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COMPUTER-AIDED DESIGN AT THE STAGE OF THE TECHNICAL APPEARANCE ANALYSIS OF AEROSPACE PLANE

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Abstract—*The method of solving the problem of technical appearance of aerospace plane is considered. The generalized criteria of estimation, restrictions and assumptions are given. The mathematical model of movement of an aerospace plane on rebound trajectory is described. The results of calculation of aerodynamic and trajectory characteristics of aerospace airplane with the use of proposed programs computer simulation are presented. The calculation of aerodynamic characteristics is performed using the computer simulation system ANSYS FLUENT. For the computer aerodynamic modelling the electronic three dimensional (3D) model of the speaker in the SolidWorks program, corresponding to the size and configuration of the general view drawing is developed. In the Workbench environment the calculation grid of the modeling area is developed, which together with the calculation grid of the surface of the modeling object is 1304186 knots and 7325935 elements.*

Index Terms—Aerospace plane; mathematical model; computer-aided design; rebound trajectory.

I. INTRODUCTION

With the expansion of human activities in the near space, it became apparent that the maintenance of orbital stations should be carried out by airplane-type aerospace vehicles.

The most cost-effective concept of a transport system for orbital stations is a system consisting of an aerospace plane (AP) and an acceleration rocket booster or launch vehicle. The aerospace plane delivers the goods and crew to the orbital station and returns to the ground in the planning mode after the target task is completed, and the acceleration rocket accelerator or booster launches the AP into the low orbit.

Design at the initial stages begins with the definition of the general appearance, mass and geometric dimensions of the AP, and ends with a synthesis of possible variants of the AP, differing aerodynamic scheme and layout. The final stage of the AP design is to evaluate the possible variants of the AP appearance according to the established criteria (parameters), taking into account the limitations.

The most important generalized parameters influencing the appearance of the AP are:

- planning parameter $\sigma_y = C_y / (G / S)$ – ratio of the lifting force coefficient on the flight angle of the attack to the unit load on the wing in the plan;
- lift-drag ratio $K = C_y / C_x$ – ratio of the coefficient of lifting force to the coefficient of force of the frontal resistance.

The σ_y and K parameters affect:

- temperature level (with the increase of the parameter σ_y the temperature of aerodynamic heating decreases);
- lateral range of descent $Z \sim K^2$;
- inclination of the landing glide $\theta \approx \mathrm{arctg}(1/K)$;
- landing velocity $V \sim \sqrt{2/\left(\rho\sigma_y\right)}$, where ρ is the density of the atmosphere.

The parameters σ_y and K are constrained as a permissible maximum normal overload of $n_{y_{\max}}$, which is assigned based on the physical capabilities of the person and the strength of the design of the AP.

For the selected variants of an AP the aerodynamic relat and balancing characteristics, and also longitudinal, lateral and on-list stability in the given range of numbers Mach stagnation airflow M_∞, angles of attack of α, sliding angles β and angles of the roll γ are calculated.

Checking of the selected variants of the speaker for compliance with the specified requirements and limitations is performed according to the results of mathematical modeling of the flight trajectory in the atmosphere taking into account the restrictions imposed on control functions and parameters trajectory.

The following is a mathematical model of the arc descent trajectory in the atmosphere with the results of the calculation of aerodynamic and trajectory characteristics of the AP, which can be used in the development of software for the CAD system.

II. BASELINE DATA AND CONDITIONS OF THE PROBLEM SOLUTION

As the object of the study is considered an AP, executed under the scheme "lifting body" (Fig. 1).

The aerospace plane is in orbit of the Earth satellite, the plane of which coincides with the plane of the equator. At some time the apparatus under the influence of the braking pulse of thrust descends from an orbit and with the known value of a vector of velocity approaches to a conditional boundary of an atmosphere before the beginning of a section of a descent trajectory.

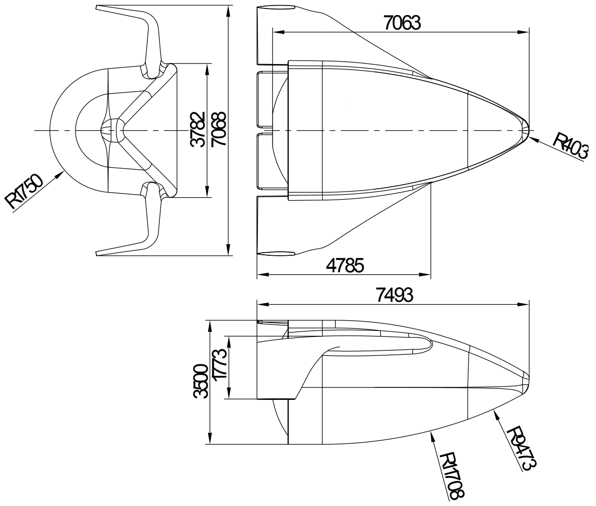

Fig. 1. General view of the AP

Control of the speaker on the descent path is carried out through two channels: by changing the velocity angle of the roll $\gamma_a(t)$ and the angle of attack $\alpha(t)$. When simulating the motion of an au on the descent trajectory of the program changes of the specified angles are selected from the conditions $10° \le \alpha(t) \le 45°$, $\gamma_a(t) \le 80°$ (according to statistics) and taking into account the limit on the maximum value of normal overload $n_{y_{\max}} \le 5$ (set).

As the initial conditions of movement at the moment of time $t = 0$ input of an AP in an atmosphere at height $H_0 = 100$ km the following values are accepted: earth velocity $V_0 = 7500$ m/s, the vertical angle of path $\theta_0 = -4°$, the horizontal angle of the path $\chi_0 = 0$, latitude $\varphi_0 = 0$ and longitude $\lambda_0 = 0$. The thrust of the mid-flight engine equals 0 (planning descent).

As a casting surface, the ellipsoid of the rotation (Krasovsky ellipsoid) with the center of the Earth, passing at a height of 20 km above the Earth's surface, is adopted.

The final longitude λ_{fin} to determines the final longitudinal range of descent $D_{\text{f.l}}$, and the final latitude of the φ_{fin} to determine the final crossrange $D_{\text{c.f}}$.

Aerodynamic characteristics of the AP are set in tabular and calculated in the calculation model of movement with the help of interpolation functions.

The parameters of the standard atmosphere are also tabled in accordance with the standard values [1].

The equations of motion took into account the nonsphericity field of gravity of the earth and its rotation around its own axis.

The return mass of the AP is $m_0 = 9600$ kg.

Because many AP and control parameters are not known at the initial design stage, the task should be simplified.

At the simplest statement of a problem when the speaker is considered as a material point, and its trajectory passes in one plane, from all aerodynamic coefficients it is enough to define factors of lifting force C_y, force of a frontal resistance C_x and the longitudinal moment m_z.

III. CALCULATION OF THE AERODYNAMIC CHARACTERISTICS OF THE AP

The calculation of aerodynamic characteristics is performed using the computer simulation system ANSYS FLUENT.

For the computer aerodynamic modelling the electronic three dimensional (3D) model of the speaker in the SolidWorks program (Fig. 2), corresponding to the size and configuration of the general view drawing (see Fig. 1) is developed.

In the Workbench environment the calculation grid of the modeling area is developed, which together with the calculation grid of the surface of the modeling object is 1304186 knots and 7325935 elements (Fig. 3).

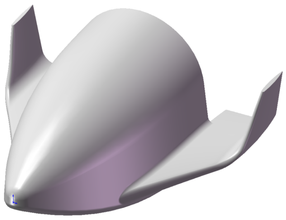

Fig. 2. 3D AP model

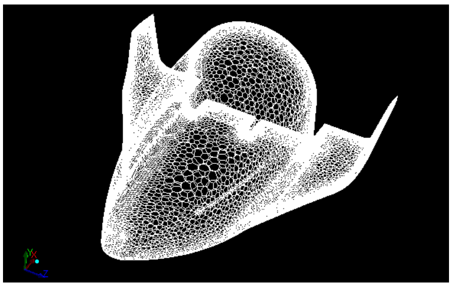

Fig. 3. Design grid of the AP model

The static pressure distribution fields on the AC surface for mach $M = 0.8$ and the angle of attack $\alpha = 24°$ are shown in Fig. 4, for the number of Mach $M = 1.5$ and the angle of attack $\alpha = 4°$ are shown in Fig. 5.

As a result of the simulation of the approach flow, the values of the aerodynamic force projections on the vertical axis of the *OY* and the longitudinal axis *OX* of the coupled coordinate system (CS), as well as the longitudinal aerodynamic moment relative to transverse axis *OZ* coupled CS, which serve to determine the aerodynamic coefficients.

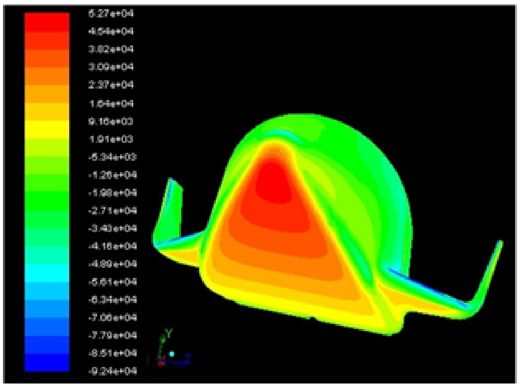

Fig. 4. Distribution of static pressure on the surface of the AP at $M = 0.8$ and $\alpha = 24°$

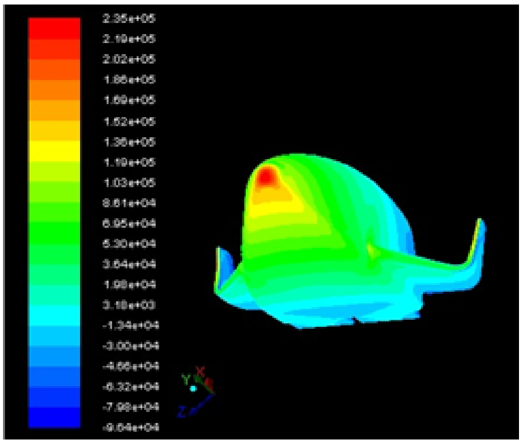

Fig. 5. Distribution of static pressure on the surface of the AP at $M = 1.5$ and $\alpha = 4°$

The coefficient of frontal resistance of the C_x and lifting force C_y in the coupled CS, as well as the coefficient of longitudinal moment m_z determined by the formulas:

$$C_x = (2X)/(\rho_h V^2 S_{\text{mid}}),$$

$$C_y = (2Y)/(\rho_h V^2 S_{\text{mid}}),$$

$$m_z = (2M_z)/(\rho_h V^2 S_{\text{mid}} L_f),$$

where X is the force of the frontal resistance in the coupled CS; Y is the lifting force in the coupled CS; M_z is the longitudinal moment relative to the transverse axis *OZ* the coupled CS; ρ_h is the density of the atmosphere at the given altitude; V is the velocity of the approach flow; S_{mid} is the characteristic area; L_f is the characteristic length.

The conversion of aerodynamic forces from the coupled CS into velocity CS is performed by the following formulas:

$$C_{xa} = C_x \cos\alpha + C_y \sin\alpha,$$

$$C_{ya} = C_y \cos\alpha - C_x \sin\alpha,$$

where C_{ya} is the coefficient of lifting force in the velocity CS, C_{xa} is the coefficient of force of the frontal resistance in velocity CS, α is the angle of attack.

The degree of longitudinal static stability of the AP is determined by the formula: $m_z / C_y = -(x_{\text{c.p}} - x_{\text{c.m}}) / L_f$, where $x_{\text{c.p}}$ is the center of pressure of the AP, $x_{\text{c.m}}$ is the position of the AP mass centre.

Aerodynamic quality of the speaker is determined by the formula: $K = C_{ya} / C_{xa}$.

Graphs of the dependencies of aerodynamic forces and moment and the maximum aerodynamic quality in the velocity CS are shown in Figs 6 and 7.

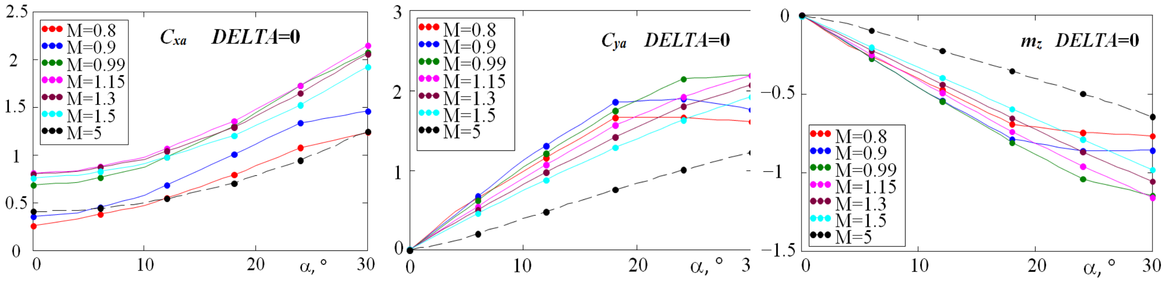

Fig. 6. Coefficients C_{xa}, C_{ya} and m_z depending on angles of attack and referenced numbers of Mach (at fixed rudders)

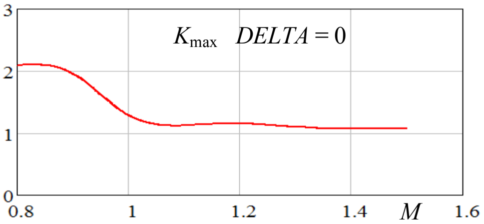

Fig. 7. Maximum lift-drag ratio AP $K_{\max}$ depending on referenced Mach numbers (at fixed rudders)

IV. CALCULATION OF THE DESCENT TRAJECTORY IN THE ATMOSPHERE

A. Model of the AP movement

The type of equations of movement of the center of mass AP is determined by the selected CS and composition of the active forces. In the mathematical model under consideration, the speaker moves above the surface having the form of an ellipsoid of rotation with the equatorial radius $R_e = 6378.160$ km and the polar radius $R_p = 6356.863$ km (Krasovsky ellipsoid). The movement of the AP relative to the Earth takes place under the influence of gravitational force, full aerodynamic force, thrust force of engines and forces caused by noninertial system of reference. The system of differential equations of motion in the trajectories CS taking into account the rotation of the Earth, the noncentrality of gravity and in the absence of wind in the atmosphere, supplemented by the equation of mass change AP, has the form [2]–[4]:

$$\dot V = -\sigma_x \rho V^2 - g_r \sin\theta + g_z \sin\chi\cos\theta + \frac{P_x}{m} + R\Omega^2\cos\varphi(\sin\theta\cos\varphi - \cos\theta\sin\varphi\sin\chi),$$

$$\dot\theta = \sigma_y \rho V\cos\gamma_a + \left(\frac{V}{R} - \frac{g_r}{V}\right)\cos\theta - \frac{g_r}{V}\sin\chi\sin\theta + \frac{P_y}{Vm} + 2\Omega\cos\varphi\cos\chi + \frac{R\Omega^2}{V}\cos\varphi \cdot (\cos\theta\cos\varphi + \sin\theta\sin\varphi\sin\chi),$$

$$\dot\chi = -\frac{\sigma_y \rho V}{\cos\theta}\sin\gamma_a - \frac{V\cos\theta}{R}\mathrm{tg}\varphi\cos\chi + g_z\frac{\cos\chi}{V\cos\theta} - \frac{P_z}{mV\cos\theta} - 2\Omega(\sin\varphi - \cos\varphi\sin\chi\,\mathrm{tg}\,\theta) - \frac{R\Omega^2}{V\cos\theta}\sin\varphi\cos\varphi\cos\chi,$$

$$\dot R = V\sin\theta,$$

$$\dot\varphi = \frac{V\cos\theta}{R}\sin\chi,$$

$$\dot\lambda = \frac{V\cos\theta}{R}\frac{\cos\chi}{\cos\varphi},$$

$$\dot m = -m_c,$$

where V is the Earth velocity (in the absence of wind coincides with the air); θ is the angle of inclination of the trajectory; χ is the angle of the path; φ is the geographical latitude; λ is the geographic longitude; m is the weight of the airplane; m_c is the throughput weight fuel; ρ is the density of the atmosphere; $\Omega \approx 0.727 \cdot 10^{-4}$ s^{-1} is the angular velocity of the rotation of the Earth around its axis.

The radial and transversal components of the gravitational acceleration vector $\dot g$, lying in the meridian plane, are determined by the formulas [1]:

$$g_r = \frac{3.9861679 \cdot 10^{14}}{R^2} - \frac{3}{2} \cdot \frac{\frac{2}{3} \cdot 26.32785 \cdot 10^{24}}{R^4}(5\sin^2\varphi - 1),$$

$$g_z = 3 \cdot \frac{\frac{2}{3} \cdot 26.32785 \cdot 10^{24}}{R^4}\sin\varphi,$$

where g_r is the radial component of the gravitational acceleration vector; g_z is the transversal component of the gravitational acceleration vector; R is the distance from the center of the Earth to the AP.

The projections of the thrust force vector of engines, rigidly fixed and oriented along the longitudinal axis of the AP, are calculated according to the following formulas:

$$P_x = P\cos\alpha;\ P_y = P\sin\alpha\,\cos\gamma_a;\ P_z = P\sin\alpha\,\sin\gamma_a,$$

where $P = P_{\text{sp}}\, m_c$ is the force of engine thrust; P_{sp} is the specific thrust.

The coefficients σ_x, σ_y and aerodynamic quality K are determined by the following formulas:

$$\sigma_x = \frac{C_{xa}S}{2m},\quad \sigma_y = \frac{C_{ya}S}{2m},\quad K = \frac{C_{ya}}{C_{xa}},$$

where C_{xa}, C_{ya} are the coefficients of aerodynamic force of frontal resistance and lifting force in velocity CS; S is the characteristic area of AP.

B. Calculation of trajectory parameters

The Mach number is calculated as the ratio of the air velocity of the AP, which in the absence of wind coincides with the velocity relative to the Earth, and the sound velocity at this altitude: $M = V/a$, where sound velocity a is associated with the air temperature T ratio: $a = 20.0463\sqrt{T}$.

Altitude H over the surface of the Earth, which has the form of an ellipsoid of rotation with the above parameters, is calculated by the formula:

$$H = R - \frac{R_p}{\sqrt{1 - 0.0066934\cos^2\varphi}}.$$

The components of the overload vector in the projections on the connected longitudinal and normal axis of the AP are determined by the ratios:

$$n_x = \frac{P}{g_0 m} + \frac{S}{g_0 m}\frac{\rho V^2}{2}\left(C_{ya}\sin\alpha - C_{xa}\cos\alpha\right),$$

$$n_y = \frac{S}{g_0 m}\frac{\rho V^2}{2}\left(C_{ya}\cos\alpha + C_{xa}\sin\alpha\right),$$

where $g_0 \approx 9.81$ m/s^2 is the gravitational acceleration on the Earth's surface.

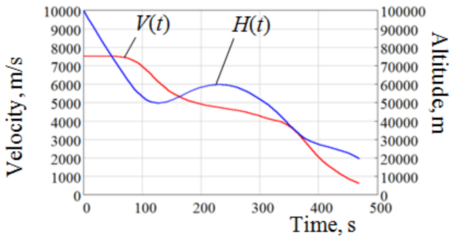

Fig. 8. Velocity $V(t)$ and altitude $H(t)$ depending on time

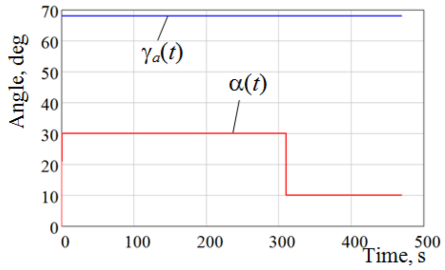

Fig. 10. Velocities angle of bank $\gamma_a(t)$ and angle of attack $\alpha(t)$ variation program depending on time

Final longitudinal distance $D_{\text{l.f}}$, km:

$$D_{\text{lf}} = (R_e + 20)\lambda_{\text{fin}} = (6378.16 + 20)\frac{17.64}{57.3} = 1970,$$

where R_e is the equatorial radius of Earth; λ_{fin} is the final angle of geographical longitude.

Final crossrange $D_{\text{c.f}}$, km:

$$D_{\text{cf}} = (R_1 + 20)\varphi_{\text{fin}} = (6376 + 20)\frac{5.68}{57.3} = 635,$$

where R_1 is the radius of Earth inplane local meridian; conducted from a center Earth under the corner of 5.68° (Fig. 12); φ_{fin} is the final angle of geographical latitude.

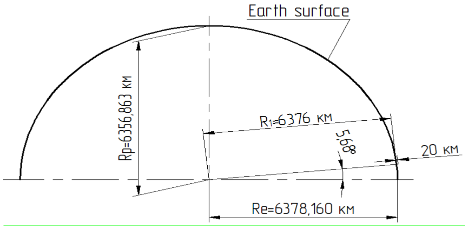

Fig. 12. Krasovsky ellipsoid

When an AP enters the atmosphere at a velocity close to the first cosmic velocity (8000 m/s) there is a phenomenon of aerodynamic heating. This leads to great temperatures on its surface and can lead to the destruction of the structure. To reduce the influence of this factor, a rebound trajectory was chosen as the descent path. At such a decrease the AP "is reflected" from dense layers of atmosphere and gradually resets velocity at each "reflection". This allows it to cool when moving on the upper sections of the trajectory, dispelling energy in the form of radiation.

The simulation results are shown in Figs 8–11.

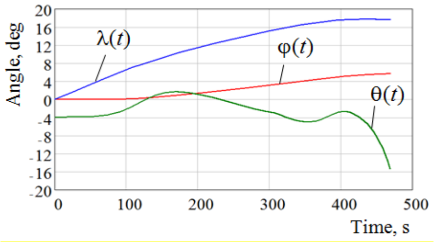

Fig. 9. Angle of flight path $\theta(t)$, angle geographical latitude $\varphi(t)$ and geographical longitude $\lambda(t)$ depending on time

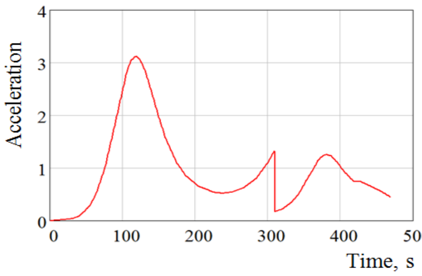

Fig. 11. Projection of cross-axis acceleration force vector $n_y(t)$ depending on time

V. RESULTS

As a result of modeling the AP motion during descent in the atmosphere, the following parameters were obtained at the final of the descent: height $H_{\text{fin}} =$ = 20 km; speed V_{fin} = 565 m/s; angle of inclination of the trajectory $\theta_{\text{fin}} = -15°$; latitude angle φ_{fin} = 5.68; angle of geographical longitude λ_{fin} = 17.64; maximum vertical overload $n_{y\max}$ = 3.14; longitudinal range D_{long} = 1970 km; lateral range D_{lat} = 635 km.

The values of the parameters of the AP movement at the end of the descent trajectory are obtained taking into account the restrictions imposed on the control dependences of the angle of attack $\alpha(t)$ and roll angle $\gamma_a(t)$, as well as the maximum value of normal overload $n_{y\ \max}$. However, the restrictions that should be imposed on other parameters of motion, for example, on the final speed, were not taken into account V_{fin}, trajectory final angle θ_{fin}, at maximum speed head $q_{\max}$ and heat flow at a critical point on the surface of the speaker $q_{\text{h max}}$.

Since the descent trajectories with rebound are unstable in the sense that they can significantly change their profile with a small change in the control dependences in the process of descent control [2], in addition to the above conditions, when the AP is descent in the atmosphere, the dependence of the altitude on time should also be limited: $H_j^{\max} - H_j^{\min} \le \Delta H_{j\ \text{per.}}, j \le j_{\max}$, where $H_j^{\max}$, $H_j^{\min}$ are maximum and minimum rebound heights; $\Delta H_{j\text{per}}$ is the acceptable rebound value; j is the total number of bounce paths.

VI. CONCLUSIONS

The necessity of computer-aided design at the aerospace technical appearance is proved.

For the problem solution it is used the computer simulation system ANSYS FIUENT, SolidWorks program. The use of this software permitted to get good results for given example.

The values of the final longitudinal and lateral ranges, taking into account all the above restrictions imposed on the parameters of the AP motion during descent in the atmosphere, may differ from those originally obtained in the direction of decreasing.

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А. В. Брикалов. Автоматизоване проектування на етапі технічного аналізу зовнішнього вигляду аерокосмічного літака

Розглянуто спосіб розв'язання задачі оцінювання технічного вигляду аерокосмічного літака. Наведено узагальнені критерії оцінювання, обмеження і допущення. Описано математичну модель руху аерокосмічного літака за траєкторією рикошету. Представлено результати розрахунку аеродинамічних та траєкторій характеристик аерокосмічного літака із застосуванням запропонованих програм комп'ютерного моделювання. Розрахунок аеродинамічних характеристик виконується за допомогою системи комп'ютерного моделювання ANSYS FLUENT. Для комп'ютерного аеродинамічного моделювання розроблена електронна тривимірна (3D) модель аерокосмічного літака в програмі SolidWorks, що відповідає розміру та конфігурації загального виду малюнка. У середовищі Workbench розроблена обчислювальна сітка області моделювання, яка разом із обчислювальною сіткою поверхні об'єкта моделювання становить 1304186 вузлів та 7325935 елементів.

Ключові слова: аерокосмічний літак; математична модель; комп'ютерне проектування; траєкторія рикошету.

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А. В. Брикалов. Автоматизированное проектирование на этапе технического анализа внешнего вида аэрокосмического самолета

Рассмотрен способ решения задачи оценки технического облика аэрокосмического самолета. Приведены обобщенные критерии оценки, ограничения и допущения. Описана математическая модель движения аэрокосмического самолета по рикошетирующей траектории. Представлены результаты расчета аэродинамических и траекторных характеристик аэрокосмического самолета с использованием предложенных программ компьютерного моделирования. Расчет аэродинамических характеристик выполняется с использованием системы компьютерного моделирования ANSYS FLUENT. Для компьютерного аэродинамического моделирования разработана электронная трехмерная (3D) модель аэрокосмического самолета в программе SolidWorks, соответствующая размеру и конфигурации чертежа общего вида. В среде Workbench разработана расчетная сетка области моделирования, которая вместе с расчетной сеткой поверхности моделирующего объекта составляет 1304186 узлов и 7325935 элементов.

Ключевые слова: аэрокосмический самолет; математическая модель; компьютерное проектирование; траектория рикошета.

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