Analysis of the dynamics of movement landing vehicle with an inflatable braking device on final stage of trajectory

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\textbf{Abstract.} For various missions that are currently being designed and planned at the present time, it is necessary to ensure reliably the stage of landing on the surface of the planet. Among the currently proposed devices that help to perform the landing of the landing vehicle, a separate interest is inflatable devices. Using inflatable device instead of rigid device has advantages, such as a small mass and a great compacity. Studies have focused on the angular motion of landing vehicles entering the atmosphere, with allowance of small asymmetries. During the descent in the atmosphere, the landing vehicle and its braking device are subjects to important perturbations, due to external environment. Thus, the inflatable device can be deformed, due to its flexibility, and the movement can become unstable. In the paper is analyzes the movement of such a landing vehicle, which uses such special devices made of inflatable devices. The paper is devoted to the analysis of movement at the final stage of landing - approaching the surface, touching the surface and further interaction with the surface. As a result, it is concluded that the most unfavorable approach to the surface, when the resulting overload is of the greatest importance.

1. Introduction

Currently, a large number of space missions are being designed. It is increasingly important to carry out missions that provide for the return of cargo from an orbit or space to small automatic stations. This may be the return of samples in interplanetary missions, there may also be the return of cargo from orbit around the Earth and so on. For such missions, it is necessary to perform a reliable landing of the landing vehicle. To do this, it is necessary to perform braking in the atmosphere at very high speeds when entering the atmosphere and to acceptable speed values when approaching the surface \cite{1}. It is possible to use various devices that help to perform such braking \cite{2-5}.

This paper is devoted to the final stage of landing, when contact with the surface occurs, large values of overload occur and it is necessary to analyze the search for optimal variants of the initial parameters of the approach to the surface (Figure 1, stage IV).
2. Theoretical part: determination of the angular motion of landing vehicles entering atmosphere
One of the interesting and effective options is the use of inflatable devices to perform a successful landing. Such devices can be used for the entire length of the landing - from the moment of entry to the moment of contact. An example of such a project is the MetNet project [6, 7], which is well described in scientific works and papers [8, 2] (Figure 1).

Previously, the authors considered various stages of the landing vehicle in the atmosphere of the planet, to which articles are devoted [2]. Materials of other scientists who work in the field of flexible structures are presented here [9, 10]. In addition, there are a number of articles on deployable structures in space that are also of interest to our research [11-13].

In this part, we will study the angular motion of a landing vehicle in the atmosphere with allowance of small asymmetries [2]. To brake into the atmosphere, we will consider that the landing vehicle has inflatable braking device, and that there are two of them: the primary braking device, used in the upper atmosphere, and the additional one, used in the lower atmosphere. During the descent, the landing vehicle and its braking device are subjects to important perturbations, due to external environment. Thus, the inflatable device can be deformed, due to his flexibility, and the movement can become unstable.

Let’s determine the equations of the angular motion. We will use a method that analyze how the design parameters and the aerodynamics coefficients influence the asymmetry of a deviation from the longitudinal axis of the vehicle velocity vector and give them coefficients corresponding to the degree of their influence. We suppose that there is a rapid development of resonance modes of motion.

We can write:

\[
\begin{align*}
\omega_x &= \frac{d\omega_x}{dt} = \frac{1}{J_x} \left[ J_y \cdot (\omega_z \cdot \omega_y - \omega_x \cdot \omega_z) + J_z \cdot (\omega_x \cdot \omega_z - \omega_y \cdot \omega_x) + (J_y - J_z) \cdot \omega_y \cdot \omega_z + g \cdot S \cdot l \cdot \left( m_{x0} + m_{x0} \cdot \frac{\omega_z}{V} \cdot \frac{J_z}{l} - C_a \frac{\Delta z}{l} - C_b \frac{\Delta y}{l} \right) \right] \\
\omega_y &= \frac{d\omega_y}{dt} = \frac{1}{J_y} \left[ J_x \cdot (\omega_z \cdot \omega_y - \omega_x \cdot \omega_z) + J_z \cdot (\omega_x \cdot \omega_z - \omega_y \cdot \omega_x) + (J_y - J_z) \cdot \omega_x \cdot \omega_z + g \cdot S \cdot l \cdot \left( m_{y0} + m_{y0} \cdot \frac{\omega_z}{V} \cdot \frac{J_z}{l} - C_a \frac{\Delta z}{l} - C_b \frac{\Delta y}{l} \right) \right] \\
\omega_z &= \frac{d\omega_z}{dt} = \frac{1}{J_z} \left[ J_x \cdot (\omega_y \cdot \omega_x - \omega_z \cdot \omega_y) + J_y \cdot (\omega_z \cdot \omega_x - \omega_y \cdot \omega_z) + (J_y - J_z) \cdot \omega_y \cdot \omega_z + g \cdot S \cdot l \cdot \left( m_{z0} + m_{z0} \cdot \frac{\omega_y}{V} \cdot \frac{J_y}{l} - C_a \frac{\Delta z}{l} - C_b \frac{\Delta y}{l} \right) \right].
\end{align*}
\]

Where: \( \omega_x, \omega_y, \omega_z \) are the projections of the angular velocity of the landing vehicle on the axis of the related coordinate system;

\( q = \frac{\rho V^2}{2} \) is the dynamic pressure;

\( V \) is the velocity of the landing vehicle;

\( S \) is the mid-section area;

\( l \) is the length of the landing vehicle;

\( J_x, J_y, J_z \) are the principal moments of inertia;

\( C_a, C_b, C_c \) are the aerodynamic coefficients of axial and transverse forces.

\( m_{x0} \) is the aerodynamic moment coefficient relative to the longitudinal axis;

\( m_{y0}^{\beta}, m_{z0}^{\alpha}, m_{z0}^{\beta} \) are derivatives of aerodynamic coefficients on the angle of attack (\( \alpha \)) and glide (\( \beta \));

\( m_{x1}^{\alpha}, m_{x1}^{\beta}, m_{y1}^{\beta} \) are the derivatives of the aerodynamics coefficients on the projections of the angular velocity of the landing vehicle on the axis of the related coordinate system;

\( \Delta y, \Delta z \) are the lateral displacements of the real center of mass relative too the longitudinal axis of the landing vehicle;

\( J_{x0}, J_{y0}, J_{z0} \) are the centrifugal moments of inertia;

\( m_{y0}, m_{z0} \) are the aerodynamic coefficients of transverse moments at zero values of angles of attack and glide angle.

Several studies show that the duration of the resonance regime is around several seconds. We can then, in our equations above, neglect the influence of gravity in the dynamic equations of translational
motion, and the products of angular velocities in the dynamic equations of rotational motion. We suppose that the aerodynamic coefficients and their derivatives are constant.

We then have the following simplifications, where $C_n^\alpha$ is the derivative of the aerodynamic coefficient of normal force:

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

$$m_y = -|m_y^\alpha| \beta; \ m_z = -|m_z^\alpha| \alpha;$$

$$C_x = C_x, \ C_y = C_y^\alpha \cdot \alpha, \ C_z = -C_z^\alpha \beta.$$

We can replace all these simplifications in the equations. We then have:

$$\dot{\alpha} = \frac{S}{m} \left( C_n^\alpha - C_n^\beta \right) + \frac{SI^2}{J} w_n^\alpha \frac{q}{V} \alpha -$$

$$- \frac{qSI}{m} \frac{J - J_x}{m} \omega_x^2 + \frac{J - J_x}{m} \left( C_n^\alpha - C_n^\beta \right) w_n^\alpha \alpha -$$

$$- \frac{qSI}{m} \frac{J - J_x}{m} \omega_x^2 + \frac{J - J_x}{m} \left( C_n^\alpha - C_n^\beta \right) w_n^\alpha \beta -$$

$$2 \frac{J - J_x}{J} \omega_x \beta \left[ \frac{SI}{m} \frac{J - J_x}{m} \left( C_n^\alpha - C_n^\beta \right) w_n^\alpha \alpha + \frac{SL}{J} \frac{J - J_x}{m} \omega_x \beta + \frac{SL}{J} \frac{J - J_x}{m} \omega_x \alpha + \right.$$  

$$h_{\alpha} = \frac{J_{yz}}{J - J_x}, \ h_{\beta} = \frac{J_{xy}}{J - J_x}, \ \text{are relative centrifugal moments of inertia.}$$

3 Modelling part and analysis

With the equations determined in the first part, we can write program which that give us data on the landing. We will focus only on one stage of the landing, the last one: the landing on the planet surface. We consider several options for approaching the surface: it is a multifactorial problem. First, we consider that the deviation of the vertical axis of the landing vehicle can be 10 degrees, 20 degrees or 30 degrees. Then, for each of these deviations, we model the landing on a hard surface (such as rock soil) and on a soft surface (such as sand). We then have 6 landing options to analyze. The conditions of the landing are the Earth conditions. Finally, we consider the following data:

- Approach speed to the surface (vertical component of speed): 35 m/s.
- Horizontal component of speed (simulating wind): 10 m/s.

The modelling give us as results the values of the overload along each axis and the total value of the overload for the apparatus, and also for the container with payload that is located inside the landing vehicle. This is landing vehicle like MetNet projects [6].

Figure 1 shows the main stages of the movement: I - Atmosphere entry. Opening primary inflatable braking device; II - Entering the additional inflatable braking device; III - Braking with the additional inflatable braking device; IV - Landing vehicle touch the ground.

![Figure 1. Descent scheme of landing vehicle movement](image-url)
With this data, we can draw curves of the overload. The final goal is to determine the most optimal and the most dangerous approach options.

3.1. Modelling on soft soil (sand)

In this part, we will study the influence on the deviation of the vertical axis of the landing vehicle when it lands on soft soil, such as sand (Figure 1, Stage IV). Let’s compare the overload in each of these situations. At first, we focus on the apparatus itself.

![Figure 2. Overload of the apparatus when landing on soft soil](image)

![Figure 3. Overload of the apparatus on the X axis when landing on soft soil](image)

![Figure 4. Overload of the apparatus on the Y axis when landing on soft soil](image)

What is important to look at when comparing these graphics is the maximum of the overload and the duration in which the overload is non-zero.

On the Figure 2, we can see that the amplitude of the overload with a deviation of 30 degrees is lower than for the two other curves, but it presents another peak after. This last occurrence is not a good thing. The peak for a deviation of 20 degrees has the same amplitude than the one of 10 degrees, but lasts longer. The situation with an approach of 10 degrees seems to be the best.

On the Figure 3, the 10 degrees deviation and the 20 degrees deviation curves have the same amplitude, but the 20 degrees curves lasts longer. The 30 degrees curve has a lower amplitude, but still has the second peak, that is not good for the apparatus.
On the Figure 4, the amplitude of the 30 degrees curve is much higher than the one of two other curves. The 20 degrees deviation curve has a higher amplitude and lasts longer than the 10 degrees deviation one.

So, when landing on a soft soil and considering the entire apparatus, the optimal approach option is a 10 degrees deviation of the vertical axis of the landing vehicle, and the most dangerous one is the 30 degrees deviation of the vertical axis of the landing vehicle. However, the results of a 20 degrees deviation are quite close to the one obtained with a 10 degrees deviation.

Let’s see if the results are the same in the container with payload that is located inside the landing vehicle. For the container, we have the following graphics.

![Figure 5. Overload of the container when landing on soft soil](image)

![Figure 6. Overload of the container on the X axis when landing on soft soil](image)

![Figure 7. Overload of the container on the Y axis when landing on soft soil](image)

On the Figure 5, we can see that the curve for the 30 degrees deviation is almost the highest, is the longest and presents a second peak. The one with the lowest amplitude is the curve for 20 degrees. But this curve lasts longer than the 10 degrees one, which has the highest amplitude.

On the Figure 6, we can make the same remarks than on the Figure 5.

On the Figure 7, it is shown that the 30 degrees deviation curve has, by far, the highest peak, and presents two of them. The 20 degrees deviation curve has the same amplitude than the 10 degrees one, but last longer.
So, in the container, when landing on a soft soil, the most optimal approach option is a 10 degrees deviation of the vertical axis of the landing vehicle, and the most dangerous one is the 30 degrees deviation of the vertical axis of the landing vehicle.

We can then conclude that, when the vehicle lands on a soft soil, such as sand, it is more optimal for it, when focusing on the overload of the apparatus and of the container with payload located inside it, to have a 10 degrees deviation of its vertical axis. It is also more dangerous to land with a 30 degrees deviation of its vertical axis.

3.2. Modelling on hard soil (rocks)
Now we will study the results of the simulations of landing on a hard soil, such as rocks, and compare the overload in the different deviation situations. Let’s focus first on the apparatus.

![Figure 8. Overload of the apparatus when landing on hard soil](image1)

![Figure 9. Overload of the apparatus on the X axis when landing on hard soil](image2)

![Figure 10. Overload of the apparatus on the Y axis when landing on hard soil](image3)

On the Figure 8, we can see that the 30 degrees deviation curve present three peaks, which amplitudes are not the highest, but the duration of the non-zero overload is very long. The 10 degrees deviation curve and the 20 degrees deviation have the same duration time and present only one peak, but the peak of the 20 degrees deviation one is much higher.

On the Figure 9 and 10, we can make the same remarks, as for the Figure 8.
So, when landing on a hard soil and considering the entire apparatus, the optimal approach option is a 10 degrees deviation of the vertical axis of the landing vehicle, and the most dangerous one, by far, is the 30 degrees deviation of the vertical axis of the landing vehicle. Let’s see if the results are the same in the container with payload that is located inside the landing vehicle. For the container, we have the following graphics.

![Figure 11. Overload of the container when landing on hard soil](image)

On the Figure 11, we can see that the 30 degrees deviation curve presents three peaks. The maximum amplitude of each of the three curves are almost the same, the 10 degrees deviation one a little bit higher. The 10 degrees and 20 degrees curves last the same. On the Figure 12, we can make the same remarks.

![Figure 12. Overload of the container on the X axis when landing on hard soil](image)

On the Figure 13, we can see that the amplitude of the peaks of the 30 degrees deviation curve are much higher than the ones of the other curves. These curves have the same duration, but the peak on the 20 degrees deviation curve is higher.

![Figure 13. Overload of the container on the Y axis when landing on hard soil](image)

So, in the container, when landing on a hard soil, the most optimal approach option is a 10 degrees deviation of the vertical axis of the landing vehicle, and the most dangerous one, by far is the 30 degrees deviation of the vertical axis of the landing vehicle.
We can then conclude that, when the vehicle lands on a hard soil, such as rocks, it is more optimal for it, when focusing on the overload of the apparatus and the container, to have a 10 degrees deviation of its vertical axis. It is also more dangerous, and by far, to land with a 30 degrees deviation of its vertical axis.

4. Conclusion
The paper analyzes the movement of the landing vehicle at the final stage of its movement. For this, a system of equations was compiled describing the motion of the landing vehicle. For the composed system of equations, a special program was created that allows one to calculate the motion of such a landing vehicle.

At the final stage of the movement, at the stage of contact with the surface, one of the most important quantities arising is the magnitude of the resulting overloads. It is for this parameter, overloads, taking into account the developed algorithm, the movement was analyzed at the final stage of movement - contact with the surface.

After analyzing the data given by the algorithm, we can say as a conclusion that, during the landing of an apparatus, the deviation of its vertical axis has impact on the landing: the more important the deviation is, the more dangerous the landing become. So the optimal approach options are when the deviation of the vertical axis of the landing vehicle is the lowest, and the most dangerous approach options are when it is the highest.

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