} \) and \( \xi_{st} \) of the closed-loop stabilization system clearly define its response time \( \tau \) and the amount of emission \( \Delta_1 \) on the intermittent control command (figure 2). The parameters of the transition process \( \tau \), \( \Delta_1 \) are specified in the technical specification for development of the UAV.

The coefficients \( k_{\text{AVS}} \) and \( k_{\text{LAS}} \) affect the parameters of the transfer function \( W_{st}(p) \), the transition process and thus on the dynamic properties of the UAV, improving them (figure 2). Providing the required dynamic properties of the UAV with the stabilization system and requirements of its stability and determine, ultimately, the choice of the required values of the coefficients \( k_{\text{AVS}} \) and \( k_{\text{LAS}} \).

To ensure of the stabilization system stability at the frequencies of elastic oscillations of the UAV, a filter with a transfer function of the form is introduced into its composition

\[
W_f(p) = \frac{1 + 2\xi_1T_1p + T_1^2p^2}{1 + 2\xi_2T_2p + T_2^2p^2}.
\]

The filter is tuned to the frequency of the suppression of the 1st and optionally the 2nd tone of the bending vibrations of the UAVs body. The ratio of the time constants \( T_2/T_1 \) in equation (3) is typically in the range of from 0.5 to 2, the damping coefficients \( \xi_1 \) is from 0 to 0.2, and \( \xi_2 = 0.3 \) to 1.
2.3. Separate design of the airframe structure and the stabilization system

The next stage of the considered problem (figure 1, stage II) is separate design of subsystems: airframe design and stabilization system. The purpose of this stage is to obtain a rational design and technological solutions of UAV from the standpoint of functional and technological perfections, as well as a stabilization system with the required characteristics of accuracy, speed and reliability with minimum size and weight. At this stage, the design of individual UAV subsystems is carried out by traditional methods, the most acceptable for each subsystem, in compliance with the requirements formulated at the previous stage of solving the problem under consideration – the problem of choosing the parameters of the stabilization loop of the elastic UAV.

2.4. Coordination of the selected parameters of the airframe and the stabilization system

The solution of this problem (figure 1, stage III) is aimed at ensuring the requirements of aeroservoelasticity. The mathematical model of UAV stabilization loop stability study is based on the computational model of aeroelastic oscillations of UAV. The construction of the computational model is associated with the choice of the most important forms of motion. For the considered highly maneuverable UAV, these are: bending and torsional oscillations of the rudders (generalized coordinates $q_1$, $q_2$) and bending oscillations of the UAV body on the 1st and 2nd tones (generalized coordinates $q_3$, $q_4$). Oscillations of the wing lower tones are taken into account through the bending oscillations of the UAV body. The system of equations, compiled by the method of generalized coordinates and recorded in the operator form, has the form:

$$
\sum_{j=1}^{4} f_{ij}(p) = 0; \quad f_{ij}(p) = m_{ij} p^2 + (h_{ij} + d_{ij} V^2)p + g_{ij} + b_{ij} V^2; \quad (i, j) = 1, 2, 3, 4,
$$

where $m_{ij}, h_{ij}, g_{ij}$ – the coefficients of inertia, damping and stiffness; $h_{ij}, b_{ij}$ – aerodynamic coefficients (damping and stiffness).

As an example, we give expressions for the nonzero coefficients of equation (4) for a wingless UAV of the normal aerodynamic layout and "+" scheme equipped with aerodynamic rudders with a straight axis of rotation in a supersonic flow:

- coefficients of inertia:
  
  \begin{align*}
  m_{11} &= 2J_{xz}; \\
  m_{12} &= m_{13} = 2J_{zz} + 2J_{xx}; \\
  m_{14} &= 2S_x \psi_2(x_0) + 2J_{xx} \psi_1(x_0); \\
  m_{15} &= m_{16} = 2S_y \psi_2(x_0) + 2J_{zz} \psi_1(x_0); \\
  m_{24} &= -2S_x \psi_2(x_0) - 2J_{xx} \psi_2(x_0); \\
  m_{33} &= \int_0^1 m_b(x) \psi_1^2(x) dx; \\
  m_{44} &= \int_0^1 m_b(x) \psi_2^2(x) dx,
  \end{align*}

  
  where $J_{xz}, J_{zz}, J_{xx}$ and $S_x, S_z$ – the moments of inertia and the static moments of the rudder around the axes Ox and Oz (the Oz-axis coincides with the axis of rotation); $\psi_1(x), \psi_2(x)$ – the forms of the deflections of the UAV body axis during its deformation by the 1st and 2nd tones, respectively (normalized so that $\psi_1(x_0) = \psi_2(x_0) = 1$); $l_b, m_b(x)$ – the length and the mass per unit of the UAV body; $x_0$ – the coordinate of the axis of rotation of the rudder;

- coefficients of stiffness and structural damping:

  \begin{align*}
  g_{ii} &= m_{ii} (2\pi f_i)^2; \\
  h_{ii} &= 2\nu_i f_i m_{ii}; \quad i = 1, 2, 3, 4,
  \end{align*}

where $f_1, f_2$ – frequencies and logarithmic decrements of respective natural oscillations of the UAV;

- aerodynamic coefficients:
The coefficients \( \bar{b}_2 \), \( \bar{b}_3 \), \( \bar{b}_{11} \), \( \bar{b}_{12} \), \( \bar{b}_{21} \), \( \bar{b}_{22} \) are defined for two rudders at the motionless of the UAV body:

\[
\begin{align*}
\bar{b}_2 &= -\rho c^\delta \int_{z_0}^{1+z_0} b(z) dz; \\
\bar{b}_3 &= -\rho c^\delta \int_{z_0}^{1+z_0} z^2 (\bar{x}_0 - \bar{x}_F) dz; \\
\bar{b}_{11} &= \rho c^\delta \int_{z_0}^{1+z_0} b(z) dz; \\
\bar{b}_{12} &= \rho c^\delta \int_{z_0}^{1+z_0} z^2 (\bar{x}_0 - \bar{x}_F) dz; \\
\bar{b}_{21} &= \rho c^\delta \int_{z_0}^{1+z_0} b(z) dz; \\
\bar{b}_{22} &= \rho c^\delta \int_{z_0}^{1+z_0} z^2 (\bar{x}_0 - \bar{x}_F) dz,
\end{align*}
\]

where \( \rho \) – the density of air; \( c^\delta \) – the derivative of lift coefficient by angle of rudder deflection; \( b, l \) – the chord and the span of the rudder; \( z_0 \) – the distance from the place of fastening of the rudder shaft to the side chord; \( z \) – the distance to the considered chord section of the rudder; \( \bar{x}_0 = x_0 / b \), \( \bar{x}_F = x_F / b \) – the distance from the rudder nose to the axis of rotation and the aerodynamic focus, respectively, divided by the rudder chord.

From equation (4) can determine transfer functions \( W_1(p) \) and \( W_2(p) \) from the generalized coordinate \( q_2 \), representing the deviation of the rudder, \( \delta \) to coordinates \( q_3 \) and \( q_4 \), characterizing the UAV body motion. Considering the deflection forms of the UAV body axis in the AVS installation place \( (\psi_1(x_{AVS}), \psi_2(x_{AVS})) \) and derived forms in the LAS installation place \( (\psi_1(x_{LAS}), \psi_2(x_{LAS})) \) when the flexural deformations of the UAV body on the 1st and 2nd tone, respectively, we write the transfer function of the elastic UAV in the channel pitch by angular velocity (in the place of installation AVS) and linear acceleration (in place of LAS):

\[
W_1(p)_{AVS} = \frac{\omega}{\delta} \bigg|_{AVS} = \psi_1(x_{AVS}) p W_1(p) + \psi_2(x_{AVS}) p W_2(p); \\
W_2(p)_{AVS} = \frac{\omega}{\delta} \bigg|_{AVS} = \psi_1(x_{AVS}) p W_1(p) + \psi_2(x_{AVS}) p W_2(p),
\]

The complete transfer functions of the UAV \( W_0_{UAV}(p) \) and \( W_{UAV}(p) \) can be obtained by summing the corresponding transfer functions (1), (5) and (2), (6).

One possible way of analyzing the UAV stabilization loop stability is the comparison of the amplitude and phase frequency characteristics of the transfer function \( W_{UAV}(p) \) and feedback transfer function \( W_{ACS}(p) \). According to the frequency the Nyquist criterion the product of these transfer functions on the boundary of stability is equal to one. The transfer function \( W_{UAV}(p) \) includes a transfer function of the hard and the flexible UAV, and the transfer function \( W_{ACS}(p) \) – the transfer functions of the sensors, the amplifier-converter tract of the stabilization system and the control surface actuator.
Depending on the studied circuit (damping or stabilization), $W_{UAV}^a(p)$ or $W^w_{UAV}(p)$ are considered as $W_{UAV}(p)$, and $W_{ACS}^a(p)$ or $W^w_{ACS}(p)$ as $W_{ACS}(p)$.

Using the proposed model, the study of the UAV stabilization loop stability (figure 1, stage III). In case of noncompliance of the requirements of aeroservoelasticity performed parametric analysis of the influence of the main parameters of the airframe and system stabilization on the stability of the loop, which produced measures to the parameters of the airframe and system stabilization. These measures can be associated with the correction of the characteristics of the airframe design (primarily, natural oscillation frequencies) or the parameters of the stabilization system (optimization of the location of sensors along the length of the UAV body, correction of parameters or installation of new filters configured to suppress elastic vibrations of the UAV), changing the frequency characteristics of the steering actuators). In the first case, a new problem of designing the UAV design is solved, in the second-the stabilization system. The iterative design process ends when the requirements of aeroservoelasticity will be satisfied.

3. Results and discussion
Let's consider an example of application of the offered approach to joint design of the airframe structure and the stabilization system of the UAV taking into account requirements of aeroservoelasticity. We consider the hypothetical highly maneuverable UAV of the normal aerodynamic layout, having aerodynamic rudders and the stabilization system with two feedbacks. For the design mode is adopted, the mode with the maximum dynamic pressure ($q = q_{max} = 1$ MPa), corresponding to the end of the active leg of the UAVs flight.

When forming the stabilization loop (figure 1, stage I), the requirements of aeroservoelasticity were provided, including due to:
- the rational placement of the AVS near the antinode of the elastic line of the 1st tone of elastic oscillations of the UAVs body (taking into account the possibility of UAV layout);
- the filter settings to suppress the elastic oscillations of the body on the 1st tone.

Next, the tasks of separate design of the airframe structure and stabilization system were solved (figure 1, stage II). The characteristics of the natural oscillations of the UAV body are shown in the figure 3. There are also two characteristic cross sections of the body: the section with AVS and LAS (section I-I) and the section with axis of rotation of the rudders (section II-II). The parameters of the rudder are presented in table 1. The logarithmic decrements of the rudder and UAV body oscillations were assumed to be 0.05.

Analysis of the UAV stabilization loop stability in the framework of the design parameters harmonization of the airframe and stabilization system (figure 1, stage III) showed a lack of stability in the damping circuit at the frequency of the 2nd tone of flexural oscillations of the of the UAV body, which is evidenced by the intersection of the frequency response of transfer functions $W_{UAV}^a(p)$ (curve 1) and $(W_{ACS}^a(p))^{-1}$ (curve 2) in figure 4. Since we will use only the amplitude methods to ensure stability, we will limit ourselves to considering only the amplitude frequency characteristics of the elastic UAV and the stabilization system.

Figure 3. Forms of natural bending oscillations of the UAV body:
1 – 1st tone, \( f_3 = 40 \text{ Hz} \); 2nd tone, \( f_4 = 96 \text{ Hz} \).

### Table 1. Rudder parameters.

| Rudder parameter | Modified Rudder | Source Rudder |
|------------------|-----------------|---------------|
| \( J_{xx} (\text{kg} \cdot \text{m}^2) \) | 0.135           | 0.15          |
| \( J_{zz} (\text{kg} \cdot \text{m}^2) \) | 0.0085          | 0.01          |
| \( J_{xz} (\text{kg} \cdot \text{m}^2) \) | -0.005          | 0.005         |
| \( f_1 (\text{Hz}) \) | 97              | 107           |
| \( f_2 (\text{Hz}) \) | 285             | 320           |

**Figure 4.** To the study of measures aimed at ensuring the damping circuit stability.

A detailed analysis of the presented dependencies allows us to conclude that a significant rise in the module \( W_{\text{UAV}}(p) \) (figure 4, curve 1) is caused by the proximity of the frequencies of the body's own bending oscillations along the 2nd tone and the bending oscillations of the rudder, which led to a resonant amplification of the amplitude at this frequency. Therefore, it is advisable as a measure to ensure the damping circuit stability to modify the design of the rudder in order to increase its frequency of bending oscillations (up to 107 Hz). As the result of solving a new design problem with an additional restriction on the frequency of natural bending oscillations of the rudder \( f_i \geq 107 \text{Hz} \), the rudder with new parameters is obtained (table 1). Figure 4 presents the results of the study of the stability of the damping circuit of the UAV with a modified rudder, from which it follows that now the circuit has sufficient reserves of stability modulo \( \Delta A \)-modulo margin): stability is achieved by significantly reducing the modulus of the transfer function of the elastic UAV with the modified rudder \( W_{\text{UAV}}(p) \) (figure 4, curve 2).

### 4. Conclusion

The problem of joint design of the airframe structure and the stabilization system of the highly maneuverable UAV is formulated taking into account the requirements of aeroservoelasticity and the iterative approach to its solution is proposed, including:

- choice of structure and main parameters of UAV stabilization loop;
- separate design of the airframe structure and the stabilization system;
- coordination of the selected parameters of the airframe and the stabilization system, aimed at fulfilling of the aeroservoelasticity requirements.
The problems of selecting the main parameters of the UAV stabilization loop and matching the parameters of the airframe design and stabilization system in order to meet the requirement of aeroservoelasticity are considered in more detail. An example of the matching problem of the parameters of the airframe design and stabilization system of the highly maneuverable UAV is solving.

The novelty of the manuscript lies primarily in the authors' original approach to the joint design of the construction and the stabilization system of the highly maneuverable unmanned aerial vehicles with requirements of aeroservoelasticity, as well as original models, reflecting the specific use of such UAVS.

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