Spacecraft Control During The Descent to The Surface of Jupiter's Satellite Callisto

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***Abstract*—The work study the landing of a spacecraft on the Jupiter satellite Callisto with minimal energy costs, and the minimum required thrust of the engines and the duration of the soft landing maneuver of a spacecraft with a given mass on the satellite were estimated. A distinctive feature of this study is taking into account the weak atmosphere of Callisto, which, however, in the immediate vicinity of the surface has a noticeable aerodynamic drag. Motion modeling was carried out numerically; all the graphical dependencies necessary for motion analysis were built.**

Keywords—spacecraft, landing, jupiter satellite, mathematical modeling, callisto

I. Introduction

Jupiter is the fifth and largest planet in the Solar System. One of Jupiter's moons is Callisto. It is the second largest among all the natural satellites of the planet and, according to NASA experts [1], is one of the most promising objects of the Solar System for colonization. This is due to the remoteness of Callisto from Jupiter, which ensures its geological stability. The orbit of Callisto is almost circular (eccentricity 0.0074) and lies outside the radiation belts of Jupiter (the semimajor axis is 1882700 km) [2], which is also a favorable factor from the point of view of colonization. Callisto is in synchronous rotation with Jupiter, that is, one of the hemispheres is always facing Jupiter, which creates favorable conditions for observing the planet. The satellite has the shape of a ball and its mass characteristics are very similar to the Moon. More recently, scientists have suggested that there may be a salt ocean on the surface of Callisto, which may lie under the ice crust, but the surface of Callisto is dark, most likely polluted with dust and various impurities. There are a huge number of craters on the surface, as well as a large amount of water vapor. The temperature on the satellite can rise up to 150 K, but quickly decreases after sunset. It is also worth noting that so far no landing has been carried out on any of the satellites of Jupiter.

The purpose of this study is to develop a universal mathematical complex for calculating the landing of a spacecraft (spacecraft) on the Jupiter satellite Callisto with minimal energy costs, provided that a ballistic flight scheme is implemented using the Earth-Earth gravitational maneuver to approach the orbit of Jupiter [3].

II. Mathematical model of controlled motion

The chosen ballistic scheme of the mission as a whole assumes that the research spacecraft, after arriving at the Callisto orbit, will be divided into an orbital and two descent vehicles. The main, orbital module, will be used to transmit information to Earth, as well as to map the surface and study the space near Callisto, two identical descent vehicles are designed to descend to the surface in order to conduct research directly on the surface.

The descent vehicle (Fig. 1) is divided into an upper compartment with scientific and service equipment and a lower compartment with a propulsion system and filled tanks. The propulsion system with a total thrust of 80 H includes four engines with a thrust of 20 N each with an exhaust velocity of 2865 m/s. In accordance with the objectives of the mission, the mass of the scientific instruments of the lander was determined, amounting to 6.47 kg. The total weight of the refueled the descent vehicle is 40 kg.

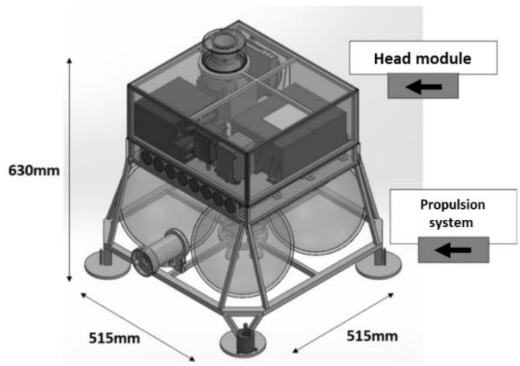

Fig. 1. The descent vehicle

It is assumed that the spacecraft, after reaching the sphere of action of Jupiter and completing all maneuvers, moves into a low circular polar orbit around Callisto. Such an orbit allows for a short time to inspect the entire surface of the satellite from a close distance and choose a landing site taking into account the terrain and prospects for conducting research.

To land from a circular orbit, two pulses of the propulsion system are required. The first pulse from $t_0 = 0$ to t_1 reduces the orbital velocity and the spacecraft makes a gravity turn, that is, it goes from horizontal flight (relative to the surface of Callisto) to vertical descent. The second pulse from $t_1 + t_2$ to $t_1 + t_2 + t_3$ ensures simultaneous equality of altitude and flight speed to zero, that is, a soft landing. During the time from t_1 to $t_1 + t_2$, the spacecraft engine is turned off.

Thus, we need to determine three engine on-off times in order to fulfill three soft landing conditions for the height h, the velocity V and flight path angle θ at the finish time $t_1 + t_2 + t_3$:

$$
\begin{aligned}
&h(t_1+t_2+t_3)=0,\\
&V(t_1+t_2+t_3)=0,\\
&\theta(t_1+t_2+t_3)=-\frac{\pi}{2}.
\end{aligned}
\tag{1}
$$

The motion of the lander is considered under the following assumptions:

1. The descent vehicle is affected only by gravity and the thrust force of the propulsion system;

2. The Callisto's gravity field is considered homogeneous, the gravitational parameter $\mu_{Cal} = 7.17487 \cdot 10^{12}$ m^3/s^2 [3];

3. Callisto is a sphere with radius R_{Cal}=2410.3 km [3];

4. The influence of the Callisto atmosphere is not taken into account on the stage of the gravity turn. In the vertical landing stage we calculated the density of the atmosphere of Callisto in accordance with the data of work [4].

At the stage of the gravity turn, the motion of the descent vehicle is considered in the plane of the waiting orbit in the associated coordinate system:

$$
\begin{aligned}
&\frac{dh}{dt}=V\sin\theta,\\
&\frac{dL}{dt}=V\cos\theta\frac{R_{Cal}}{R_{Cal}+h},\\
&\frac{dV}{dt}=-\frac{P}{m_0-\frac{P}{c}t}-\frac{\mu_{Cal}}{\left(R_{Cal}+h\right)^2}\sin\theta,\\
&\frac{d\theta}{dt}=-\frac{\mu_{Cal}}{\left(R_{Cal}+h\right)^2V}\cos\theta+\frac{V\cos\theta}{R_{Cal}+h}.
\end{aligned}
\tag{2}
$$

Here h is the height of the descent vehicle above the surface, L is range; V is the velocity; θ is the flight path angle; P and c are the thrust and the exhaust velocity corresponding of descent vehicle, m_0 is the initial mass of the descent vehicle.

The gravity turn method is the simplest control method in which the control system orients the thrust vector of the engine against the velocity vector. At the same time, fuel consumption is close to the minimum. At the end of the braking section, the velocity of the spacecraft tends to zero, and the orientation of the longitudinal axis of the spacecraft due to the action of gravitational acceleration to the vertical position. That is, at the end of this section, we fulfill the last condition of (1).

After these conditions are met, the vertical landing stage begins. The equations of motion of the spacecraft on the vertical landing stage has a following form.

$$
\begin{aligned}
&\frac{dh}{dt}=-V,\\
&\frac{dV}{dt}=-\frac{P\delta}{m_1-\frac{P}{c}\delta t}+\frac{\mu_{Cal}}{\left(R_{Cal}+h\right)^2}-\sigma\frac{\rho(h)V^2}{2}.
\end{aligned}
\tag{3}
$$

Here m_1 is the mass of the descent vehicle at the end of the gravity reversal stage; $\delta\in\{0,1\}$ is the function of turning on and off the engines of the descent vehicle, in the second section of the vertical descent, if $\delta=1$ then the engine is turned on; σ is the ballistic coefficient of the descent vehicle and $\rho(h)$ is the density of Callisto's atmosphere.

The minimum fuel consumption at the stage of vertical descent is provided by a single activation of the propulsion system. The trajectory of the vertical descent begins with the passive section, where the spacecraft accelerates under the influence of gravity, and the active section, where braking occurs under the influence of the thrust of the propulsion system. In the absence of an atmosphere the durations of the passive and active sections can be calculated analytically, as a solution of two equations.

$$
\begin{aligned}
&V_1+\frac{\mu_{Cal}}{R_{Cal}^2}(t_2+t_3)+c\ln\left(1-\frac{P}{c\cdot m_1}t_3\right)=0,\\
&h_1-V_1(t_2+t_3)-\frac{\mu_{Cal}}{2R_{Cal}^2}(t_2+t_3)^2-\\
&-\frac{c^2m_1}{P}\left(\left(\frac{P}{c\cdot m_1}t_3-1\right)\left(\ln\left(1-\frac{P}{c\cdot m_1}t_3\right)-1\right)-1\right)=0.
\end{aligned}
\tag{4}
$$

Here h_1 is the height and V_1 is the velocity of the descent vehicle at the end of the gravity reversal section, t_2 is the duration of passive vertical movement, t_3 is the duration of active vertical movement.

However, if we take into account the influence of the weak atmosphere of Callisto, the duration of the on-off sections of the engines should be clarified. This refinement cannot be performed analytically, we solved the problem of determining two control parameters - t_2 and t_3 for simultaneous fulfillment the two remaining boundary conditions. At the same time, the values obtained by formulas (4) were used as initial approximations.

III. Simulation Results

We numerically simulate a controlled motion of descent vehicle after arrival spacecraft in circular orbit around Callisto. The gravity turn section was calculated for the following initial conditions: the orbital altitude of $h=700$ km, the velocity of the descent vehicle is equal to the circular velocity of $V=1.519$ km/s, the initial flight path angle is $\theta=-0.1$ deg. The duration of the gravity turn was $t_1=610.4$ s. Fig. 2 shows the simulated trajectory of the gravity turn section of descent and Fig. 3 shows the flight path angle changing.

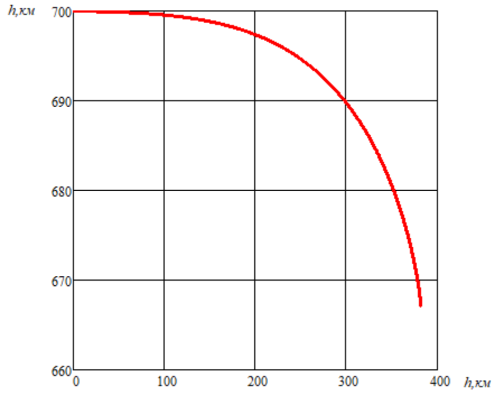

Fig. 2. The simulated trajectory of the gravity turn section

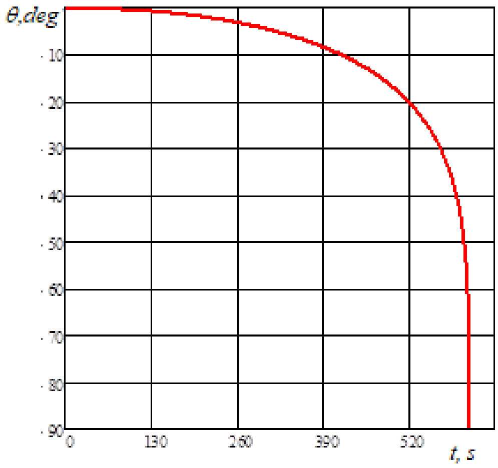

Fig. 3. The flight path angle changing at the site of the gravity turn

In the process of performing a gravity turn, the height of the descent vehicle decreases to h_1 = 667.1 km, and the velocity reaches V_1 = 0.257 m/s. The maneuver consumes 17.047 kg of the working fluid of the propulsion system, that is, the mass of the descent vehicle is m_1 = 22.953 kg. These data are the initial conditions for the vertical descent stage.

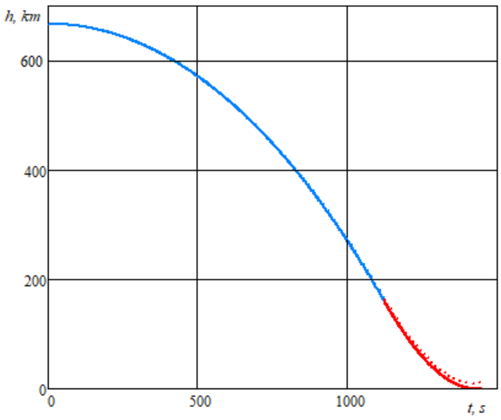

Fig. 4. Graphs of the height on time in the vertical descent section

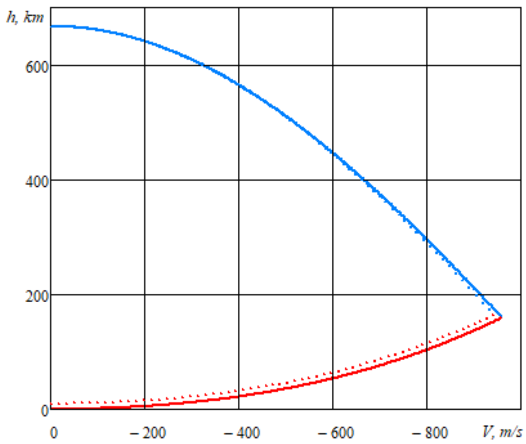

Fig. 5. Graph of the height on velocity in the vertical descent section

Taking into account these initial conditions of the initial approximately durations of passive and active vertical movement, the resulting solutions of the system of equations (4) t_2 = 869.1 s and t_3 = 332.5 s. After clarification, taking into account the braking from the Callisto atmosphere, the duration of the sections was t_2 = 1124.2 s and t_3 = 322.6 s.

Fig. 4 and 5 show the results of modeling the vertical descent section. In both figures, the blue line shows the passive path, the red line shows the braking area before landing. The Fig. 4 shows the graphs height on time dependence for two cases. The dotted line corresponds the using of initial approximately durations t_2 and t_3, the solid line corresponds to the final solution.

The Fig. 5 shows the graphs of the height on velocity dependence for two cases. Although the lengths of the sections have changed slightly, it can be noted that if the correction had not been carried out, the soft landing conditions would not have been met. In addition, the maximum speed of the descent vehicle on the trajectory decreased from 1056 m/s to 987 m/s. After the vertical descent, the mass of the spacecraft will be 13.64 kg. It took 26.36 kg of working fluid to implement the entire descent.

CONCLUSION

The paper studied the landing of a spacecraft on Jupiter's satellite Callisto, taking into account the weak atmosphere of Callisto, which, however, in the immediate vicinity of the surface has a noticeable aerodynamic drag, which affects the control parameters of the soft landing process. It is shown that the descent parameters obtained without taking into account the atmosphere cannot meet all the requirements of a soft landing. As a result of the research, a mathematical complex was developed to calculate the landing of a spacecraft on the Jupiter satellite Callisto with minimal energy costs, and the minimum required for a soft landing of a spacecraft with a given mass on the satellite was estimated.

ACKNOWLEDGMENT

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