INVESTIGATION OF THE STABILITY OF THE STEADY MOTIONS OF A ROTATIONAL MECHANICAL SYSTEM

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Abstract: The conditional stability of steady motions of a mechanical isolated system consisting of a rotating carrier body, a material point creating its static imbalance, and a passive automatic balancer consisting of two identical mathematical pendulums are investigated. The pendulums are mounted on the longitudinal axis of the supporting body and move in the plane of static imbalance. The relative motion of the pendulums is impeded by viscous drag forces. It is established that in the case when the imbalance is and the pendulums can eliminate it with a certain margin, there is one basic movement; in the absence of imbalance, there is a one-parameter family of basic movements; in the case of maximum unbalance, which pendulums can eliminate, there is one basic movement, but it generates a pseudo-family of basic motions. It is also established that conditionally asymptotically stable are separate basic motions, if they are isolated, or a family, or pseudo-families of basic motions. For pendulum, ball and liquid automatic balancers, an approximate law is obtained for the variation of large nutation angles in the case of an axisymmetric and non-axisymmetric supporting body.

It is established that the rate of change of the nutation angle is significantly affected by the ratio between the axial moments of inertia of the rotating carrier and the coefficient of viscous drag. An empirical formula is proposed for estimating the residual nutation angle, which occurs when the passive automatic balancers (nutation dampers) are incorrectly installed on the spacecraft and stabilized by rotation, and an example of its application for a particular satellite is given. It is shown that incorrect installation of the auto balance on the supporting body can lead to the formation of a residual nutation angle even in the case of a "stable" supporting body. The obtained results can be used in the design of passive automatic balancers (nutation damping) (pendulum, ball and liquid) for spacecrafts stabilized by rotation.

Keywords: carrying body, pendulums, stability of motion, spacecraft, passive automatic balancers, damper, static imbalance, nutation angle.

1. Introduction

Taking into account the active development of microelectronics, technologies and materials, the tendency in the space industry of various countries to increase the share of so-called small spacecraft [1, 2], whose mass does not exceed 1000 kg. Small spacecrafts have a number of important advantages [3] in front of large spacecrafts, namely:

– relatively short project implementation times (no more than 3–4 years);

– lower costs and risks associated with the development, launching into orbit and their further operation;

– the possibility of creating simple, reliable and universal platforms for solving various scientific and national economic problems.

The further development and increase in the share of small spacecrafts also indicated by the development of so-called “cluster” space communication systems, remote sensing of outer space and the Earth, based on mini-, micro- and nanosatellites [4, 5]. Such space systems have an increased coverage of space, high efficiency and reliability of the system as a whole due to the formation and maintenance of the orbital grouping.

It is important to note that the degree of implementation of various tasks (for example, early detection of changes in the natural environment, global monitoring and forecasting of the state of atmospheric and “cosmic” weather, radio monitoring and video surveillance of territories and objects, gravimetry, geodesy, radiophysics, etc.) space with the help of small spacecrafts, largely depends on the technical and operational characteristics of stabilization systems. Considering the size and weight of small spacecraft, very strict limitations are imposed on stabilization systems (small mass and overall dimensions, low energy consumption, simplicity of design, reliability, etc.). The passive stabilization systems satisfy these requirements to the greatest extent [6–8]. Despite this, the use of passive stabilization systems is rather limited, due to their low accuracy. For example, according to the data of [9–11], for different spacecrafts, the nutation angle (pendulum, spherical, liquid) stabilized by rotation with pendant damping stabilized on them, the residual nutation angle reached degrees, and was observed even after a long period of time.

An attempt to explain the occurrence of such “anomalous” residual nutation angles, for fluid damping of the nutation angle, was made in [10, 11]. Thus, the appearance of the nutation angle was due to the imbalance formed due to the large surface tension of mercury. Surface tension forces can’t collect all the mercury together, so they collect it in separate parts. But given that the imbalance from mercury is not as high as possible, such model does not explain the large residual nutation angles that occur when, for example, alcohol dampers of the nutation angle are used (it is known that the alcohol has a slight surface tension).

It was shown in [12] that the damping of the nutation angle can significantly affect the motion of the spacecraft, while the movements in which the spacecraft rotates not around the longitudinal axis but around the axis close to it can be stable.

Let’s note that the work devoted to the study of the dynamics and stability of the motions of the rotating spacecraft-damper system has one general significant drawback, which even today does not allow to explain the resulting residual nutation angles. Namely, the fact that passive dampers of nutation angle (pendulum, ball and liquid) simultaneously possess the properties of passive automatic balancers is not taken into account. All this leads to the need to study the stability of steady-state motion of systems in which bodies attached to a rotating spacecraft manifest the properties of not only the damper, but also the automatic balancer.

To increase the accuracy and efficiency of passive stabilization systems used on rotating spacecrafts, it was suggested in [13–18] to use passive classical (pendulum, spherical) and non-classical (in the form of absolutely rigid bodies, in some way fixed in place of longitudinal axis of the spacecraft) automatic balancers.

The aim of this work is studying the process of eliminating both linear and angular deviations of the longitudinal axis of the spacecraft from the axis of rotation by classical passive automatic balancers (pendulum or ball).

To achieve this aim, the following tasks are accomplished:

– to investigate the stability of the steady movements of a mechanical system consisting of a rotating spacecrafts with a pendulum (ball) passive automatic balancer;

– to investigate the effect of system parameters on the speed of arrival of the system to the motion, in which the longitudinal axis of the spacecraft coincides with the axis of rotation;

– to investigate the process of eliminating large nutation angles by passive automatic balancers (pendulum, spherical and liquid).

A mechanical model of an isolated system with viscous dissipation of energy is used for research. The isolated system consists of a rotating carrier and attached bodies. The relative motion of the attached bodies is impeded by viscous drag forces (internal dissipative forces). Since the system is isolated, for it the laws of motion conservation of the center of mass and the kinetic moment of the system hold. In concrete isolated systems consisting of a supporting body and attached bodies, which form passive automatic balancers, there are basic and secondary steady movements. On the main movements in which the position of the rotation axis of the supporting body stabilizes, the longitudinal axis of the supporting body coincides with its axis of rotation, and on the side axes – no.

2. Methods

In mechanical systems, which are spacecrafts stabilized by rotation with pendulum or ball automatic balancers, unlike known ones, along with isolated steady movements, one- or multi-parameter families of steady motions can appear. Since in practice only stable movements are realized, the study of such mechanical systems reduces to isolating all the steady movements and examining them for conditional stability (provided that the conservation laws of the motion of the center of mass and the kinetic moment of the system hold).

Studies of the conditional stability of steady motions are conveniently carried out with respect to moving axes, in connection with which:

– the conditional stability of steady-state motions is considered for the relative equilibrium position of an isolated mechanical system;

– to study the relative stability of the relative equilibrium position of an isolated mechanical system, the theory of conditional stability of stationary motions of nonlinear autonomous systems is applicable;

– to study the elimination of large angle corners of the nutations of spacecrafts stabilized by rotation by passive automatic balancers, the energy sink method is applicable.

3. Results

In the framework of the theoretical–mechanical model of considered isolated system, it is established that the basic motions in which the position of the rotation axis of the supporting body stabilizes are conditionally asymptotically stable. The conditional asymptotic stability of the basic motions occurs only in the case when the transverse axial moments of inertia of the supporting body are greater than the longitudinal axial moment of inertia, and the distance from the equilibrium plane to the center of mass of the system does not exceed a certain limiting value.

The optimum values of the system parameters (the number of rotations of the supporting body, the distance from the equilibration plane to the center of mass of the system, the coefficient of resistance, the height of the generatrix of the cylindrical body of the supporting body, the mass and length of the pendulums) are found at which the speed of arrival of the system to the main motion will be the greatest. It has also been established that the values of the system parameters at which the basic motions are stable can vary within fairly wide limits.

For pendulum, ball and liquid automatic balancers, an approximate law of variation of large nutation angles is obtained and it is shown how attached bodies in the form of pendulum, ball or liquid automatic balancers (nutation damping) change the behavior of the supporting body (**Fig. 1**). It is established that the rate of change of the nutation angle is significantly affected by the relationship between the axial moments of inertia of the bearing body and the coefficient of viscous drag forces.

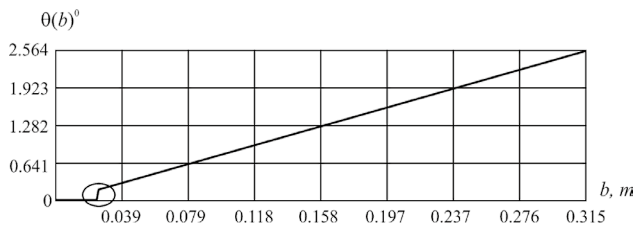

Fig. 1. The graph of nutation angle change θ(*b*) from the distance from the center of mass of the supporting body to the balance plane of the automatic balancer (nutation angle dampers) b if it is incorrectly installed

4. Discussion

The theoretical significance lies in the fact that with the help of the developed approaches it is possible to solve a wide class of problems on the stability of steady-state motions of rotating mechanical systems with viscous energy dissipation. The practical significance lies in the fact that a single passive method for eliminating the nutation angle of an unbalanced rotating spacecraft with passive automatic balancers has been developed. Conditions for the stability of the basic motions of various mechanical systems that simulate spacecrafts and artificial satellites of the Earth are determined, which can be used in the design and calculation of their parameters.

The obtained results can be used in the design of automatic balancers (nutation angle dampers) for spacecrafts whose position in space is stabilized by rotation.

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