Research of the influence of the volumetric-mass layout of the aircraft on the dynamics of rotational motion in the longitudinal plane

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Abstract. In this paper, the influence of the volumetric-mass layout of the aircraft on the dynamics of rotational motion in the longitudinal plane is considered. The studies allow us to evaluate the relationship between the space-mass layout of the aircraft and the perturbing aerodynamic effects that occur during the transition process. The deviation of the empirical values of the aerodynamic moment from the linear dependence and the time of the transition process were considered to be quantitative estimates of the quality of the transient process. An original aerodynamic experiment with a moving aircraft model was proposed as a research method. The continuous change in the position of the aerodynamic model in the experiment made it possible to analyze the effects and their influence on the motion parameters in real time, and take into account the unsteadiness of the flow on the airframe surface. The conducted experiment shows that to reduce the time of the transient process, the value of the moment of inertia of the aircraft should be reduced but, in this case, the aerodynamic moments caused by the inertia of the medium and various unsteady flows will increase. As a result, when choosing the ratios of stability and controllability of an aircraft, one should pay attention not only to the geometric location of the center of mass and focus of the aircraft, but also to the mass-volume characteristics of the aircraft.

1 Introduction

At present, the creation of a modern competitive aircraft is impossible without a clear understanding of the basics of flight dynamics by the designer [1]. One has to deal with the solution to these problems both at the initial and subsequent stages of the aircraft’s life cycle and during its operation [2]. At the stage of developing a technical proposal, preliminary studies of various aerodynamic schemes and layouts are carried out, and the possibility of creating an aircraft that meets the specified requirements is assessed [3, 4].

As the project is developed and a reliable one is obtained, the range of problems of flight dynamics expands, and mathematical models become more complicated, considering the influence of the weight characteristics of mass-inertial properties [5, 6].

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When solving problems of aerodynamics and aeroelasticity, the use of numerical methods is hindered by the presence of essentially nonlinear components in mathematical models and the imperfection of the similarity coefficients selected for the numerical solution [7].

So, for example, the function of the aerodynamic moment coefficient \( m_z \) in the longitudinal plane (1), in its most general form, depends not only on a set of dynamically changing parameters but also on random perturbations, which cannot be considered theoretically:

\[
m_z = m_z(M, Re, Eu, Fr, V, \alpha, \delta, \bar{\omega}, \bar{\alpha}, f_v),
\]

(1)

where \( f_v \) is the random function characterizing a real system with perturbations.

Therefore, the aerodynamic experiment is the main way to study the aerodynamic characteristics of the developed aircraft.

In the classical approach, the aerodynamic experiment is divided into two groups depending on the relative motion of the air medium and the object under study:

1) The object under study moves at a certain speed in a stationary air environment.
2) A stationary object under study in an air medium moving at a certain speed.

The experiments of the first group include devices that rotate an aircraft in a stationary environment, ballistic installations, and flight tests. The experiments of the second group include tests carried out in wind tunnels with a statically fixed aircraft model.

Quantitative and qualitative results recorded in the process of performing flight tests have the highest accuracy. Under such conditions, the maneuvering of the apparatus causes opposition to the environment of the existence of the aircraft:

1) A sharp change in aerodynamic angles leads to the appearance of damping aerodynamic moments.
2) The longitudinal arrangement of the aerodynamic surfaces one behind the other leads to sharply changing forces on the tail. Such phenomena are especially typical for sharp changes in the angles of attack (there are moments of delay in the flow bevel on the plumage), as well as when the aircraft moves at supercritical angles of attack, accompanied by flow stalls from the bearing surfaces.

A comprehensive study of these effects is impossible with the introduction of restrictions on the degrees of freedom in an aerodynamic experiment. The model statically fixed in the wind tunnel does not allow for accurately determine the components of the aerodynamic moment, which are caused by intensive maneuvering. Approximation of the results obtained at different, discretely set, angles of attack are quite acceptable for sections of the trajectory in which the aircraft does not go beyond the critical angles of attack, however, the lack of mobility of the model does not allow us to judge the quality of the control system used, the stability of the aircraft in extreme flight modes and possible occurrence of steady-state phenomena of aeroelasticity.

2 Aerodynamic experiment with a moving aircraft model

Another approach to conducting an aerodynamic experiment is possible, which combines the advantages of each group - the possibility of assessing non-stationary phenomena that appear with a continuous change in the position of the aircraft, the relatively low cost of the experiment, and its safety.

Such results can be obtained by introducing a degree of freedom into a model statically fixed in a wind tunnel. The original stand design (Fig. 1), developed at the Department of Aircraft Motion Dynamics and Control Systems, BSTU “VOENMEH”, allows you to study the rotational motion of the aircraft in the longitudinal plane without using simplifying
assumptions, modeling all aerodynamic effects directly. The design of the HIL laboratory bench allows the aerodynamic model to rotate freely in the wind tunnel due to the deflection of the elevators. Measuring the angle of attack, drag force, and lift by the stand measurement system provides all the necessary information for generating control commands and plotting the flight path of the aircraft [8].

Direct modeling of the equation of rotational motion of an aircraft (2) makes it possible to study the influence of a volume-mass layout on the time of transients and the effects that occur at high speeds of rotation of the vehicle.

\[ I_z \frac{d\omega_z}{dt} = \sum M_z(t), \]  

(2)

where \( \sum M_z(t) \) is the total moment of aerodynamic forces acting on the aircraft in flight.

![Fig. 1. HIL simulation stands for flight dynamics.](image)

3 Research of the influence of the results obtained in the experiment on the choice of technical characteristics of the aircraft

When designing an aircraft, the most important issue is the choice of stability and controllability ratios. Since the nature of the rotational motion of the aircraft is primarily due to the volume-mass characteristics and aerodynamic moments, the transient processes obtained for different moments of inertia of the aircraft, with unchanged geometric dimensions of the model itself, are of interest.

Quantitative estimates of the quality of the transient process were considered to be the deviation of the empirical values of the aerodynamic moment from the linear dependence and the time of the transient process [9].

In a full-scale experiment, a change in the volumetric-mass layout was simulated by the movement of loads along the main axis of the aircraft.

During the experiment, the aircraft model was deflected to a large angle of attack (~6°) and held in this position, then, after establishing a constant speed in the wind tunnel, the
model began to move freely around the center of mass, while the change in the angle of attack of the model was recorded at a frequency of 80 times per second.

As a result, it was found that a decrease in the moment of inertia of the aircraft and, as a result, an increase in angular velocities leads to a decrease in the time of the transition process, however, in this case, the dependence of the aerodynamic moment on the angle of attack becomes nonlinear in all sections of the trajectory (Fig. 2, 3). Such results indicate that the influence of the aerodynamic moment associated with the external layout of the aircraft is comparable in magnitude with the influence of the moments associated with the inertia of the environment of the existence of the aircraft. With an increase in the moment of inertia of the model, the function of the dependence of the aerodynamic moment on the angle of attack acquires rectilinear sections, while the time of the transition process increases (Fig. 4, 5) [10]. In this case, the motion of the aircraft is significantly affected by the inertial properties of the object itself.

Fig. 2. Transient process at $I_z = 0.0023 \text{ [kg} \cdot \text{m}^2\text{]}$.

Fig. 3. Dependence $M_z(\alpha)$ in the experiment at $I_z = 0.0023 \text{ [kg} \cdot \text{m}^2\text{]}$. 
The model began to move freely around the center of mass, while the change in the angle of attack of the model was recorded at a frequency of 80 times per second. As a result, it was found that a decrease in the moment of inertia of the aircraft and, as a result, an increase in angular velocities leads to a decrease in the time of the transition process, however, in this case, the dependence of the aerodynamic moment on the angle of attack becomes nonlinear in all sections of the trajectory (Fig. 2, 3). Such results indicate that the influence of the aerodynamic moment associated with the external layout of the aircraft is comparable in magnitude with the influence of the moments associated with the inertia of the environment of the existence of the aircraft. With an increase in the moment of inertia of the model, the function of the dependence of the aerodynamic moment on the angle of attack acquires rectilinear sections, while the time of the transition process increases (Fig. 4, 5) [10]. In this case, the motion of the aircraft is significantly affected by the inertial properties of the object itself.

Fig. 2. Transient process at $I_z = 0.0023$ [kg $\cdot$ m$^2$].

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Fig. 4. Transient process at $I_z = 0.055$ [kg $\cdot$ m$^2$].

Fig. 5. Dependence $M_z(\alpha)$ in the experiment at $I_z = 0.055$ [kg $\cdot$ m$^2$].

The results show that to reduce the time of the transient process, the value of the moment of inertia of the aircraft should be reduced, but in this case, the aerodynamic moments caused by the inertia of the medium and various unsteady flows will increase. To describe such a movement, high-order derivatives should be considered, which leads to an increase in the time of formation of the control signal.

An interesting part of the graphs (Fig. 3, 5) corresponds to a change in the direction of the aircraft angular velocity vector and an intensive change in the processes of flow around the airframe. At this moment, the dependence of the aerodynamic moment takes the most non-linear form, and its value reaches a maximum. Under such conditions, at high angular speeds and insufficient resistance of the fuselage to the bending moment, there is a possibility of the development of tail buffing and, as a result, loss of stability and destruction of the aircraft airframe.

4 Conclusion

Thus, the experiment shows that when choosing the ratios of stability and controllability of an aircraft, one should pay attention not only to the geometric location of the center of mass and focus of the aircraft but also to the volume-mass characteristics of the aircraft. The functional relationship between the aerodynamic moment and the derivative of the angular velocity (3) plays a significant role in describing the rotational motion of an aircraft and can only be studied in dynamic experiments.
\[ M_z = J(\dot{\omega}_z) \]  

(3)

The excess moment of inertia of the aircraft increases the time of the transient process and the reaction time of the aircraft to the control signal. A decrease in the moment of inertia, in turn, causes an increase in the derivative of the angular velocity. As a result, in the total aerodynamic moment, not only the aerodynamic moments associated with the aircraft geometry but also the damping properties of the environment for the existence of the aircraft and the unsteadiness of the flow on the surfaces of the aircraft begin to play a significant role. This leads to difficulties in the formation of the control signal and under certain conditions can cause loss of stability and destruction of the aircraft structure.

References


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