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Effect of the spherical hollow space on the aircraft path

The paper shows the research results of the effect of a spherical hollow space on the aircraft flight path. By flow simulation of the hollow space, there was plotted an analytical dependence of the surface pressure force on the parameters of the oncoming gas flow. The aircraft deflection caused by the presence of a spherical hollow space is estimated depending on its position, the initial speed of flight and the pitch attitude.

Keywords: hypersonic aircraft, flight path, aerodynamic resistance, eddy simulation.

Introduction

The development of hypersonic aircraft (A/C) and manned transportation reentry vehicles involves an in-depth analysis of the high-velocity gas flow process around the structure. The aerodynamic characteristics of the aircraft or spacecraft must be determined with a high accuracy. Moreover, it is required to investigate the influence of various geometric elements of the structure surface (shoulders, projections, cuts, typical sizes of which are much smaller than structural sizes) on the flow around the aircraft structure and, therefore, their influence on aircraft flight.

The papers [1, 2] give a summary of multiple experimental and numerical investigations related to separated flows, plus a detailed description of the gas flow physics in cavities and around shoulders. The papers describe calculation methods that allow to determine the pressure in a small area on the surface of a hollow space (hereinafter – the hollow space), for example, near the edge. However, it is difficult to use these calculations for determining the pressure force on the hollow space surface. According to pressure distribution graphs represented in [1], we may estimate the type of dependence by the length of the hollow space for different Mach numbers, but it is impossible to obtain the dependence in an analytical form.

Experimental and numerical studies of the cavity flow are described in [3]. The paper shows the dependence of the pressure in the cavity and the skin friction coefficient upon the temperature factor, oncoming flow Mach number and cavity configuration. According to the paper, during formation of the flow in the cavity with a shock wave near the leading edge, the dependence on the temperature factor loses its steadiness: the pressure drops at low temperature factors but rises in the cavity under adiabatic conditions.

The paper [4] describes comparison of turbulence models in the *ANSYS Fluent* and *VP2/3* software packages. According to the paper, the $k-\varepsilon$ and *SA* models are not fit for calculating separated flows, because they diminish their intensity, while calculations conducted with the help of the *SST* $k-\varepsilon$ model are in good agreement with experimental data. It is also noted that the type of the grid has an insignificant effect on flow parameters.

The paper describes a numerical study intended to investigate how the flow in the spherical hollow space on the aircraft surface affect its flight. Using the *ANSYS Fluent* software package, the cavity flow process was simulated at different values of Mach number, pressure of oncoming flow, depth and length of the cavity. The *SST* $k-\varepsilon$ turbulence model was applied. For the purpose of aircraft simulation without the engine and control system, a pointed cone of 1.5 m in height with the semivertex angle $\beta_k = 10°$ and weight of 150 kg was selected. The centre-of-pressure coefficient and centre-of-mass coefficient are $x_{цд} = 0.6874$ and $x_{цм} = 0.5$, respectively. The centre of the hollow space is located on the lower cone generatrix. The length is assumed to be equal to distance L between the leading and trailing edges (Fig. 1).

The following assumptions have been made:

- the aircraft moves in the vertical plane;

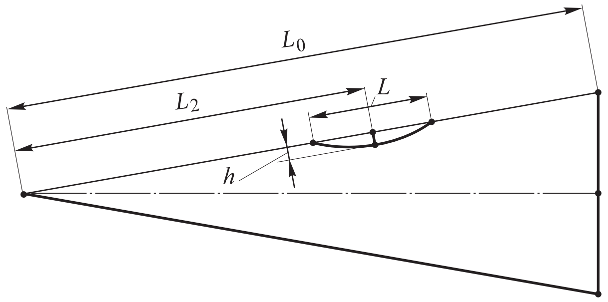


Fig. 1. Aircraft diagram:
h – hollow space depth (mm)

- there is no heat transfer between the flow and the structure;
- there are no chemical reactions in the gas flow;
- the aircraft is analysed as an individual object with constant aerodynamic coefficients, regardless of the hollow space on its surface;
- the effect produced by the hollow space is substituted with the force normal to the aircraft surface, where the force is equal to the integral of excess pressure on the hollow space surface and in surrounding areas;
- hollow space's pressure force is a function of oncoming flow parameters and hollow space sizes;
- the aircraft is statically balanced.

When analysing the dependence of the pressure force on the hollow space surface upon hollow space extension (Fig. 2), we observed an increase in the force value due to a change in the flow pattern in the hollow space. As the open-type flow will have a minor effect as compared with that of the closed type, we selected hollow spaces with the extension value exceeding the critical value and equal to 10 in order to estimate the effect of oncoming flow parameters upon the pressure force. For all the calculations, the flow temperature is assumed to be equal to 1200 K.

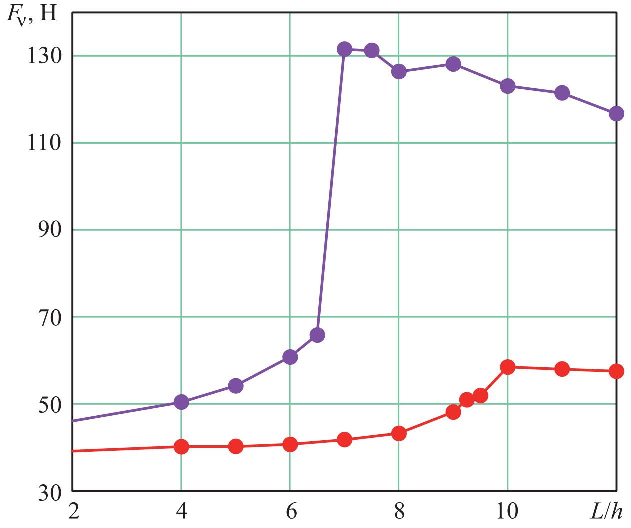


Fig. 2. Dependence of pressure force F_v on the hollow space surface upon its extension at $M_2 = 3.5$, $p_2 = 150$ kPa: — – $h = 10$; — – $h = 5$

Results of pressure force calculations at different Mach numbers and different pressures of oncoming flow are shown in Fig. 3. The resulted values of the pressure force on the hollow space surface are approximated by function

$$F_v = aM_2^{n_1} + bp_2^{n_2} + c\left(p_2 M_2\right)^{n_3},$$

where coefficients $a = -24.18$; $b = -5.79$; $c = 0.0033$;

M_2 – Mach number downstream of oblique shock wave, upstream of hollow space;

p_2 – pressure (kPa);

$n_1 = 0.88$;

$n_2 = -50.2$;

$n_3 = 0.80474$.

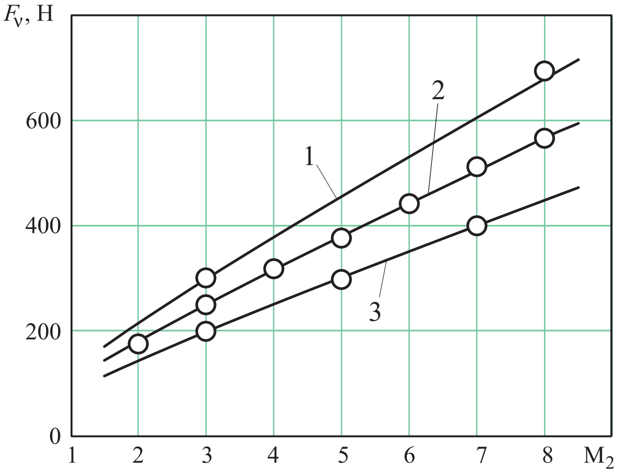


Fig. 3. Pressure force F_v on the hollow space surface, depending on M_2 at $h = 5$, $L/h = 10$:
$1 - p_2 = 620$; $2 - p_2 = 510$; $3 - p_2 = 400$;
○ – approximation; — – numerical experiment

Function F_v can be used if $p_2 > 80$ kPa; at lower values of the oncoming flow static pressure, the vacuum pressure value downstream of the leading edge is comparable with the compression pressure value upstream of the trailing edge.

Therefore, the integral of the excess pressure on the hollow space surface can be taken equal to zero value. Based on the above, the effect of the hollow space on the aircraft flight will appear in the dense atmosphere only.

The aircraft flight is performed in a balance mode, therefore, the cone's normal force moment compensates the action of moment M_v caused by the force in the hollow space. As a result, we get the following equation

$$F_\text{v}\left(l - x_\text{цм}\right) = Y_n\left(x_\text{цд} - x_\text{цм}\right),$$

where $l = L2 / L10$ – the distance from the vertex of the cone to the centre of the hollow space reduced to the generatrix length (see Fig. 1).

The normal force and flow parameters upstream of the hollow space are the functions of parameters of the flow oncoming to the aircraft and angle of attack α. To determine the parameters of the flow around a pointed cone at angle of attack α, including values p_2 and M_2, we used calculation results given in [5]. Based on the equality of normal aerodynamic force moment and pressure force moments, we determined the function of angle of attack

$$\alpha = \frac{F_\text{v}\left(l - x_\text{цм}\right)}{qS_M c_{Y_n}^{\alpha}\left(x_\text{цд} - x_\text{цм}\right)},$$

where q – ram air pressure;

S_M – midsection area;

$c_{Y_n}^{\alpha}$ – derivative of normal aerodynamic force by angle of attack α.

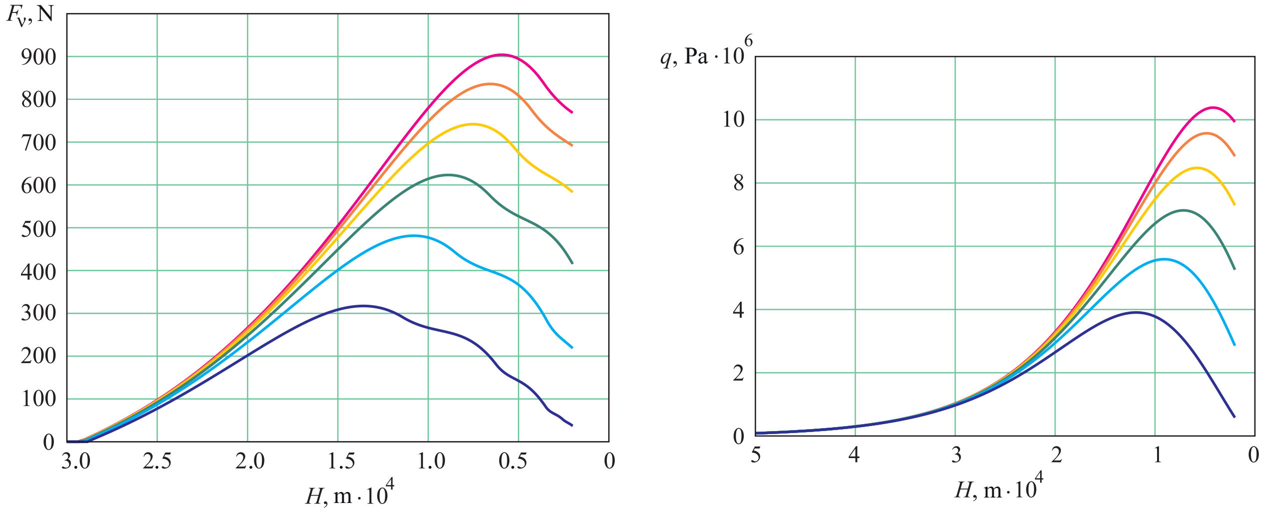
If we analyse the function of angle of attack α, it is obvious that this angle is inversely proportional to the squared cone base radius and to the centre-of-pressure coefficient. Based on the above, we may conclude that aircraft stability augmentation will lead to minimization of the effect of the hollow space on angle of attack α. Using the function of angle of attack α, we obtained the equation of the cone's lift force with the available hollow space

$$Y = Y_a + F_\text{v}\cos\left(\alpha - \beta_k\right),$$

where Y_a – cone's lift force without any hollow space.

The system of equations describing the aircraft movement was updated by adding the function of pressure force and the function of angle of attack α, as well as functions of flow parameters downstream of the shock wave, depending on oncoming flow parameters, and the equation of cone's lift force when the hollow space is in place.

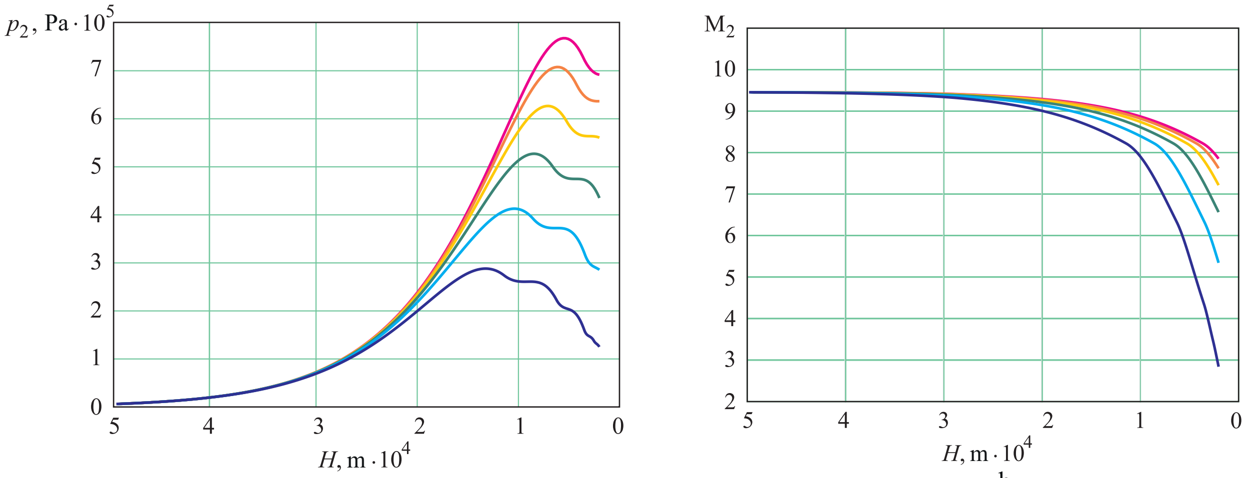
This system of equations is solved for several combinations of initial conditions for further analysis of their influence on the deviation. Initial speed v_0 varies within 5…8 km/s; initial pitch angle is $\theta_0 = -20...-70°$ relative distance from the vertex of the cone to the centre of hollow space is $l = 1...0.2$; depth of hollow space h is 5 and 10 mm, respectively; extension of the hollow space is $L / h = 10$. The results of the solution to



a

b

Fig. 4. Dependence of pressure force F_v located on the hollow space surface (a) and ram air pressure q (b) on flight altitude H at $v_0 = 8$, $h = 5$, $l = 0.2$:
— – $\theta_0 = -20°$; — – $\theta_0 = -30°$; — – $\theta_0 = -40°$; — – $\theta_0 = -50°$; — – $\theta_0 = -60°$; — – $\theta_0 = -70°$



a

b

Fig. 5. Dependence of pressure force F_v upstream of the hollow space (a) and Mach number (b) on flight altitude at $v_0 = 8$, $h = 5$, $l = 0.2$: — – $\theta_0 = –20°$; — – $\theta_0 = –30°$; — – $\theta_0 = –40°$; — – $\theta_0 = –50°$; — – $\theta_0 = –60°$; — – $\theta_0 = –70°$

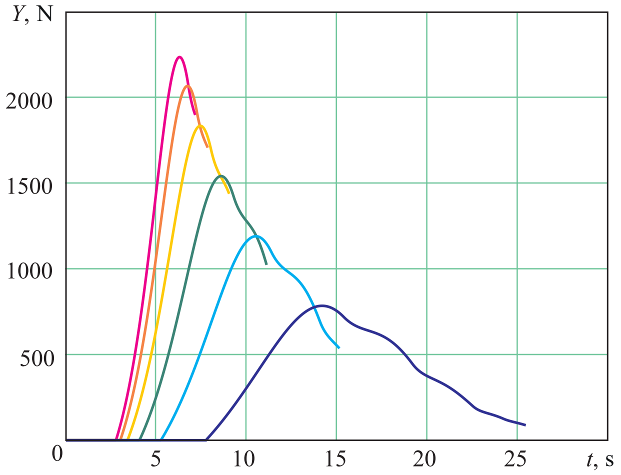


Fig. 6. Dependence of aircraft lift force on in-flight time with account for the influence of hollow space at $v_0 = 8$, $h = 5$, $l = 0.2$: — – $\theta_0 = –20°$; — – $\theta_0 = –30°$; — – $\theta_0 = –40°$; — – $\theta_0 = –50°$; — – $\theta_0 = –60°$; — – $\theta_0 = –70°$

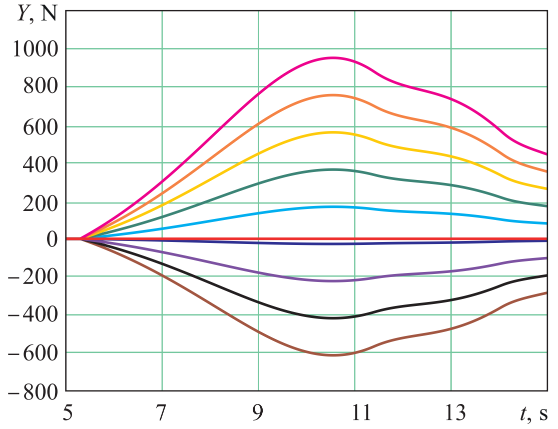


Fig. 7. Dependence of aircraft lift force on in-flight time with account for the influence of hollow space at $v_0 = 8$, $h = 5$, $l = 0.2$:
— – $l = 0.2$; — – $l = 0.3$; — – $l = 0.4$; — – $l = 0.5$;
— – $l = 0.6$; — – $l = 0.7$; — – $l = 0.8$; — – $l = 1$

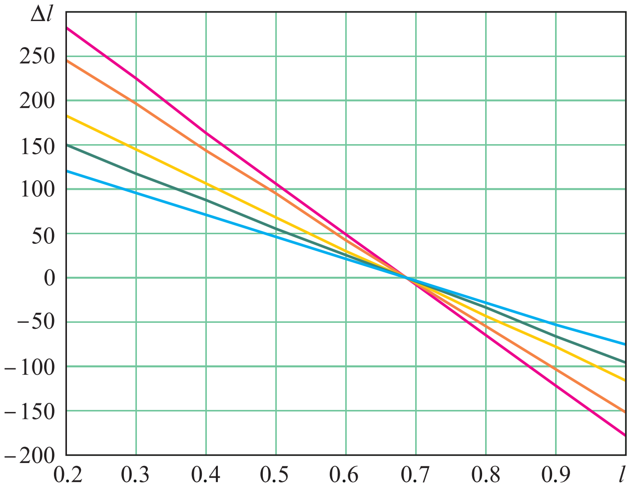


Fig. 8. Aircraft deviation from its flight path for various positions of the hollow space at $\theta_0 = –30°$, $h = 5$:
— – $v_0 = 5$; — – $v_0 = 5.5$; — – $v_0 = 6$;
— – $v_0 = 7$; — – $v_0 = 8$

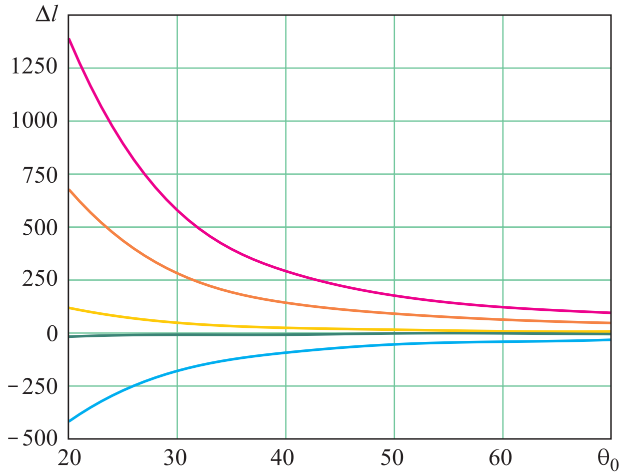


Fig. 9. Aircraft deviation from its flight path for initial pitch angles at $v_0 = 8$:
— – $h = 10$, $l = 0.2$; — – $h = 5$, $l = 0.2$; — – $h = 5$, $l = 0.6$; — – $h = 5$, $l = 0.7$; — – $h = 5$, $l = 1$

the system of equations are shown in Figs. 4–9.

The similar behaviour of curves illustrating force F_v, lift force, ram air pressure, and pressure upstream of the hollow space (see Figs. 4, 5, a, b) is caused by the influence of opposing parameters on these values. Thus, the lower the altitude (see Fig. 5, b), the lower the movement velocity, and the atmospheric pressure increases. Consequently, the curves described above have extrema.

An increase in deviation from the rise of initial speed is caused by the rise of ram air pressure. Flight path deviation for aircraft with a hollow space is calculated at altitude of 2 km as the difference between the aircraft flight range with and without a hollow space. The flight range is selected as the horizontal distance from the initial calculation point to the end point at altitude of 2 km.

Under the effect of a 10-mm-deep hollow space located in the nose section, the aircraft flying at the initial speed of 8 km/s will cover a distance greater by 1.35 km as compared with that covered by the aircraft without a hollow space (see Figs. 8, 9). If the hollow space is located in the tail section, the aircraft will cover a distance shorter by 400 m. If the hollow space is located near the centre of pressure, there is no effect on the flight path (see Figs. 8, 9) under any flight conditions. The flight path is not affected because in this case the lift force is equal to force F_v, but acts in the opposite direction and compensates the latter. For all the calculations of the flight path, angle of attack α did not exceed 0.001 rad. That is why there is no effect on drag force.

An increase in pitch angle θ_0 results in an increase in the in-flight time (see Fig. 6); therefore, the hollow place will affect the flight path for a longer period of time, resulting in greater deviation from the predetermined aircraft flight path (see Fig. 9). In case the position of a hollow space is changed relative to the generatrix, we can observe a lift force variation (see Fig. 7): the maximum value will be reached if a hollow space is located near the aircraft nose.

Thus, the study proves that a decrease in the initial pitch angle along with an increase in the initial aircraft speed increases the influence of the hollow space. Also, according to the study, a hollow space located in the nose section has greater influence than that located in the tail section. Besides, if a hollow space is located near the centre of pressure, it has no effect on the aircraft flight path. Quantitative results of aircraft flight path deviation have been obtained.

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Влияние сферической выемки на траекторию движения летательного аппарата

Представлены результаты исследования влияния сферической выемки на полет летательного аппарата. С помощью моделирования обтекания выемки построена аналитическая зависимость силы давления на ее поверхности от параметров набегающего потока газа. Рассчитано отклонение летательного аппарата, вызванное наличием сферической выемки, в зависимости от ее положения, начальной скорости полета и угла тангажа.

Ключевые слова: гиперзвуковой летательный аппарат, траектория полета, аэродинамическое сопротивление, моделирование турбулентного течения.

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