Dynamics of Angular Motion of Landing Vehicle in Martian Atmosphere with Allowance for Small Asymmetries

Vsevolod V. Koryanov and Victor P. Kazakovtsev
Special Machinery, Bauman Moscow State Technical University, Moscow, Russian Federation
Email: vkoryanov@mail.ru, kafsm3@bmstu.ru

***Abstract*—We study dynamics of the motion of a landing vehicle under descent in the atmosphere of Mars. In the final stage of the landing vehicle's movement, that is, its landing, significant perturbations are caused by the external environment. This can affect the performance of the entire flight mission of the spacecraft. Therefore, it is necessary to develop methods for calculating the dynamics of the landing vehicle in the atmosphere of Mars. In the first part of paper, we present a method for calculating the motion of a landing vehicle in the resonance mode. In the second part, we present a method for calculating the parameters of angular motion of the landing vehicle based on joint integration of the differential equations of motion. The modeling results of the movement of the landing vehicle with inflatable braking devices show that the main factor causing changes in the parameters of the angular motion of the landing vehicle is the asymmetry of its external form.**

***Index Terms*—landing vehicle, dynamics of motion, asymmetry, inflatable braking device, movement in atmosphere, perturbing factors, numerical simulation**

I. Introduction

In the present study, we analyze movement of a landing vehicle in the atmosphere of Mars when the vehicle descends from orbit. For braking in the atmosphere of Mars, special inflatable braking devices are used [1]. The main advantage of such devices is the possibility of their application throughout the course of descent through the atmosphere.

The design of this type landing vehicles, the design assumes the presence of two inflatable braking devices [2], namely, a primary braking device and an additional braking device. The primary braking device is used for braking in the upper atmosphere, and the additional device is used in the lower layers of the atmosphere [3], [4].

The inflatable device has a certain flexibility because of which the forces that deform the inflatable device may arise under the influence of the external environment [5]. Thus, the shape of the inflatable devices may exhibit asymmetry, which can lead to "tipping" moments and cause unstable movement of the vehicle [6].

The exterior view of the landing vehicle is shown in Fig. 1.

In addition, during the motion of such a landing vehicle in the atmosphere of Mars, there are fluctuations in the form of the inflatable braking device. In addition, it is necessary to consider separately the case of resonance. In the first part of the paper, a method is proposed for calculating the motion of a landing vehicle under resonance conditions. In the second part of the paper, calculations are performed using a method based on joint integration of the differential equations of motion and partial differential equations describing the changes in the form of the inflatable braking devices when the landing vehicle moves in the atmosphere.

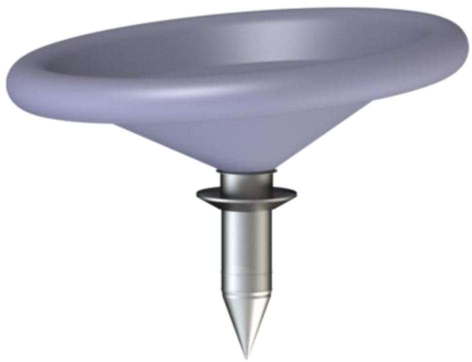

Figure 1. Exterior view of landing vehicle with inflatable braking device

II. Theoretical Part

The proposed method helps analyze the values of the design parameters and the aerodynamic coefficients based on their degrees of their influence by considering the asymmetry of deviations from the longitudinal axis of the vehicle velocity vector. This method is based on the assumption that the resonance modes of motion are developed rapidly. An example of the calculations performed using for modeling the spatial movement of landing vehicle by using the proposed method is given, which demonstrates the adequacy of the results obtained. An example of the influence of small asymmetries of the landing vehicle designed for the descent into the Martian atmosphere under resonance conditions is given in [5]. The motion of a similar lander is described in [7].

Thus, we can write:

Manuscript received January 7, 2018; revised April 23, 2018.

© 2018 Int. J. Mech. Eng. Rob. Res
doi: 10.18178/ijmerr.7.4.385-391

$$\dot{\omega}_x = \frac{d\omega_x}{dt} = \frac{1}{J_x}\Bigg[J_{xy}\cdot(\dot{\omega}_y - \omega_x\cdot\omega_z) +$$

$$+ J_{xz}\cdot(\dot{\omega}_z+\omega_x\cdot\omega_y) + J_{yz}\cdot(\omega_y^2-\omega_z^2) +$$

$$+ (J_y-J_z)\cdot\omega_y\cdot\omega_z + q\cdot S\cdot l\cdot\Bigg(m_{x_0} + m_x^{\varpi_x}\cdot\frac{\omega_x\cdot l}{V} +$$

$$+ C_y\cdot\frac{\Delta z}{l} - C_z\cdot\frac{\Delta y}{l}\Bigg)\Bigg],$$

$$\dot{\omega}_y = \frac{d\omega_y}{dt} = \frac{1}{J_y}\Bigg[J_{xy}\cdot(\dot{\omega}_x+\omega_y\cdot\omega_z) + J_{xz}\cdot(\omega_z^2-\omega_x^2) +$$

$$+ (J_z-J_x)\cdot\omega_x\cdot\omega_z + J_{yz}\cdot(\dot{\omega}_z-\omega_x\cdot\omega_y) +$$

$$+ q\cdot S\cdot l\cdot\Bigg(m_{y_0} + m_y^{\beta}\beta + m_y^{\varpi_y}\cdot\frac{\omega_y\cdot l}{V} + C_x\cdot\frac{\Delta z}{l}\Bigg)\Bigg], \qquad (1)$$

$$\dot{\omega}_z = \frac{d\omega_z}{dt} = \frac{1}{J_z}\Bigg[J_{xy}\cdot(\omega_x^2-\omega_y^2) + J_{xz}\cdot(\dot{\omega}_x-\omega_y\cdot\omega_z) +$$

$$+ J_{yz}\cdot(\dot{\omega}_y+\omega_x\cdot\omega_z) + (J_x-J_y)\cdot\omega_x\cdot\omega_y +$$

$$+ q\cdot S\cdot l\cdot\Bigg(m_{z_0} + m_z^{\alpha}\alpha + m_z^{\varpi_z}\cdot\frac{\omega_z\cdot l}{V} - C_x\cdot\frac{\Delta y}{l}\Bigg)\Bigg].$$

where $\omega_x, \omega_y, \omega_z$ are the projections of the angular velocity of the landing vehicle on the axes of the related coordinate system.

$q = \frac{\rho V^2}{2}$ – dynamic pressure

V –velocity of landing vehicle

S –area of mid-section

l –length of landing vehicle

J_x, J_y, J_z –principal moments of inertia

C_x, C_y, C_z –aerodynamic coefficients of axial and transverse forces

m_{x0} –aerodynamic moment coefficient relative to longitudinal axis

$m_y^{\beta}, m_z^{\alpha}$ –derivatives of aerodynamic coefficients on with respect to angle of attack (α) and glide (β)

$m_x^{\varpi_x}, m_y^{\varpi_y}, m_z^{\varpi_z}$ –derivatives of aerodynamic coefficients with respect to projections of angular velocity of landing vehicle on the axes of the related coordinate system.

Small asymmetry: $\Delta y, \Delta z$ –lateral displacement of real center of mass relative to longitudinal axis of landing vehicle

J_{zy}, J_{xz}, J_{yz} –centrifugal moments of inertia m_{y0}, m_{z0}– aerodynamic coefficients of transverse moments at zero values of angles of attack and glide.

Numerous studies of resonant modes of motion of uncontrolled devices have shown that the development of the resonance regime (maximum deviation of the longitudinal axis of the apparatus from the velocity vector) passes within a short time of the order of several seconds.

Based on this information, we transformed the second and third expressions in (1) by under the following assumptions: (1) the influence of gravity on the dynamic equations of translational motion is negligible; (2) all the aerodynamic coefficients and their derivatives are constant; (3) as quantities of second smallness, the products of angular velocities in the dynamic equations of rotational motion are negligible.

Thus

$J_{yz} = 0$; $J = J_y = J_z$; $C_z^{\beta} = -C_n^{\alpha}$; $|m_y^{\beta}| = |m_z^{\alpha}|$;

$m_y = -|m_z^{\alpha}|\cdot\beta$; $m_z = -|m_z^{\alpha}|\cdot\alpha$;

$C_x = C_{\tau}$, $C_y = C_n^{\alpha}\cdot\alpha$, $C_z = -C_n^{\alpha}\cdot\beta$.

Here, in addition, C_n^{α}, which is the derivative of the aerodynamic coefficient of normal force with respect to the angle of attack, is indicated.

After transforming the second and third equations in (1) and considering the aforementioned assumptions, we obtain the following second-order differential equations for the angles of attack and slip:

$$\ddot{\alpha} = -\left[\frac{S}{m}\left(C_n^{\alpha} - C_{\tau}\right) + \frac{Sl^2}{J}\left|m_z^{\omega}\right|\right]\frac{q}{V}\dot{\alpha} -$$

$$-\left[\frac{qSl}{J}\left|m_z^{\alpha}\right| - \frac{J-J_x}{J}\omega_x^2 + \frac{q^2S^2l^2}{mJV^2}\left(C_n^{\alpha}-C_{\tau}\right)\left|m_z^{\omega}\right|\right]\alpha -$$

$$-\frac{2J-J_x}{J}\omega_x\dot{\beta} - \left[\frac{Sl}{J}\left|m_z^{\varpi}\right| + \frac{J-J_x}{J}\frac{S}{m}\left(C_n^{\alpha}-C_{\tau}\right)\right]\frac{q}{V}\omega_x\beta +$$

$$+ h_{\beta}\frac{J-J_x}{J}\omega_x^2 + \frac{qSl}{J}\left|m_z^{\alpha}\right|\alpha_a - \frac{qSC_x}{J}\Delta y,$$

$$\ddot{\beta} = -\left[\frac{S}{m}\left(C_n^{\alpha} - C_{\tau}\right) + \frac{Sl^2}{J}\left|m_z^{\omega}\right|\right]\frac{q}{V}\dot{\beta} -$$

$$-\left[\frac{qSl}{J}\left|m_z^{\alpha}\right| - \frac{J-J_x}{J}\omega_x^2 + \frac{q^2S^2l^2}{mJV^2}\left(C_n^{\alpha}-C_{\tau}\right)\left|m_z^{\varpi}\right|\right]\beta - \qquad (2)$$

$$-\frac{2J-J_x}{J}\omega_x\dot{\alpha} - \left[\frac{Sl}{J}\left|m_z^{\omega}\right| + \frac{J-J_x}{J}\frac{S}{m}\left(C_n^{\alpha}-C_{\tau}\right)\right]\frac{q}{V}\omega_x\alpha +$$

$$+ h_{\alpha}\frac{J-J_x}{J}\omega_x^2 + \frac{qSl}{J}\left|m_z^{\alpha}\right|\beta_a - \frac{qSC_x}{J}\Delta z.$$

where

α_a, β_a–balancing corners of attack and slip due to a small asymmetry of the form

$h_{\alpha} = \frac{J_{xz}}{J-J_x}, h_{\beta} = \frac{J_{xy}}{J-J_x},$ –Relative centrifugal moments of inertia.

III. Modeling

Influence of inflatable braking device deformation on dynamics of angular motion of landing vehicle with primary inflatable braking device in resonance mode.

Here, we investigate the dynamics of the angular motion of a landing vehicle (LV) with a non-rigid primary inflatable braking device (PIBD) in the second stage of the descent trajectory in the atmosphere of Mars. This phase begins with the intersection of the angular velocity of the longitudinal axis of the landing vehicle and the resonance frequency.

In the calculations for the landing vehicle with undeformed PIBD, even in the absence of small asymmetry at this point, the value of the spatial angle of attack starts to increase.

The presence of small structural asymmetries in the landing vehicle owing to the undeformed PIBD, the spatial angle of attack increased further. The PIBD deforms during descent because it is not rigid by design, and the presence of a transverse load leads to additional asymmetry owing to lateral displacement of the center of mass of inertia and asymmetry of the external form.

In our example, the weight of the flexible PIBD is about ten times smaller than that of the landing vehicle. Therefore, PIBD strain leads to additional lateral displacement of the center of mass, in this way, projections Δy_{def} and Δz_{def} less than 10^{-3}. Also, the additional relative centrifugal moments of inertia I_{xydef} / I_y, I_{xzdef} / I_z fewer than 10^{-3}. These values are the asymmetries that do not change the dynamics of angular motion of the landing vehicle.

Meanwhile, PIBD deformation leads to sufficiently large asymmetries in the external form. In our example, the value of the coefficient of the aerodynamic transverse moment (m_{adef}) could reach values of the order of 0.001. Thus, PIBD deformation manifests as an increase in the aerodynamic coefficient transverse moment, leading to changes in the spatial angle of attack.

Figs. 2–3 show the calculated temporal changes in the value of the spatial angle of attack without influence effect of deformation of the PIBD and with influence effect of deformation of the PIBD at the initial angular velocity of rotation of the landing vehicle around the longitudinal axis ω_{x0} =1 1/s.

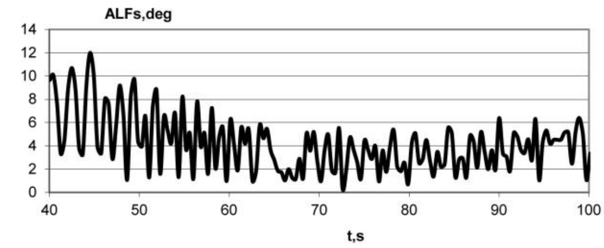

Figure 2. Graph of spatial angle of attack without influence of PIBD strain

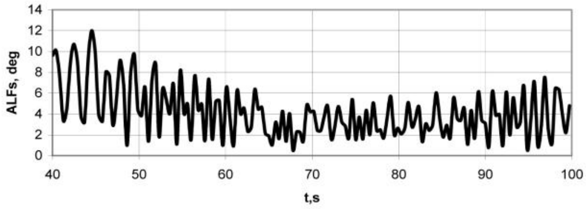

Figure 3. Graph of spatial angle of attack with influence of PIBD strain

In both cases, the calculation was made considering the effect of small structural asymmetries of the landing vehicle (LV). Analysis of the graphs of the spatial angle of attack showed that the additional effect of deformation in the region of LV descent into the atmosphere of Mars is insignificant. Within 90 s of motion after entry of the LV into the atmosphere, PIBD deformation led to a significant (about two degrees) further increase in the spatial angle of attack.

Consider the graphs (Figs. 4–6) of the spatial angle of attack of subsequent LV motion with PIBD before disclosure. In these graphs, the previously defined small structural asymmetry of LV is considered, when considering the influence of PIBD deformation and additional evaluation asymmetry PIBD external form.

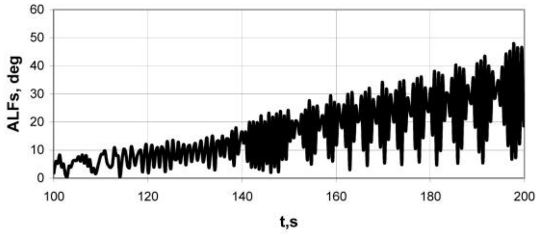

Figure 4. Plot of magnitude of spatial angle of attack before PIBD deformation

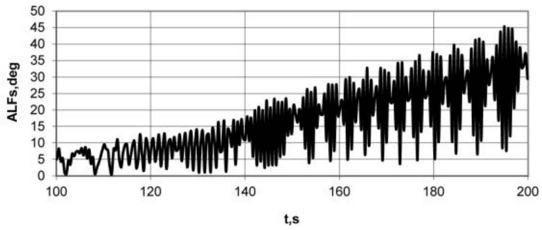

Figure 5. Plot of magnitude of spatial angle of attack for a fixed value of coefficient of aerodynamic m_{af} = 0.001 at a fixed value of transverse load q_{sf} = 100 Pa

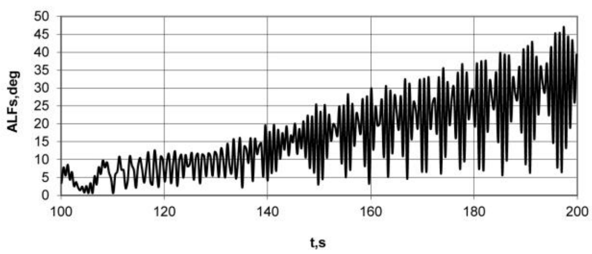

Figure 6. Plot of magnitude of spatial angle of attack for m_{af} = 0.002 at a fixed value of transverse load q_{sf} = 100 Pa

The analysis of the graphs of the spatial angle of attack showed that the additional effect of deformation in this region of PIBD descent in the atmosphere of Mars is negligible as well. Only when the value m_{af} = 0.002 for a fixed value of the transverse load, that is, q_{sf} = 100 Pa, PIBD deformation results in a small (about two degrees) further increase in the spatial angle of attack.

The oscillation of LV with PIBD occurs at a high value of velocity head. Therefore, the solid angle of attack induces an increase in the lateral load ($q_s = q \sin \alpha_s$), which increases the value of the coefficient of aerodynamic transverse moment (m_{adef}). This, in turn, increases the solid angle of attack.

During motion of the LV with PIBD in the last stage of descent before disclosure, the additional inflatable braking device (AIBD) value ram decreases greatly. Therefore, even with a large spatial angle of attack, the level of transverse load corresponds to small deformations of the main inflatable braking device (Fig. 7).

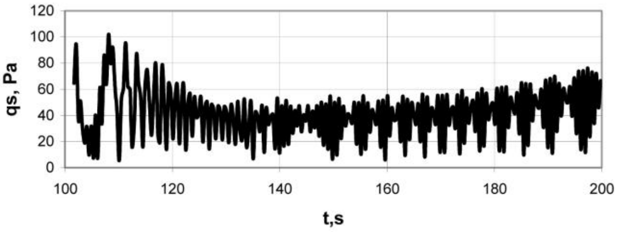

Figure 7. Graph of transverse load on PIBD

Note that the PIBD has sufficient lateral stiffness, so small PIBD deformations during descent into the Martian atmosphere do not cause affect the stability of angular motion of the LV.

Method for calculating parameters of angular motion of LV based on joint integration of differential equations of motion and partial differential equations describing change in shape of inflatable braking device in atmosphere.

To determine the shape of the non-rigid shell inflatable braking device of the LV, we developed a mathematical model of the shell forming the inflatable braking device based on the following assumptions:

– the shell of the inflatable brake device of the landing device is closed, is in excess of internal pressure;

– internal pressure is constant;

– shell material is isotropic, with an average modulus of elasticity.

The last assumption was made because often in the initial stages of development of a LV with an inflatable braking device, the shell material of the inflatable braking device and its characteristics are unknown.

Displacement of shell and its symmetry axis in the coordinate system was defined as $O_1X_1Y_1Z_1$ in association with the wrapper. The planes containing the axes are O_1Y_1 and O_1Z_1, located in the plane connection of a non-rigid inflatable braking device with a rigid. Axis O_1X_1 coincides with the axis of symmetry of the LV with an inflatable braking device, and it runs along the opposite direction from the direction of movement of the landing vehicle. Axis O_1Y_1 lies in the plane of the spatial angle of attack.

For the symmetrical conical inflatable braking device and zero angle of attack, the surface pressure distribution is symmetric. The angle of attack disrupts the symmetry of surface pressure distribution of the inflatable braking device. This symmetry is not as dependent on the angle of attack and Mach number.

As an example, Fig. 8 shows graphs of the distribution of pressure on the outer surface of the conical inflatable braking device at different angles of attack.

Asymmetrical pressure distribution over the surface of the inflatable braking device leads to the following scenarios:

– Deformation of the shell of the inflatable braking device;

– Turning of the longitudinal axis of the shell.

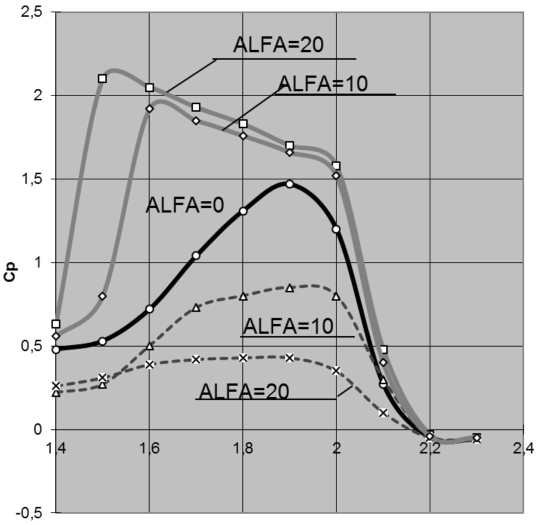

Figure 8. Graphs of pressure distribution on surface of non-rigid inflatable braking device at M = 3.32 for different angles of attack

The outer aerodynamic load distributed on the lateral surface of a conical shell for hypersonic and supersonic flight speeds can be determined using a modified version of Newton's formula:

$$p_{внеш} = q_\infty \bar{p} = q_\infty \bar{p}_0 \Big\{ \cos\alpha_s \sin\gamma - \\ - \cos\gamma \sin\varphi \left[\sin\alpha_s + \frac{\omega_z}{V_\infty}(r tg\gamma + x - x_T) \right] \Big\}^2, \quad (3)$$

where,

$\bar{p}_0$ –pressure coefficient at the point of complete inhibition;

α_s–spatial angle of attack;

γ–angle of conical shell inflatable braking device.

At the hyper and supersonic stage of the landing vehicle movement a curvilinear disconnected shock wave arises. In this case, the pressure ratio at the point of complete inhibition can be determined using the direct shock wave theory. In the case of supersonic gas flows at Mach $3 < M_\infty \leq 6$, direct shock in a gas stream with constant specific heat, the pressure coefficient at full braking is determined by the formula:

$$\bar{p}_0 = \frac{2(1-\delta)}{(1+\delta)M_\infty^2}\left\{\left[(1+\delta)M_\infty^2 - \delta\right]^{\frac{(\delta-1)}{2\delta}} M_\infty^{\frac{(1+\delta)}{\delta}} (1-\delta)^{-\frac{(1+\delta)}{2\delta}} - 1\right\}$$

where, $\delta = \frac{k-1}{k+1}$, $k = \frac{C_p}{C_v}$,

k – ratio of specific heats.

At high supersonic and hypersonic speeds ($6 < M_\infty < 10$) and a constant specific heat ratio, the gas pressure at the point of complete inhibition is determined by the following expression:

$$\bar{p}_0 = 2(1-\delta)^{\frac{(\delta-1)}{2\delta}}(1+\delta)^{-\frac{(1+\delta)}{2\delta}}$$

At very high Mach numbers $M_\infty \geq 10$, the distribution coefficient of pressure shock waves in a gas flow with variable specific heats is determined considering dissociation and ionization as follows:

$$\bar{p}_0 = 0.5kM_\infty^2\left(\frac{p_0'}{p_\infty} - 1\right)$$

where: p_0' – determined from thermodynamic tables or diagrams i-S.

Base pressure is determined using the following relationship:

$$p_д = \left(\frac{1+0.4M_\infty}{0.7+M_\infty^2}\right)p_\infty \tag{4}$$

where: p_∞ –pressure of the incident flow,

M_∞ – free-stream Mach number.

Given the above assumptions (the shell of the inflatable brake device of the landing device is closed, is in excess of internal pressure; internal pressure is constant; shell material is isotropic, with an average modulus of elasticity) the mathematical model of the shaping of the shell of the inflatable brake device of the descent vehicle under the influence of the oncoming flow included:

The equation for reshaping the symmetry axis of the shell is as follows:

$$m_n \frac{\partial^2 u}{\partial t^2} - \left[\frac{(p_0 - p_Д)R_k^2}{2\cos\gamma(R_Г + x\tan\gamma}(1+\sin\gamma) + ,\right. \tag{5}$$

$$\left. + x\Delta p\sin\gamma\tan\gamma\right]\frac{\partial^2 u}{\partial x^2} = \Delta p\cos\gamma$$

and the equation governing the change in the form of the loose shell inflatable braking device is as follows:

$$m_п \frac{\partial^2 w}{\partial t^2} - \frac{R_k^2(p_o - p_д)(1+\sin\gamma)}{2(R_г + \tilde{x}\sin\gamma)\cos\gamma}\frac{\partial^2 w}{\partial \tilde{x}^2} - \frac{E\delta}{(R_г + \tilde{x}\sin\gamma)^2}w - , \tag{6}$$

$$-\frac{2E\delta}{0.0003(R_г + \tilde{x}\sin\gamma)^3}w\frac{\partial^2 w}{\partial \varphi_1^2} = p_o - p_{внеш}$$

where: u–displacement of the axis of symmetry of the shell element inflatable braking device;

w–displacement of shell element inflatable braking device;

$m_п$–linear mass of shell inflatable braking device;

p_o–internal pressure of shell;

E–modulus of elasticity;

δ–shell thickness;

γ – half angle of conical shell solution

The conical shell is broken at "i" layers along the longitudinal axis of the inflation device and along the braking element j at the periphery of each layer. Lateral displacement of the center of mass of the inflatable braking device, due to its deformation, lies in the plane spatial angle of attack, and it is calculated by using the following formula:

$$\Delta\rho_1 = \frac{1}{m_1}\sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}\left(u_{ij} + w_{ij}\cos\gamma\right) \tag{7}$$

Lateral displacement of the center of mass of the lander with a deformed inflatable braking device lies in the plane spatial angle of attack:

$$\Delta\rho_S = \frac{m_1}{m}\Delta\rho_1 \tag{8}$$

Projections of the lateral displacement of the center of mass due to the deformation of the inflatable braking device on the OY, OZ axes are expressed as follows:

$$\begin{aligned} \Delta y_{def} &= \Delta\rho_S\cos\varphi_s \\ \Delta z_{def} &= \Delta\rho_S\sin\varphi_s \end{aligned} \tag{9}$$

where: φ_s –angle between the deformed inflatable braking device and plane OYZ;

Additional centrifugal inertia caused by deformation of the shell of the inflatable braking device can be determined using the following formula:

$$I_S = m_1 x_1 \Delta\rho_1, \tag{10}$$

x_1–distance between the centers of mass of the landing vehicle with inflatable braking device before and after deformation.

Projections of the centrifugal inertia caused by deformation of the inflatable braking device on the axes OY, OZ are expressed as follows:

$$\begin{aligned} I_{xydef} &= I_S\cos\varphi_s \\ I_{xzdef} &= I_S\sin\varphi_s \end{aligned} \tag{11}$$

The most difficult part is determining the coefficient of aerodynamic moment due to deformation of the inflatable braking device. We introduce the assumption that a balanced movement lander with a deformed inflatable braking device runs from the corner, which almost equals the angle of displacement of the center of mass of the inflatable braking device relative to the mass center of the landing vehicle. Then, the following formula can be used to determine the angle:

$$\delta_S = \Delta\rho_1\frac{1}{x_1} \tag{12}$$

The aerodynamic moment coefficient lies in the plane of the spatial angle of attack, and it is determined as follows:

$$m_{\delta} = \left| m_z^{\alpha} \right| \delta_S , \tag{13}$$

$\left| m_z^{\alpha} \right|$ – Derivative of aerodynamic torque angle of attack.

Projections of the aerodynamic moment coefficient on the OY, OZ axes due to deformation of the inflatable braking device are expressed as follows:

$$m_{ydef} = m_{\delta} \cos \varphi_s$$
$$m_{zdef} = m_{\delta} \sin \varphi_s \tag{14}$$

The dynamics of the angular motion of the lander with an inflatable braking device in each step of integration of the equations of motion of the landing gear performed using the fourth-order Runge-Kutta method was determined considering the additional asymmetries due to deformation of the shell inflatable braking device. Integration of the changes in the position of the symmetry axis of the shell inflatable braking device lander (5) was carried out using the FDTD method with a three-layer explicit difference scheme. For integration of the equation of changes in form of the loose shell inflatable braking device (6), the finite-difference method of variable directions with the longitudinal-transverse scheme was used.

In each integration step, the magnitude of resonance angular velocity was computed:

$$\omega_{rez} = \sqrt{\frac{Sl\left|m_z^{\alpha}\right|}{I_z - I_x} q}$$

Fig. 9 shows the graphs of the following quantities as functions of time: angular velocity of rotation of landing vehicle relative to the longitudinal axis of the resonance velocity, and velocity head. The intersection curves and ω_{rez} ω_x appear at the 10^{th} second of flight in the atmosphere, which is, perhaps, a manifestation of the resonance effect.

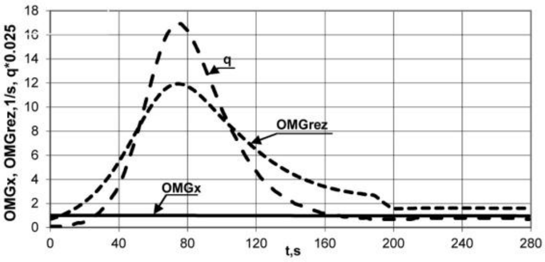

Figure 9. Graphs pf dynamic pressure q, resonant speed ω_{rez} (OMGrez), and angular velocity of rotation of ω_x (OMGx) of landing vehicle

Consider in more detail the moment of possible manifestation of the resonance effect (Fig. 9). At Fig. 10 shows a graph of the changes in the spatial angle of attack in the presence of complex structural asymmetries. We see that at the moment of passage, the resonance value of the spatial angle of attack increases instead of decreasing. However, owing to static stability of the landing vehicle, the spatial angle of attack decreased gradually.

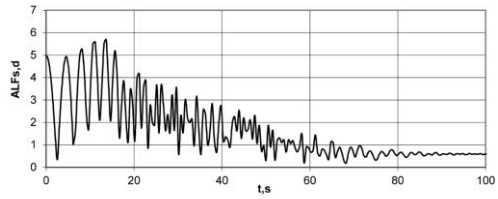

Figure 10. Graph of spatial angle of attack αs (ALFs) in presence of complex structural asymmetries

Fig. 11 shows a graph of the changes in the spatial angle of attack in the presence of complex structural asymmetries without any influence of the stiffness of the inflatable braking device. Until the moment of resonance, the graph of the spatial angle of attack is the same as the previous one (Fig. 10). Then, with increasing speed and pressure, the lateral load begins to affect the non-rigid inflatable braking device.

This leads to a further increase in the magnitude of the spatial angle of attack. After passage of the maximum dynamic pressure (t = 80 s), the value of the spatial angle of attack begins to decrease. Note that depending on the rigidity of the second inflatable braking device, the increase in the spatial angle of attack can be considerable, at low level of rigidity of the inflatable braking device, this can lead to loss of stability of the descent vehicle movement.

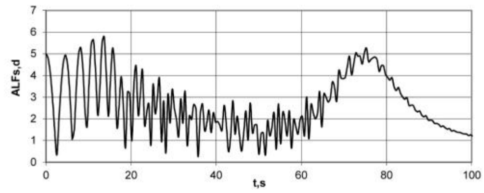

Figure 11. Graph of spatial angle of attack in presence of complex structural asymmetries and non-rigid inflatable braking device

The calculation results of the motion of the lander, with and without consideration of the forming shell, for supersonic flight speeds led to the following conclusions.

IV. Conclusions

1. Analysis of the calculation results of driving dynamics the landing vehicle showed that

– Deformation of the inflatable braking device obtained in a plane substantially spatial angle of attack;

– Influence of the non-rigid inflatable braking device on the value of the spatial angle of attack depends on the dynamic pressure, initial values of spatial angle of attack, and lateral stiffness parameters of inflatable braking device;

2. Owing to deformation of the inflatable braking device, asymmetry has an alternating character in the projections on the axis of the related coordinate system. The external shape of the inflatable braking device, which produces a drag coefficient of transverse moment at zero angle of attack, has the greatest impact on the value of the spatial asymmetry of the angle of attack.

3. Analysis of the additional small asymmetries of a landing vehicle with the main inflatable braking device and an additional inflatable braking device showed that

the maximum lateral displacement of the center of mass and relative centrifugal moments of inertia did not exceed one-thousandth unnit. This is because of the small mass of the inflatable braking device relative to that of the machine. Therefore, these asymmetries do not affect the dynamics of angular motion of a small weather station.

Asymmetry of the external shape of the inflatable braking device due to deformation led to a significant value of the coefficient of aerodynamic asymmetry. This, in turn, caused changes in the dynamics of the angular motion of a small weather station.

4. The proposed method for studying the influence of the deformation of the inflatable braking device on the dynamics of the angular motion of a space lander allows one to determine in the design stage the required lateral rigidity of the inflatable braking device to ensure stable movement of space landers during descent into the Martian atmosphere.

References

[1] V. Koryanov. “Research of the dynamics motion of landing vehicle with inflatable braking device in the planet atmosphere,” in *Proc. the International Astronautical Congress*, IAC vol. 8, 2013. pp. 5831-5836.

[2] V. P. Kazakovtsev, V. V. Koryanov, “Research technique of the attitude dynamics of a landing unmanned space vehicle with an inflatable braking device,” Herald of the Bauman Moscow State Technical University. Series Mechanical Engineering, 2012, N3 (88), pp. 39-46.

[3] S. N. Aleksashkin, K. M. Pichkhadze, V. S. Finchenko, “Design principles in planetary atmospheres reentry vehicles with inflatable braking systems,” *Herald Federal State Unitary Enterprise Scientific and Production Association Named after Lavochkin*, 2012, No. 2. pp. 4-11.

[4] K. M. Pichkhadze, V. A. Vorontsov, A. M. Zashchirinskiy, V. A. Ponomarev, “Descent system from orbit and emergency rescue based on an inflatable braking device,” *Flight. All-Russian Scientific and Technical Journal*, 2003. No. 8, pp. 9-13.

[5] J. Heilimo, A. M. Harri, S. Aleksashkin, V. Koryanov, I. Arruego, W. Schmidt, H. Haukka, V. Finchenko, M. Martynov, B. Ostresko, A. Ponomarenko, V. Kazakovtsev, S. Martin, and T. Siili, “RITD - adapting mars entry, descent and landing system for earth. geophysical research abstracts,” vol. 16, EGU2014-5506-1, 2014, EGU General Assembly 2014

[6] V. Koryanov, “Method of calculating the descent of the spacecraft in the atmosphere using technology adaptation landing in different environmental conditions,” in *Proc. the International Astronautical Congress*, IAC vol. 8, 2014. pp. 5628-5632.

[7] M. Iacovazzo, V. Carandente, R. Savino, G. Zuppardi, “Longitudinal stability analysis of a suborbital re-entry demonstrator for a deployable capsule,” *Acta Astronautica*, vol. 106, January–February 2015, pp. 101–110.

Vsevolod V. Koryanov born in 1982, Soviet Union. Ph.D. (Eng.), assoc. professor, first Deputy head of «Dynamics and flight control of rockets and spacecraft» department of the Bauman Moscow State Technical University, Moscow, Russian University.

In 2006 finished the Moscow State Technical University, faculty of "Special engineering", Department "Ballistics and aerodynamics". In 2011 defended his dissertation for the degree of candidate of technical sciences. Since September 2011 Vsevolod works first Deputy head of «Dynamics and flight control of rockets and spacecraft» department of the Bauman Moscow State Technical University.

Reward: Medal of Merit of the Cosmonautics named after Yu.A. Gagarin Federation of Cosmonautics Russian Federation (2013).

Educational work:

In 2011-2012 academic year, the best teacher of the Bauman Moscow State Technical University won the competition in the nomination "Best Young Teacher".

In 2014-2015 academic year the best teacher of the Bauman Moscow State Technical University won the competition in the nomination "Management course and diploma projects."

International Scientific work:

Vsevolod since 2011 is the responsible executor of the international grant "Re-entry: inflatable technology development in Russian collaboration (RITD)". The work was supported by the European Union under the Seventh Framework Program FP7 / 2007-2013 under the Grant Agreement No. 263255 RITD.

International Conferences:

International Astronautical Congress (IAC): in Beijing (China) in 2013, in Toronto (Canada) in 2014, in Jerusalem (Israel) in 2015, in Guadalajara (Mexico) in 2016;

40th Scientific Assembly of the International Committee for the Exploration (COSPAR 2014);

International Conference on Mechanical, System and Control Engineering (2016 Moscow, St. Petersburg 2017);

14th European Conference on Spacecraft Structures, Materials and Environmental Testing (ECSSMET) (2016 in Toulouse, France).

Publications:

More than 60 scientific publications in Russian scientific journals;

8 scientific publications in international journals (Scopus indexed and etc.);

3 scientific publications in international journals (Web of Science indexed).

Victor P. Kazakovtsev, born in the Soviet Union in 1934. Doctor of technical science, professor, professor of «Dynamics and flight control of rockets and spacecraft» department of the Bauman Moscow State Technical University, Moscow, Russian University.

Academician of the Russian Academy of Cosmonautics, Honored Worker of Higher School of the Russian Federation.

In 1958 he graduated with honors from the Faculty of Mechanical Engineering of Bauman Moscow Higher Technical School and since then constantly working in the Bauman Moscow State Technical University at the Department «Dynamics and flight control of rockets and spacecraft’s". In 1964 he defended his thesis for the degree of candidate of technical sciences. In 1966 he was awarded the rank of associate professor. In 1997 thesis for the degree of Doctor of Technical Sciences. From September 1998 he has been working as a professor. In 1999 he was awarded the academic title of professor. Kazakovtsev has over one hundred and twenty published scientific works, including two inventions. The main scientific directions of research in the field of ballistics and flight dynamics of spacecraft’s and landers.

Victor has over one hundred and twenty published scientific works, including two inventions. The main scientific directions of research in the field of ballistics and flight dynamics of spacecraft’s and landers.

© 2018 Int. J. Mech. Eng. Rob. Res