METHODS OF AERODYNAMIC DESIGN OF SPACE DESCENT VEHICLES

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Optimal configuration of a space vehicle (SV) is determined through synthesis of engineering design results obtained on some general directions taking into account the most complete agreement with given performance criteria. Aerodynamic design of SV – a component of aerothermoballistic analysis – is an important stage of the vehicle development. It consists in selection of a class of geometric shapes, which satisfy requirements of its functionality and ballistics, and then – choice of rational configuration from found class that complies best with requirements imposed on SV aeroballistic parameters, stability, control capability, sensibility to varied center of gravity, minimization of balancing weight, and also requirements specific for particular vehicle

Different aspect of SV aerodynamic development are presented in works [1-13]. Let's discuss methods of aerodynamic design concerned with selection of rational configuration for a space vehicle with weight balancing adjustment in flight. In this case the space vehicle is self-established at required trim angle $\alpha_б$ under effect of outside aerodynamic load due to definite position of the vehicle center of gravity in its volume $C_T(x_T, y_T, z_T)$.

At the main part of the descent trajectory the space vehicle moves with hypersonic velocity. Therefore its aerodynamic development is to be carried out for Mach numbers M≥6 and then extended for the whole variation range of SV flight velocities.

For ballistic calculations it is natural to examine aerodynamic characteristics (ADC) of the vehicle in air-path coordinates $OX_aY_aZ_a$.

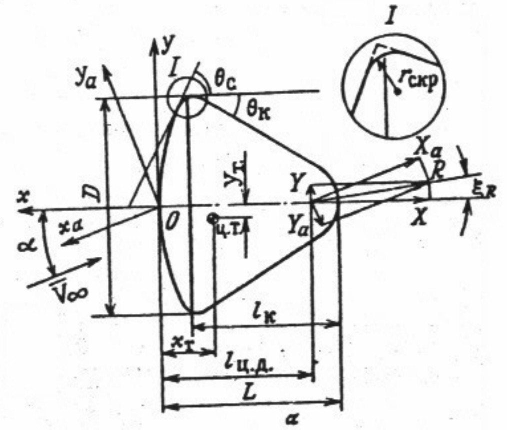


Fig.1. Space vehicle of segmental-conical configuration

But during selection of SV configuration it is more convenient to use body-axis coordinates $OXYZ$, which coincide with or are close to construction axes.

Let's illustrate procedure for selecting rational configuration of the descent vehicle from chosen class of bodies with drag and lifting nose part, for example segmental-conical shape shown in Fig.1.

Definition of a domain of possible geometrical parameters

Let's define region of geometric parameters of the descent vehicle that correspond to required values of its aeroballistic parameters (ABP): load acted on midsection – P_x, and lift-to-drag ratio – $K_б$.

ABP values are determined in the course of ballistic calculation of the space vehicle movement. So, required value for P_x is found from the condition of sufficiently effective drag of the vehicle. Then admissible values for drag coefficient $c_{xa} \leq G/P_x{\cdot}S_м$ are found, where G, $S_м$ – the vehicle weight and midsection area. SV lift-to-drag ratio K_t at trim angle of attack, in particular, must satisfies requirements imposed on admissible level of g-load, range of SV flight in atmosphere and possibility to accomplish side maneuver.

Fig. 2 illustrates the dependency $K(C_{xa})$ for the descent vehicle that is plotted with

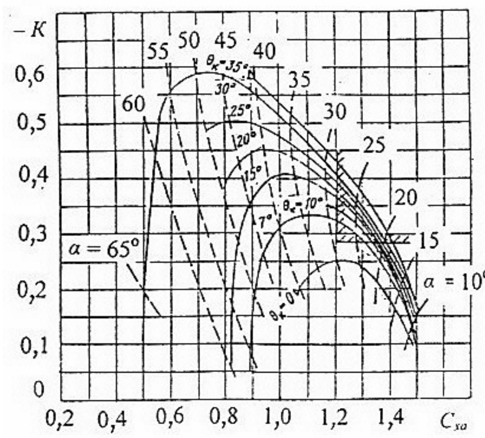


Fig.2. Drag coefficient and lift-to-drag ration for segmental-conical bodies

known aerodynamic characteristics of segmental-conical bodies at Mach number M_∞=6. Lines of limiting values for the parameters C_{xa} and K mark out a domain of values with admissible combinations of the body geometry, for example, $\theta_к \geq 7^o$, $\lambda_к \leq 0.9$ at $\theta_c = 60^o$[1].

Definition of a domain of admissible centres of gravity

A domain of admissible centers of gravity for each of considered vehicles with prescribed geometrical parameters is determined from conditions of required trim lift-to drag ratio $K_б$ and provision of its directional stability at trim angle of attack $\alpha_б$ basing on equations for the line of the vehicle centers of gravity and for degree of its directional stability [1, 3, 11, 13].

$$\bar{y}_T = \bar{y}_{on} + (\bar{x}_T - \bar{x}_{on})(c_y / c_x) + (m_{z.on} / c_x),(1)$$

$$\bar{x}_T = \bar{x}_{on} - \frac{(m_{z.on}/c_x)c_x^\alpha - (m_{z.on}^\alpha - m_{zT}^\alpha)}{(c_y/c_x)c_x^\alpha - c_y^\alpha}, (2)$$

which comprise coefficients of aerodynamic forces and moments and also their derivatives with respect to the angle of attack. All aerodynamic characteristics in (1) and (2) correspond to required trim angle of attack $\alpha_б$ (indices *on* refer to moment coefficients based on known reference point $C_{on}(x_{on}, y_{on}, z_{on})$). In practice it is convenient to analyze "diagrams of directional stability" of the vehicles with considered combinations of geometrical parameters plotted for the equations (1) and (2).

As an example, the diagram of directional stability for a segmental-conical body with geometrical parameters corresponding to the domain of required aeroballistic parameters is shown in Fig.3.

The equation for the line of the centers of gravity (1) gives linear relation between longitudinal and normal coordinates $\bar{x}_T, \bar{y}_T$ with known aerodynamic characteristics c_x, c_y, $m_{z.on}$ at

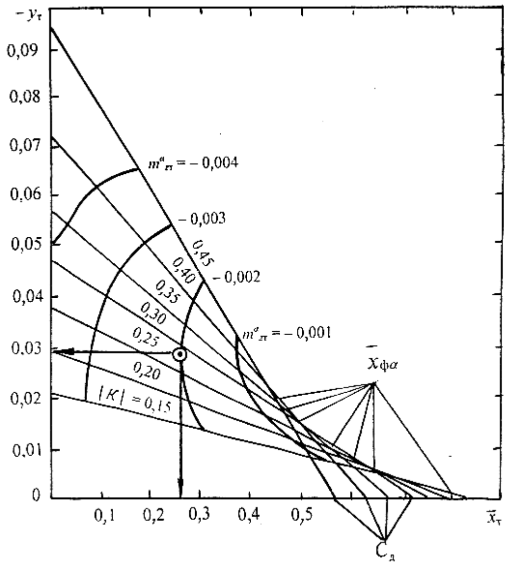


Fig. 3. Typical diagram of directional stability characteristics for the space vehicle with weight balance in flight

required trim angle of attack $\alpha_б$. The line of the centers of gravity presents all possible combinations of longitudinal and normal relative coordinates $\bar{x}_T, \bar{y}_T$ of the vehicle center of gravity that correspond to condition of its trimming at required angle α_T, so it is a line of the resultant aerodynamic force R_A action at the above angle (see Fig.1). Points of intersection between the line of the center of gravity $\bar{y}_T(\bar{x}_T)$ and X-axis are "the centers of pressure" as the points of intersection between the line of the resultant force action and the body longitudinal axis.

The equation for degree of static stability (2) defines a linear dependence between the longitudinal coordinate of the vehicle center of gravity $\bar{x}_T$ and stability degree m_{zT}^{α} at trim angle of attack $\alpha_б$. If these data are laid over the lines of the vehicle centers of gravity $\bar{y}_T(\bar{x}_T)$, we get a diagram of the vehicle static stability (see Fig.3). It is seen in the diagram that degree of the vehicle stability $\left|m_{zT}^{\alpha}\right|$ decreases when the center of gravity is displaced along the line of centers of gravity towards the vehicle base. Neutral stability $m_{zT}^{\alpha} = 0$ for rather blunted segmental conical body is reached significantly earlier than the point C_T comes to "the center of pressure".

The diagram of directional stability of the space vehicle demonstrates visually the domain of its center of gravity, which satisfies condition for the vehicle static stability, i.e. required lift-to-drag ratio K_T at admissible degree of static stability m_{zT}^{α} at trim angle of attack. Procedure for determining this center of gravity is shown in Fig.3 by arrows.

Determination of a degree of side stability for the descent vehicle at trim angle of attack

Comparative assessment of examined variant of space vehicles with respect to static stability is convenient to make using for each space vehicle "diagrams of static stability" constructed through the following equations [3, 11, 13]:

$$m_{yT}^{\beta} = m_{y.on}^{\beta} + \left(\bar{x}_T - \bar{x}_{on}\right) \times \times \left[\left(c_z / c_x\right)c_z^{\beta} - \left(m_{y.on} / c_x\right)c_x^{\beta}\right] \quad (3)$$

$$m_{zT}^{\beta} = m_{z.on}^{\beta} + \left(\bar{x}_T - \bar{x}_{on}\right)\left[\left(\frac{c_z}{c_x}\right)c_y^{\beta} - \left(\frac{c_y}{c_x}\right)c_z^{\beta}\right] - -\left[\left(\frac{m_{y.on}}{c_x}\right)c_y^{\beta} + \left(\frac{m_{y.on}}{c_x}\right)c_y^{\beta} + \left(\frac{m_{z.on}}{c_x}\right)c_z^{\beta}\right] \quad (4)$$

Exemplary diagram for side stability of one of examined space vehicles is shown in Fig.4.

Linear dependencies $m_{yT}^{\beta}(\bar{x}_T)$ are described by the formula (3). Curves of equal values for the derivative m_{xT}^{β} are found from the relation (4). Coordinates for the points of interaction between straight lines $m_{yT}^{\beta}(\bar{x}_T)$ and the abscissa axis, meeting the condition $m_{xT}^{\beta} = m_{yT}^{\beta} = 0$, describe limiting position of the vehicle center of gravity where the vehicle has neutral stability with respect to the slip angle β.

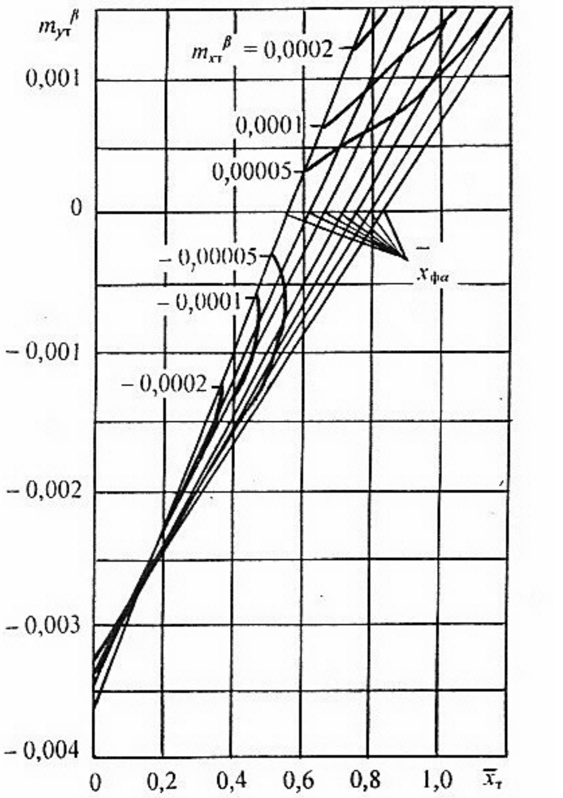


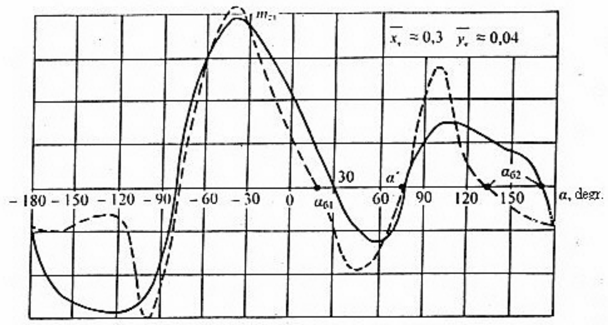
Fig.4. Typical diagram of side stability characteristics for a space vehicle

A region with negative values for both m_{yT}^{β} and m_{xT}^{β} is below the abscissa axis. The coordinates $\bar{x}_T$ for points in this region comply with conditions of side static stability of the vehicle.

Analysis of signs and values of the derivatives m_{yT}^{β} and m_{xT}^{β}, which correspond (at the diagram of side stability) to longitudinal coordinate $\bar{x}_T$ of the center of gravity that was found for examined configuration from the diagram of directional stability (Fig.3), permits to estimate stability degree of SV with such configuration with respect to the slip angle β and to exclude it from further examination if static stability is inadequate.

Rating of SV variants regarding characteristics of its stability margin

During descent of a space vehicle some disturbances may appear that cause deviation



——— - M_∞>>1; ----- - - M_∞<1

Fig. 5. Pitch moment coefficient (θ_c=60…70°; θ_k>15°; λ_k≤1)

of trim angle of attack. Characteristics of stability margin follows from analysis of typical dependency for pitch moment coefficient m_{zT} of segmental-conical vehicle plotted in Fig.5 against angle of attack α for hypersonic velocities. The space vehicle has two points of stable equilibrium where $m_{zT} = 0, m_{zT}^{\alpha} < 0$, in other words, it has two trim angles of attack $\alpha_{б1}$ and $\alpha_{б2}$, for example, 30° and 170°. So the space vehicle may pass from its main trim angle $\alpha_{б1}$ to inadmissible angle of attack $\alpha_{б2}$, if it deflects at an angle $\Delta\alpha > (\alpha' - \alpha_{б1})$ under influence of strong disturbance, α' – the angle of attack at a state of unstable equilibrium at $m_{zT} = 0$, $m_{zT}^{\alpha} > 0$.

Restoring pitch moment M_{zm} and longitudinal damping moment $M_z^{\omega z}$ impede the space vehicle from its deviation from the angle $\alpha_{б1}$. Here the moments do work, which maximum quantity may equal [13]:

$$A_1 = -S_x \ell_x \Big[\int_{\alpha_{б1}}^{\alpha'} q_\infty \cdot m_{zT}(\alpha) d\alpha + \int_{\alpha_{б1}}^{\alpha'} q_\infty \cdot \left(m_{zT}^{\omega_Z} \cdot \omega_Z + m_{zT}^{\dot{\alpha}} \cdot \dot{\alpha} \right) d\alpha \Big], \quad (5)$$

where S_x, l_x, q_∞ - reference area, reference length and dynamic pressure; m_{zT} – pitch moment coefficient, $m_z^{\omega_z}$ and $m_z^{\dot{\alpha}}$ - rotational derivatives with respect to angular velocity ω_z

of the vehicle motion and rate of change for its angle of attack.

Usually dynamic stability of space vehicle at hypersonic velocities is rather small, so it is sufficient to examine static stability only. And if variation of dynamic pressure in a short period of time is considered to be negligible, then the formula (5) may be simplified as [3, 11, 13]:

$$\overline{A}_1 = -\int_{\alpha_{б1}}^{\alpha'} m_{zT}(\alpha) d\alpha \qquad (6)$$

Expression (6) is a characteristic of "static stability margin" for the space vehicle at the primal trim angle of attack $\alpha_{б1}$ at hypersonic velocities. It may be used during trade-off of the vehicle rational configuration. Fig.6 presents $\overline{A}_1$ values for several segmental-conical

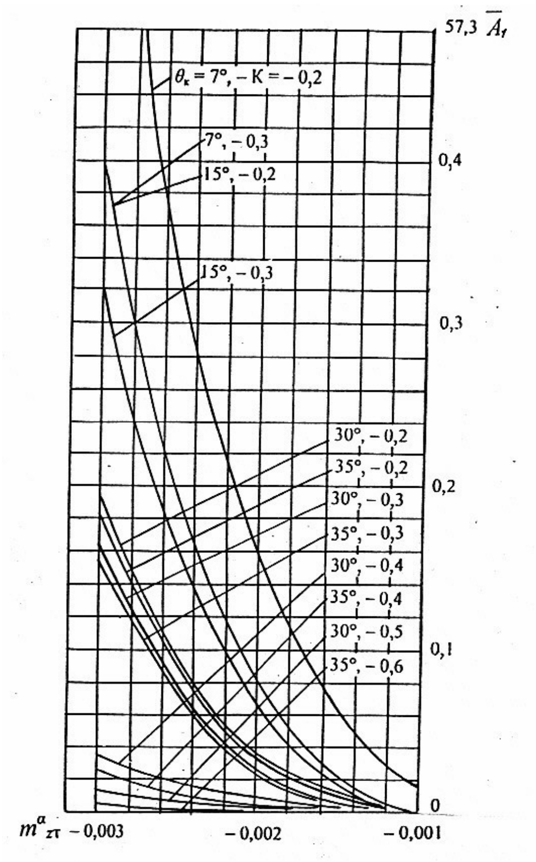


Fig.6. Normalized work of restoring pitch moment versus degree of directional stability

configurations plotted against degree of stability m^{α}_{zT}. It is seen that stability margin $\overline{A}_1$ reduces when semi-vertex angle $\theta_к$ of conical body and required lift-to-drag ratio $|K_б|$ increases.

Feature of the vehicles with geometrical or mass asymmetry is possibility to transit to regime of autorotation with respect to transverse axis in case of strong disturbing influence on SV, for example non-oriented entry of a vehicle into dense atmosphere with large initial angle of attack [14]. This is caused by non-symmetric function $m^{\alpha}_{zT}(\alpha)$ respectively to the point $\alpha_{б1}$ (see Fig.5); therefore the following integral [3,13]

$$\overline{A}_2 = \int_{\alpha_б}^{\alpha_б + 2\pi} m_{zT}(\alpha) d\alpha \qquad (7)$$

may be used as SV characteristic of "static stability margin" too.

Calculations on dynamics of the vehicle motion with respect to its center of mass have shown that depending on behavior and level of disturbing factor there is a certain limiting value $\overline{A}_{2\,\lim}$ of the integral (7) in the view of excluding transition of SV to regime of auto-rotation.

Rating of DV variants regarding sensitivity of aeroballistic parameters of the vehicle to variation of its center of gravity

While the space vehicle is being manufactured and then during its flight (due to heat protection ablation, fuel consumption in control system, and others) some displacement of its center of gravity with respect to nominal position may take place at values $\Delta\overline{x}_T, \Delta\overline{y}_T, \Delta\overline{z}_T$ that causes variation of trim angle of attack, i.e. vehicle retrimming, and, consequently, undesirable variation of aeroballistic parameters. In this connection the sensitivity of aeroballistic parameters of the vehicle to variation of its center of gravity may be also taken into consideration during trade-off of the vehicle rational configuration.

Variation of aeroballistic parameters due to displacement of the vehicle center of gravity is estimated by the following formulas [3, 13]:

$$\Delta\alpha_б = \frac{-c_{xб}\Delta\bar{y}_T + c_{yб}\Delta\bar{x}_T}{m_{zT}^{\alpha} - c_{xб}^{\alpha}\Delta\bar{y}_T + c_{yб}^{\alpha}\Delta\bar{x}_T} \qquad (8)$$

$$\Delta P_x / P_x = \left\{1 + \left[\left(c_{xб}^{\alpha} / c_{xб}\right)\Delta\alpha_б\right]^{-1}\right\}^{-1} \qquad (9)$$

$$\Delta K_б / K_б = \left(K^{\alpha} / K_б\right)\Delta\alpha_б, \qquad (10)$$

where aerodynamic coefficients and their derivatives at trim angle of attack are marked by index "б".

The lower is degree of the vehicle static stability m_{zT}^{α} at nominal trim angle of attack $\alpha_{б1}$, the greater is change of trim angle of attack for segmental-conical configuration due to longitudinal displacement of the center of gravity.

Rating of DV variants regarding required balance weight

Measures for providing required center of gravity $C_T(x_T, y_T, z_T)$ necessary for the vehicle trimming at prescribed angle of attack may include mounting a specific balance weight in the vehicle body. Relative value of the balance weight may be estimated at the stage of preliminary choice of space vehicle rational configuration by the next formula [13]:

$$\bar{G}_б = \frac{(\bar{x}_З - \bar{x}_T) - 0.5K_{WП}(\bar{x}_З - \bar{x}_П)}{\bar{x}_T - \bar{x}_б}, \qquad (11)$$

where $\bar{x}_П$, $\bar{x}_З$, $\bar{x}_T$, $\bar{x}_б$ – relative coordinates for volumes of the vehicle forebody and afterbody, and centers of gravity of the vehicle and balance weight, and $K_{WП}$ – a ratio of double volume of forebody to total volume of the vehicle.

Conclusion

Several methods of aerodynamic design of space vehicles with balance weight applied during trade-off of rational configuration are presented.

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