УДК 629.7.015
DOI: 10.26467/2079-0619-2022-25-3-73-85

About revising the computational dynamic scheme of an unmanned aerial vehicle based on the results of ground-based modal test operations in the aeroelasticity problems

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Abstract: The problem of revising the computational dynamic scheme of an unmanned aerial vehicle (UAV), based on the results of ground-based modal test operations, in order to study the UAV flutter and to assess the aeroelastic stability of an UAV with an automatic control system (ACS), is considered. It is noted that at the design stage, when there is no UAV prototype or its units yet, the determination of modal characteristics, specifically natural frequencies, modes and generalized masses, is carried out using the computational dynamic scheme developed according to the design documentation. However, the similar computations, performed even with the use of modern finite-element software systems, do not give sufficiently precise values of the parameters of the UAV design elastic-mass schematization. In this regard, it is relevant and important to specify the parameters of the design schematization in conformity with data of ground test operations for UAV prototypes. The provisions, allowing us to achieve satisfactory results when revising the UAV computational dynamic scheme, are made. The criteria of revising are considered. The features of revising the computational dynamic scheme, while studying the flutter and aeroelastic stability of the ACS-fitted UAV, are presented. It is noted that along with the provisions that are universal for dynamic aeroelasticity problems, specifically for flutter, and related to compensating of natural frequencies, modes and coefficients of structural damping for the UAV model according to the results of ground modal tests. In the problems of aeroelastic stability study of the UAV equipped with the ACS, it is also crucial to correct the UAV body transfer function from the section, corresponding to the axis of controls rotation, to the section where ACS sensors are installed. This is because the UAV hull is an integral part of the UAV stabilization loop and significantly affects its stability margin. The example of revising the computational dynamic scheme of a maneuverable cruciform UAV is given.

Key words: unmanned aerial vehicle, automatic control system, computational dynamic scheme, ground modal tests, revising, flutter, aeroelastic stability.

For citation: Parafes', S.G. (2022). About revising the computational dynamic scheme of an unmanned aerial vehicle based on the results of ground-based modal test operations in the aeroelasticity problems. Civil Aviation High Technologies, vol. 25, no. 3, pp. 73–85. DOI: 10.26467/2079-0619-2022-25-3-73-85

О корректировании расчетной динамической схемы беспилотного летательного аппарата по результатам наземных модальных испытаний в задачах аэроупругости

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Аннотация: Рассмотрена задача корректирования расчетной динамической схемы беспилотного летательного аппарата (БЛА) по результатам наземных модальных испытаний в интересах исследования флаттера БЛА и оценки аэроупругой устойчивости БЛА с системой автоматического управления (САУ). Отмечено, что на этапе проектирования, когда нет еще опытного образца БЛА или его агрегатов, определение модальных характеристик, а именно собственных частот, форм и обобщенных масс, проводится с помощью расчетной динамической схемы, разработанной по конструкторской документации. Однако подобного рода расчеты, выполненные даже с использованием современных конечно-элементных программных комплексов, не дают достаточно точных значений параметров упруго-массовой схематизации конструкции БЛА. В этой связи актуальным и важным является уточнение параметров схематизации конструкции по данным наземных испытаний опытных образцов БЛА. Сформулированы положения, позволяющие достигать удовлетворительных результатов при корректировании расчетной динамической схемы БЛА. Рассмотрены критерии корректирования. Представлены особенности корректирования расчетной динамической схемы при исследовании флаттера и аэроупругой устойчивости БЛА с САУ. Отмечено, что наряду с положениями, которые являются универсальными для задач динамической аэроупругости, в частности флаттера, и связанными с коррекцией собственных частот, форм и коэффициентов конструкционного демпфирования модели БЛА по результатам наземных модальных испытаний, в задачах исследования аэроупругой устойчивости БЛА с САУ также решающее значение имеет коррекция передаточной функции корпуса БЛА от сечения, соответствующего оси вращения рулей, до сечения, где установлены датчики САУ. Это связано с тем, что корпус БЛА является непосредственной частью контура стабилизации БЛА и существенно влияет на его запасы устойчивости. Приведен пример корректировки расчетной динамической схемы маневренного БЛА крестокрылой схемы.

Ключевые слова: летательный аппарат, система автоматического управления, расчетная динамическая схема, наземные модальные испытания, корректирование, флаттер, аэроупругая устойчивость.

Для цитирования: Парафесь С.Г. О корректировании расчетной динамической схемы беспилотного летательного аппарата по результатам наземных модальных испытаний в задачах аэроупругости // Научный Вестник МГТУ ГА. 2022. Т. 25, № 3. С. 73–85. DOI: 10.26467/2079-0619-2022-25-3-73-85

Introduction

One of the most key tasks of dynamic aeroelasticity, the science about interaction of a flexible aircraft (A/C) with air flow, is preventing hazardous self-oscillations in-flight. A solution of the problem is conducted by means of computational-experimental research at various stages of A/C development. In terms of UAVs, the determination of the boundary of (critical velocity) flutter and the boundary of the stability loop “the flexible A/C-automatic control system (ACS)” is essential.

At the design stage, when an A/C prototype or its units are not available, defining the modal performance, especially natural frequencies, modes and generalized masses, is carried out by means of the computational dynamic scheme developed in accordance with the design documentation. The domestic and international practice shows that the similar computations, based on the sophisticated finite-element software solutions, do not provide with sufficiently precise values of modal parameters for the elastic-mass structure schematization. That is why, the necessity of specifying computations, based on A/C ground tests, is required. Modal tests of the prototype are compulsory prior to flight tests [1, 2]. After revising the elastic-mass computational scheme, a model to perform computations of A/C oscillations in-flight in the problems to study the flutter and aeroelastic stability of ACS-fitted A/C, is formed.

Fairly many papers are dedicated to the issues of revising a computational dynamic scheme. Most notably, the approaches in respect to updating infinite-element models are prioritized. The model designs such as plates [3, 4], frames [5] as well as physical structures of aerospace vehicles are under consideration. For example, the techniques to revise the computational dynamic scheme, regarding aircraft manufactured from conventional materials, are discussed in the papers [6], from composite materials – in [7, 8], UAVs – in [9]. The articles [10–12] deal with updating of infinite-element models designed to describe the dynamic construction behavior (including aerospace structures) with the riveted [10] and bolted [11, 12] joints.

Let us consider in more detail the papers representing the techniques aimed at revising the computational dynamic scheme based on the method of infinite elements, taking into consideration ground modal tests results, which are utilized to investigate the A/C flutter. The work [6] describes the potential approaches to study the A/C flutter in order to incorporate the results of ground vibration tests, i.e., 1) direct use of ground vibration tests results and 2) updating of the computational finite-element model of the A/C structure. A theoretical foundation for the methods to update the computational model, including the Bayesian estimate of the parameters and more general optimization employing the powerful nonlinear gradient methods, is given. The paper [7] considers the problem of updating the computational finite-element model in order to investigate the A/C flutter with an elongated composite wing. In conformity with the results of ground modal tests, updating of the computational finite-element model by means of optimization procedures based on the methods of sensitivity analysis, was carried out.

One should note that the sensitivity analysis methods are widely utilized in the problems of updating computational dynamic models based on ground modal tests results ([3], [12–14]).

An innovative technique to update the finite-element A/C model using the results of ground modal tests is proposed in [8]. This paper provides a fresh approach towards the global/local optimization to update the finite-element A/C model made of composite material according to the scheme “flying wing” which used test data based on subsystems. Three stages of mass and rigidity distribution adjustment, while updating the computational finite-element model of the A/C, are considered. Stages I and II, i.e., local optimization, correct mass distribution for the A/C fuselage and wing to bring their mass characteristics in line with test data. Wing rigidity distribution is also adjusted on stage II using the results of ground modal wing tests. The original finite-element A/C model is updated subsequently using available experimental mass characteristics and the results of ground modal tests of the entire A/C. The iterations of global and local optimization continue until the difference between the test results and numerical results concerning finite-element models as of the entire A/C as of its subsystems (fuselage and wings) becomes less than the assigned value.

The article [15] considers the problem of updating the computational dynamic model applicable to aerospace structures, most of physical properties and boundary conditions of which depend on temperature. The approach to update the computational dynamic model, taking into consideration thermal effects and uncertainties, using a hierarchical strategy, is proposed.

At the end of a brief review of the papers dedicated to the problems of revising the computational dynamic scheme based on the results of ground modal (vibrational) tests, let us highlight the paper, in which the object of study is the UAV. Thus, the paper [9] provides the development of the finite-element structure model for a small-sized flexible UAV. It is dedicated to the development of a simple design model based on a two-stage procedure. The static and dynamic wing tests are conducted on the initial phase. These experiments give the first assessments of the UAV material properties (e.g., rigidity), upon which, the finite-element model consisting of simple beam-type components, is developed. On the second phase, the original finite-element model is updated by means of modal data, derived from ground vibrational tests of the UAV. Afterwards, the optimization problem for purpose of minimizing differences in modal UAV properties (frequencies and modes), obtained from the computational model and experimental data.

The given review of studies, concerned with revising the computational dynamic scheme based on the results of ground modal tests, emphasizes the relevance of the stated research topic. At the same time, there are papers which are primarily oriented at the solution of problems associated with the study of dynamic structure behavior, including the flutter. The issues to revise the computational dynamic scheme based on the results of ground modal tests in order to solve the problems of aeroelasticity, which are of paramount importance for UAVs fitted with ASCs, are not sufficiently covered.

The goal of research is the development of approaches to revise the computational dynamic scheme of maneuverable UAVs, in the first instance, “air-air” and “air-ground” classes, using the results of ground modal tests to solve the problems of flutter and aeroelastic stability of ACS-fitted UAVs.

Main provisions of revising the UAV computational dynamic scheme

The following integral structure characteristics like natural frequencies, generalized masses of the undamped system or more local natural modes and frequency characteristics can be the subject or the parameter of proximity of the experiment data and the revised computational scheme. While revising the computational dynamic scheme, an issue about a structural damping does not arise. The experiment can solely serve as a proper scientific methodology.

Revising of the computational dynamic scheme, elastic-mass, is traditionally conducted by frequencies alone: as a rule, they are defined in tests, sufficiently precisely, although indirectly. Basically, it refers to basic frequencies which can affect the flutter critical velocity. The correction problem, which can be considered as an inverse problem not having a single-valued solution, is quite time-consuming, and does not have developed algorithms.

However, one may note a series of utilized techniques which allows us to achieve satisfactory results.

The first provision is that, in the number of given data, specified by the design documentation, the inertial characteristics, as a rule, are more reliable. In this case, it is allowable to update rigidity data with the aim of improving convergence of computational and experimental frequencies.

The initial step for the first mode, for example, of a hull bend, can be the variation of a rigidity scale without changing rigidity distribution along the hull length. It is implemented within one step, but it is merely allowable if there are no apparent peculiar features with respect to rigidity distribution around the hull, for example, availability of degraded places.

Frequency divergence of the subsequent mode, for example, of the second hull bend, thereby changes, but not necessarily for the better. Therefore, repeated adjusting of rigidities is required, inevitably deteriorating the previous results. Thus, the procedure becomes iterational, and the number of steps is defined by the structural features and designer's experience. Both rigidities distribution and their absolute values are adjusted. On several occasions, there are obvious signs, establishing the necessity to change rigidity at a specific location and direction, for example, in the area of hull joints. The stated variant significantly facilitates the procedure of adjusting.

There is a general rule of obvious character. It is preferable to vary rigidity for the specific mode at the more stressed location, i.e., in the area of the antinode point on the shape. In terms of the UAV airframe structure sections that have lumped rigidities, primarily, for flight controls, the task becomes simplified to some degree as it reduces itself to the rigidity change of two or three springs with the known position. In any case, the rigidity change should be limited by reasonable margins, and zero divergence in frequencies should not be the purpose of adjusting.

Comparison of natural modes is another traditional step, practically significant. It is common practice that they are compared qualitatively, by the "external view", by the number of nodes or the position of node lines on the surface. One can suppose that adjusting by natural frequencies will approximate the computational eigenforms to experimental ones, although formal fundamentals are not available.

The criterion for the quantitative comparison of eigenforms is the values of generalized structure masses which represent the same integral parameter as natural frequencies. Let us explain this assertion with special reference to the oscillating system with one degree of freedom containing cargo of mass *m* on the spring with rigidity *k*. Figure 1 represents the dependence of natural frequency ω_0 on the parameters of the given oscillating system in physical coordinates *m, k.* The natural frequency magnitude only defines the straight line inclination, all the dots of which are referrred to various couples of masses and rigidities that is to different oscillating systems. The addition of the natural frequency by a magnitude of mass (or rigidity) emphasises a point on the straight, coordinates of which m_i, k_i explicitly points out to a specific oscillating system with one degree of freedom.

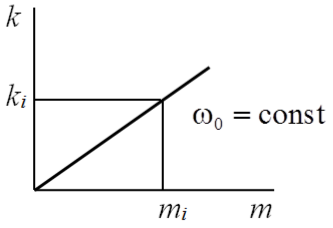

Fig. 1. Dependence of the natural frequency on the parameters of the oscillating system with one degree of freedom

Data for identification become exhausted by two integral quantitative criteria: natural frequency and mass (or rigidity). However, these criteria are generally nonsufficient. In particular, the most essential is the ratio of shifting, defined according to the eigenform of the first hull bending mode in the axis sections of the flight control rotation, $y_{\text{о.вр}}$ and installation of ACS gauges, $y_{\text{САУ}}$. The ratio is a multiplier of the amplitude-frequency characteristic (AFC) and the phase-frequency response (PFR) of the stabilization loop (SL), which identifies in-flight stability of the “flexible A/C-ACS” system. Increase in this ratio, for example, twice reduces a doubled margin of SL stability up to 0, i.e., to the boundary of self-oscillations. This example demonstrates the necessity of quantitative modes comparison and the approprite computation correction.

The locations of nodes of the bending mode on the axis of hull, the ratio of amplitudes or the node line inclination on the surface of flight control are the local quantatative characteristics of eigenmodes. An attempt to add frequency, adjusting by a quantatative comparison of modes, complicates the problem critically, so the correction with the local comparison of modes can be merely referred to the most important modes which specify the self-oscillations boundary. In this case, the procedure is iterational, considering inaccuracy of measurement during tests. It is impossible to obtain a single-valued algorythm as with the case of frequencies.

The admissible criterion for proximity of the computation results and experiment is a value $\left[\left(\Delta m_{0j}\right)^2+\left(\Delta\omega_j\right)^2\right]$ on the flat surface $\left(m_0,\omega\right)$, where $\Delta m_{0j}=m_{0j}^{\text{р}}-m_{0j}^{\text{э}}$; $\Delta\omega_j=\omega_j^{\text{р}}-\omega_j^{\text{э}}$ [16]. The magnitudes $m_{0j}^{\text{р}}, m_{0j}^{\text{э}}$ represent generalized masses and the magnitudes $\omega_j^{\text{р}}, \omega_j^{\text{э}}$ do natural frequencies obtained by computational or experimental methods (j – No of self-oscillations mode).

It is more convenient to minimize the proximity criterion of the computation and experiment results in the form of dimensionless value

$$R_{m,\omega}^2=\left(h_1\frac{\Delta m_{0j}}{m_{0j}^{\text{э}}}\right)^2+\left(\frac{\Delta\omega_j}{\omega_j^{\text{э}}}\right)^2, \qquad (1)$$

representing the sum of squared difference of two relative parameters. Since, the inaccuracy of natural frequency computation $\sigma\omega$ is less than the inaccuracy of generalized mass σm_0 ($\sigma\omega<\sigma m_0$) computation, the weighting factor $h_1<1$ is introduced into the criterion. If in the oscillating system under consideration, there are two proximate by frequency and strongly interacting modes, revising of the computational scheme should be conducted taking into consideration the characteristics of both modes.

The characteristics of structural damping reaction, which are also necessary for computation, are defined experimentally only by one value for each mode, as a rule, using a logarithmic decrement of oscillations. Its application for the computational scheme in the principal coordinates is maximally easy, the appropriate experimental value is used for each mode. The situation with the computational scheme in the method of finite elements is more complex, since a large-scale array of given data is general for all the modes, and the transition to principal coordinates arises only during the process of computation. Account must be taken of relatively low accuracy (and unstable state) to identify the damping reaction characteristics, a simplified view of their representation and, as a rule, dependence on the amplitude. The latter is referred to frequencies, due to the nonlinear condition of structure properties, especially flight controls. Therefore, a base scope of computations is essentially associated with the selected specific amplitudes.

Specifics of revising the computational dynamic scheme while investigating aeroelastic stability of the UAV with ASC

While investigating SL stability on frequencies of elastic UAV oscillations, frequency characteristics are the most obvious parameter. The frequency stability criterion of the closed loop by the frequency characteristics of the open loop embeds the hull characteristics by a factor as one of the elements (fig. 2). Subsequently, the stability margin, for example, by the modulus, is defined by AFC of each loop element, including the A/C hull. While measuring with activated but retarded control actuators (with zero signals at inputs), AFC and PFR virtually do not differ from the intensity of force on the controls or from the intensity of force on the hull in the axes section of control rotation. In any variant, while correcting, the accepted differences coincide explicitly with the permissible spread, e.g., of the complete open loop AFC. Thereby, under high stability the relatively considerable variation of the computational and experimental AFC is allowed.

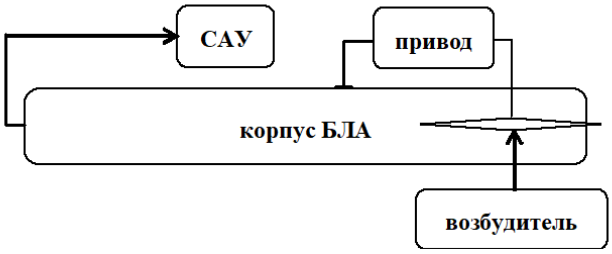

Fig. 2. Elements of the open loop of UAV stabilization

UAVs under consideration are, as a rule, axially symmetrical and, as mentioned above, have wings of small (ultra-small) elongation or do not have them at all (wingless design). Wings of these UAVs have high natural frequencies (as a general thing, several times larger than the frequency of the first bending mode of UAV hull). The dynamic properties of such high-speed maneuverable UAVs, which should be taken into consideration while developing the ACS stabilization system, are featured with bending transfer functions. So, when forming the stabilization system loop and selecting its basic parameters, it is sufficient to consider the dynamic properties of the elastic UAV hull.

The oscillating system “flexible UAV” is regarded linear; a rule of superimposition is applicable for this system, i.e., the UAV transfer function by the input effect (an angle of the control deflection) at the point of measurement (sensor installation) represents a sum of transfer function of an inflexible UAV and the dynamic response of a flexible UAV.

Transfer functions of the inflexible UAV as an object of pitch control by an angular rate ω and linear acceleration *W* (at locations of the rate gyro sensor (RGS) and linear accelerometer (LA) installation) are of the form of:

$$\mathbf{W}_{\omega}(p)\Big|_{x_{\text{ДУС}}} = \frac{\omega}{\delta}\bigg|_{x_{\text{ДУС}}} = \mp k_{\text{р}} \frac{1+T_{1\text{c}}p}{1+2\xi_{\text{р}}T_{\text{р}}p+T_{\text{р}}^{2}p^{2}}; \qquad (2)$$

$$\mathbf{W}_{W}(p)\Big|_{x_{\text{ДЛУ}}} = \frac{W}{\delta}\bigg|_{x_{\text{ДЛУ}}} = \mp Vk_{\text{р}} \frac{1}{1+2\xi_{\text{р}}T_{\text{р}}p+T_{\text{р}}^{2}p^{2}}, \qquad (3)$$

where

$$k_{\text{р}} = \frac{a_3a_4}{a_2+a_1a_4}; \quad T_{1\text{c}} = \frac{1}{a_4}; \quad \xi_{\text{р}} = \frac{a_1+a_4}{2\sqrt{a_2+a_1a_4}}; \quad T_{\text{р}} = \frac{1}{\sqrt{a_2+a_1a_4}}; \quad a_1 = -\frac{m_z^{\omega_z}qSL^2}{VI_z};$$

$$a_2 = -\frac{c_y^{\alpha}\left(\overline{x}_{\text{м}}-\overline{x}_{\text{д}}\right)qSL}{I_z}; \quad a_3 = \mp\frac{c_y^{\delta}\left(\overline{x}_{\text{м}}-\overline{x}_{\text{р}}\right)qSL}{I_z}; \quad a_4 = \frac{c_y^{\alpha}\,qS}{mV}+\frac{P}{mV};$$

V, q are UAV air speed and ram-air flow; $m_z^{\omega_z}$ is a rotary resistance derivative; c_y^{α}, c_y^{δ} are derivatives of the UAV lift coefficient by angles of attack α and the control deflection δ; P is engine thrust; $\overline{x}_{\text{м}}, \overline{x}_{\text{д}}, \overline{x}_{\text{р}}$ are the coordinates of mass centre, pressure centre and an axis of control rotation refferred to the UAV length L; m, I_z, S is the mass, moment of inertia and UAV reference area. In the given expressions, a “minus” mark conforms to the tailplane configuration, a “plus” mark corresponds to “the canard plan”.

The transfer functions, found by the expressions (2), (3), are obtained on the lift force negligibility conditions on controls (due to its insignificant effect in comparison with UAV lift force) and without considering Coriolis acceleration resulted from UAV rotation affected by jet blast. Taking into consideration the first, second hull bending modes, the complete UAV transfer functions are copied as follows [17]:

– the UAV transfer function by an angle rate at the location of RGS installation

$$\mathbf{W}_{\omega}(p)\Big|_{x_{\text{ДУС}}} = \frac{\omega(p)}{\delta(p)}\Bigg|_{x_{\text{ДУС}}} = \mp k_{\text{р}} \frac{1+T_{1\text{c}}p}{1+2\xi_{\text{р}}T_{\text{р}}p+T_{\text{р}}^2 p^2} + \sum_{i=1}^{2} \frac{p(k_{i1}+k_{i2}p^2)}{1+2\xi_i T_i p + T_i^2 p^2};$$

– the UAV transfer function by linear acceleration at the location of LA installation

$$\mathbf{W}_{W}(p)\Big|_{x_{\text{ДЛУ}}} = \frac{W(p)}{\delta(p)}\Bigg|_{x_{\text{ДЛУ}}} = \mp V k_{\text{р}} \frac{1+2\xi_W T_W p + T_W^2 p^2}{1+2\xi_{\text{р}}T_{\text{р}}p+T_{\text{р}}^2 p^2} + \sum_{i=1}^{2} \frac{k_i^W p^2}{1+2\xi_i T_i p + T_i^2 p^2}.$$

In the given expressions:

k_{i1}, k_i^W are non-dimentional factors considering an effect on UAV flexural mode (according to the first, second modes) of a normal force caused by controls deflection:

$$k_{i1} = \frac{Y^{\delta} f_i'(x_{\text{ДУС}}) f_i(x_{\text{р}})}{m_i \omega_i^2};$$

$$k_i^W = \frac{Y^{\delta} f_i(x_{\text{ДЛУ}}) f_i(x_{\text{р}})}{m_i \omega_i^2};$$

k_{i2} are the coefficients considering an effect on UAV flexural mode (corresponding to the first, second modes) of the inertia moment resulting from controls deflection:

$$k_{i2} = \frac{I_{\text{р}} f_i'(x_{\text{ДУС}}) f_i'(x_{\text{р}})}{m_i \omega_i^2};$$

ξ_i are damping coefficients of flexural modes of the hull structure (by the first, second modes) associated with the appropriate logarithmic oscilations decrements ν_i formulae $\xi_i = \dfrac{\nu_i}{2\pi}$;

$T_i = 1/\omega_i$;

Y^{δ} is the derivative of the UAV lift force by an angle of control deflection;

$I_{\text{р}}$ is the total momentum of controls inertia (e.g., for «+» scheme momentum of a pair of controls) in the general case considering the conrol actuator inertia;

$m_i = \int_0^L m(x) f_i^2(x)dx$ are UAV given masses by the first-second bending modes;

$m(x)$ is the distributed on UAV length mass;

ω_i, $f_i(x)$, $f_i'(x)$ are rotational frequencies, modes and derivatives of the first, second UAV eigenmodes.

Both in the problem for the study of ACS-fitted UAV aeroelastic stability and in the problem of computation for the UAV flutter, the essential factor is proximity of the hull and control frequencies, as well as the hull bending shape (represented in Figure 3 in the axes: amplitude A is a relative coordinate along the hull axis $\bar{x}$). However, unlike the flutter problem, the shape of hull bending is defined by a position not only of the node, proximate to the axis of controls rotation (parameter $f_i(x_{\text{р}})$), but of the node prox-

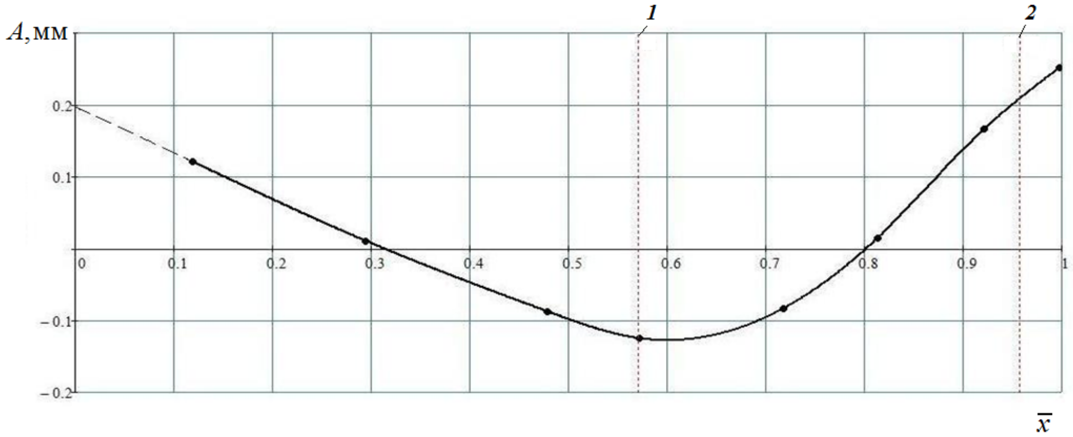

Fig. 3. Eigenmode of the first mode for UAV hull bending:
1 – hull cross section with ACS sensors; *2* – hull section corresponding to the position of the control rotation axis

imate to the hull section with ACS sensors. For this purpose, the basic parameters to revise the computational dynamic scheme are: $f_i(x_{ДЛУ})$, $f_i^{'}(x_{ДУС})$ are the shape and the derivative of UAV hull bending shape at the location of ACS sensors.

Example of the computational dynamic scheme revising

Let us consider an example of revising the computational dynamic scheme of a maneuverable UAV based on the results of ground modal tests. An unmanned aeronautical vehicle has a conventional aerodynamic configuration with the cruciform location of aerodynamic control surfaces. The UAV is equipped with the stabilization system with two feedbacks: by an angle rate and linear acceleration. For this UAV type, as noted above, loss of aeroelastic ACS-fitted UAV stability is typical along with flutter. The ACS sensors (RGS and LA) are in one unit (in one UAV hull section). For the reliable determination of stability boundaries, it is necessary to specify the computational transfer function of the flexible UAV obtained using the finite-element model based on the results of ground modal tests. As stated above, not only the close agreement of the natural oscillatory frequencies is important but also the proximity of eigenmodes, especially in the UAV hull section with ASC sensors.

In order to determine experimentally frequencies and natural modes of self-oscillations, a special simulator was used [18]. The simulator incorporates a power driver (electrodynamic – type exciters in the set with power amplifiers by TMS, USA); measurement means of oscillation parameters (accelerometers and impedance heads by PCB Piezotronics); a supervisory software-hardware system comprising a personal computer, real-time system of measurement and control CompactRIO (National Instruments, USA) and software to control test operations; portals for the UAV flexible suspension. By means of the simulator, the UAV modal test operations were conducted (more exactly, of the mass-size model, rigidity and mass-inertial properties of which coincide with a full-sized UAV). In particular, the first, second bending mode characteristics of the UAV hull were defined. In order to provide comparison of computational and experimental data of eigenmode, found experimentally, were normalized in the same manner as the computational ones.

Updating the finite-element UAV model was carried out using the criterion (1). At every stage of the process for revising the computational scheme, the proximity criterion of the computation and experiment results (h_1 is suggested equal to 1) was defined as for each of the analized bending modes as for the general one for the

Table 1

The results of revising the computational dynamic scheme

Type of data	**Iteration number**	**Generalized masses, kg m^2**		**Natural frequencies, Hz**		**Criterion (1)**
		1st mode	**2^d mode**	**1st mode**	**2^d mode**	
Experimental	–	25.03548	4.15003	44.37	123.40	–
Estimated	0	25.41704	3.90324	45.22	125.68	0.000411793
Estimated	1	24.96875	4.06949	44.59	124.14	0.000063079
Estimated	2	24.74110	4.10589	44.62	123.52	0.000035234
Estimated	3	24.72235	4.11829	44.33	123.44	0.000029396
Estimated	4	24.78914	4.11512	44.43	123.43	0.000003433
Estimated	5	24.86000	4.12423	44.35	123.41	0.000001065

both. Simulteniously, at every stage, the lack of deteriorating flexural mode values in the UAV hull cross section, in which ASC sensors are located, was monitored. The results of revising are represented in Table 1. The Table provides the UAV hull generalized masses and natural frequencies of the first, second bending modes obtained as a result of processing experimental data (the first line with the title "Experimental" in the column "Data type" and the same parameters of the computational dynamic model revised gradually for the purpose of minimizing the criterion (1) (the subsequent table lines with the title"Computational" in the same column).

A step process of adjusting rigidity distribution along the UAV hull (with stating iteria numbers) is shown in Figure 4. The physical parameters variation had an effect, although to a different degree, on the dynamic characteristics of the considered modes, but virtually did not affect the other modes. As Figure 4 illustrates, the first step in the process of correcting was efficient in terms of compensating the UAV hull first bending mode characteristics and inefficient from the point of view of compensating the second mode characteristics. It was concerned with selecting to revise the computational dynamic rigidity scheme in the area of antinode point of the UAV hull first bending mode. The opposite result was obtained at the second iteration of revising the computational dynamic scheme which was specified by the rigidity selection in the area of antinode point of the UAV hull second bending mode. The subsequent approximations showed rapid convergence of the process to revise the UAV computational dynamic scheme.

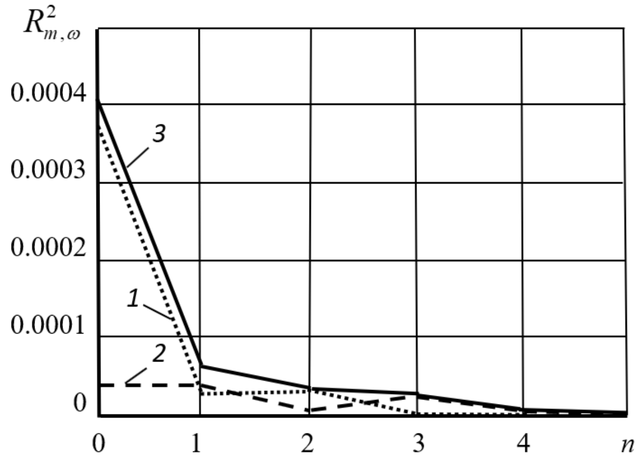

Fig. 4. Dependence of the criterion (1) on the iteration number: *1* – 1st mode, *2* – 2nd mode, *3* – both modes

Thus, in conformity with the considered approach within a small number of iterations *n,* the UAV computational dynamic scheme could be revised, based on the results of ground modal test operations, in order to solve the aeroelasticity problems, specifically, to study ASC-fitted UAV aeroelastic stability.

Conclusion

The problem of revising the UAV computational dynamic scheme, based on the results of ground modal test operations, in order to solve the problems of dynamic aeroelasticity associated with the assessment of “flexible A/C-ASC” loop stability and safety from flutter, is considered.

At the stage of design, when an UAV prototype or its units are not available, the determination of modal characteristics, specifically, of natural frequencies, modes and generalized masses is executed by means of the computational dynamic scheme developed according to the design documentation. Such a dynamic scheme does not provide us with reliable modal parameters of the elastic-mass structure model. Therefore, it is necessary to revise computations based on data of UAV ground test operations. Variants of revising the computational dynamic scheme are referred to natural frequencies, modes, generalized masses and frequency-response plots, specifically to quadratic criteria. Irrespective of this fact, there is a necessity to correlate the UAV hull experimental frequency-response plots from the section, corresponding to the position of controls rotation axis, to the section corresponding to the installation of ASC sensors. It is related to the fact, that a flexible hull as an element, forms a part of the UAV stabilization loop and significantly affects the value of stability margin by a module and phase margin (under the frequency stability criterion).

The example of revising the dynamic scheme of a maneuverable cruciform UAV, based on the results of ground modal test operations, in order to solve the problems of aeroelastic stability of the ASC-fitted UAV, is considered.

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Поступила в редакцию 10.03.2022
Принята в печать 24.05.2022

Received 10.03.2022
Accepted for publication 24.05.2022