Increasing the Accuracy of the Center of Mass Stabilization of Space Probe with Partially Invariant System

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Abstract. The publication provides analysis of stability of the synthesized control algorithms, proves availability of stability margins in partially invariant systems sufficient for practical implementation. We propose an algorithm for selection of parameters of the stabilization controller, which facilitates minimization of maximum error during stabilization of the tangential velocity of the spacecraft center of mass while ensuring adequate stability margins in the system.

Keywords: *Space probe (SP), stabilization controller (SC), on-board computer (OC), gyro-stabilized platform (GSP), propulsion system (PS), angular velocity sensor (AVS), operating device (OD), space vehicle (SV), feedback (FB), control actuator (CA), control system (CS), angular stabilization (AS), center of mass (CM)*

Introduction. The thriving space technology is characterized by an increasing complexity of the tasks to be solved by modern space vehicles (SV). The efficiency in solution of such tasks significantly depends upon technical characteristics of the on-board systems ensuring the functioning of the spacecraft. In particular, the flight control profile of the spacecraft, its power performance, dynamic and accuracy characteristics largely determine the type of tasks to be solved and the quality of their solution by a specific spacecraft.

In some cases, when using a control system built according to the principle of program control (the "robust trajectories" method) the efficiency of task solution is much influenced by the accuracy of the spacecraft stabilization system in the powered portion of flight. This concerns, for example, the trajectory correction phases during interplanetary and transfer flights, when the rated impulse execution errors during trajectory correction resulting from various disturbing influences on the spacecraft in the active phase, greatly affect the navigational accuracy. Hence, reduction of the cross error in the control impulse on the final correction phase during the interplanetary flight, facilitates almost proportional reduction of spacecraft miss in the "perspective plane". For example, in some space probes (SP) like Deep Impact [1, 2] and Rosetta mission [3, 4] reduction of cross error by one order during the execution of correction impulse (for modern stabilization systems this value shall be $0.5\ m/s$) results in reduction of spacecraft miss in the "perspective plane" from 200 to 20 km. Such reduction of the miss accordingly increases a possibility of successful implementation of the flight plan, as well as the accuracy of the research and experiments conducted.

Besides improvement of the navigational accuracy, reduction of spacecraft stabilization cross errors in the active phase, it also results in lower total characteristic velocity of corrective impulses, and, consequently, in reduction of fuel required for the correction. So, when the correction speed impulse reaches 30 m/s reduction of cross error during the correction maneuver results in proportional reduction of the required characteristic velocity during the next correction. The data referred to in [5, 6] show that improved accuracy of roll stabilization in the active phase by one order results in reduction of total characteristic correction velocity for Mars interplanetary probe (Mars-96, Russian Federation) from about 20 to 2 m/s, which corresponds to fuel savings approximately by 30 kg, or to increase of the payload mass by 4%. Due to the relatively small weight of modern scientific instruments (about 3-8 kg), even such seemingly small increase of payload weight can significantly extend the program of research and experiments implemented by the spacecraft.

Objectives: to solve the task of significant increase in stabilization accuracy of center of mass tangential velocities during the trajectory correction phases when using the "rigid" trajectory control principle.

Since the time of the active phase in correction maneuvers, which is to be determined by the required velocity impulse, shall not be clearly determined in advance, and quite limited, and because a guaranteed approach enabling to estimate the accuracy, is always used in practice for solving the targeting tasks, we shall understand the maximum dynamic error of the transition process as concerns the drift velocity of the spacecraft to mean the accuracy of the spacecraft center of mass movement stabilization.

Subject of research: The center of mass movement stabilization system in the transverse plane, which is used during the trajectory correction phases.

In order the control actions could be created during the spacecraft trajectory correction phase, a high-thrust service propulsion system with a tilting or moving in linear direction combustion chamber shall be used.

Technique. Functioning of the spacecraft movement stabilization channel in the transverse plane is based on the feedback principle, and together with the spacecraft this channel forms a closed deviation control system. We can consider two channels in this control system: an angular stabilization channel and center of mass movement stabilization channel (Fig. 1).

The angular stabilization channel facilitates angular position of the spacecraft when exposed to disturbing moments. The center of mass movement stabilization channel is to ensure proximity to zero of normal $\dot{y}$ and lateral $\dot{z}$ velocities of the spacecraft under the influence of disturbing moments and forces. In most of the known (model) spacecraft stabilization systems [7-9] the control signal in the center of mass movement stabilization channel is generated according to proportional plus integral control law based on the measurements of tangential velocity of the center of mass $\dot{y}(\dot{z})$ and its integral-linear drift $y(z)$. In the angular stabilization channel, the control signal shall be generated in proportion to the spacecraft deviation angle in the transverse plane $\vartheta(\psi)$ and the angular velocity of the spacecraft rotation in this plane $\dot{\vartheta}(\dot{\psi})$.

The required dynamic accuracy of stabilization of tangential velocities in this system shall be achieved through the choice of the gain in the stabilization controller $k_y, k_{\dot{y}}, k_\vartheta, k_{\dot{\vartheta}}$. If the requirements to the accuracy of center of mass movement stabilization are stiff, the coefficients k_y and $k_{\dot{y}}$ shall be necessarily significantly increased [7].

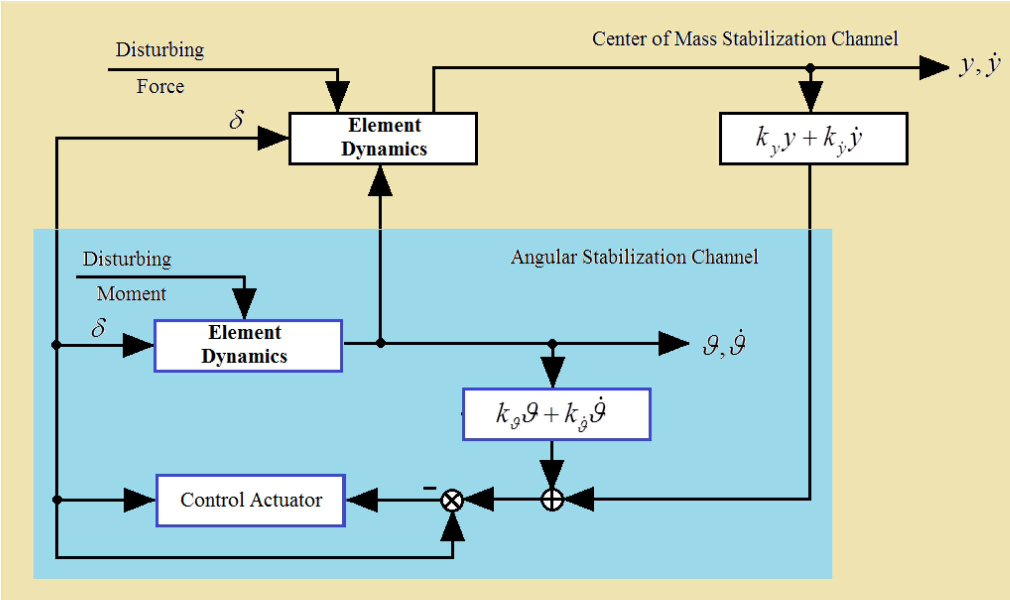

Fig. 1. Functional diagram of model spacecraft stabilization

However, if these coefficients are increased up to desired saturation, the system shall loose its motion stability, and further improvement of the accuracy of the spacecraft center of mass movement stabilization shall be impossible when this method of control is applied. This can be explained by the fact that the increase in the gain values in the center of mass movement stabilization channel results in improved performance of the channel, and the frequencies of the processes occurring in it become close to the frequencies of the angular stabilization channel, which fact enhances interaction of these two channels and makes it impossible to significantly improve the stabilization accuracy of the spacecraft center of mass tangential velocities in the control system concerned.

Results and Discussion. To improve the correction accuracy, the following additional algorithm shall be used in practice [9, 10]. The position of the steering control (turning PS) at the end of the previous active phase shall be memorized and set in its original position before PS is activated during next correction. The improvement of accuracy in this case shall be achieved by partial compensation of the main disturbing factors: eccentricity and thrust misalignment in the propulsion system already in the initial moment of operation of the propulsion system. This algorithm is based on the assumption that eccentricity and thrust misalignment in PS change slightly towards the end of the active phase during the previous correction, and PS setting before a new active phase sets in progress, ensures that the thrust vector goes approximately through the center of mass of the spacecraft, thereby considerably offsetting the disturbing moment.

A similar algorithm was applied in the stabilization system of the Apollo spacecraft [11]. For its implementation, the control system was complemented with a so-called compensation circuit of thrust misalignment influence. The purpose of the referred circuit was to form a component to offset the total control signal so that the thrust vector could pass approximately through the center of mass at zero output signals from the correction filter.

The two main elements of the thrust misalignment compensation circuit are (Fig. 2) a summing register, which is responsible for control signal offset in the correcting filter, and a digital low pass filter, which tracks composite signals from the stabilization system. The difference between the offset and output signals shall be entered into the summing register every 0.5s in order to slowly correct control errors caused by thrust misalignment. The initial value of the offset signal shall be entered into the summing register once, before the correction starts, and based on the information on the results of the previous correction, or shall be determined from special tables, which specify dependence of the position of the center of mass from the spacecraft configuration.

The stabilization systems of Titan IIIC, Kosmos-3M launchers also used subsystems tracking the center of mass positional history, and providing the thrust vector's passage through the center of mass [12].

It should be pointed out that the process of implementation of the described algorithm is confronted by a number of challenges:

- Difference in disturbing factors (moments and forces) during the previous and subsequent corrections results in additional errors in the stabilization of the tangential velocities of the spacecraft center of mass.
- Due to the limited time of the active phase, deactivation of PS during the previous correction may occur even before the completion of the transition processes in the stabilization system, and as a result, the system will remember the deviation of the steering control, which was not final.

Besides introduction of additional control algorithms, there are other ways to increase the accuracy of the center of mass movement stabilization. It is a commonly known fact that one of the ways to achieve high accuracy in automatic control systems, is to use the so-called invariant theory [13-15]. The theory was developed by G. V. Shchipanov (1939), a Soviet scientist, who formulated the task "on compensation of external disturbances" [16]. Now, thanks to research conducted by the Soviet scientists G.V. Shchipanov, B.N. Petrov, V.S. Kulebakin, A.I. Kukhtenko and others the invariant theory represents a developed approach in the general theory of automatic control.

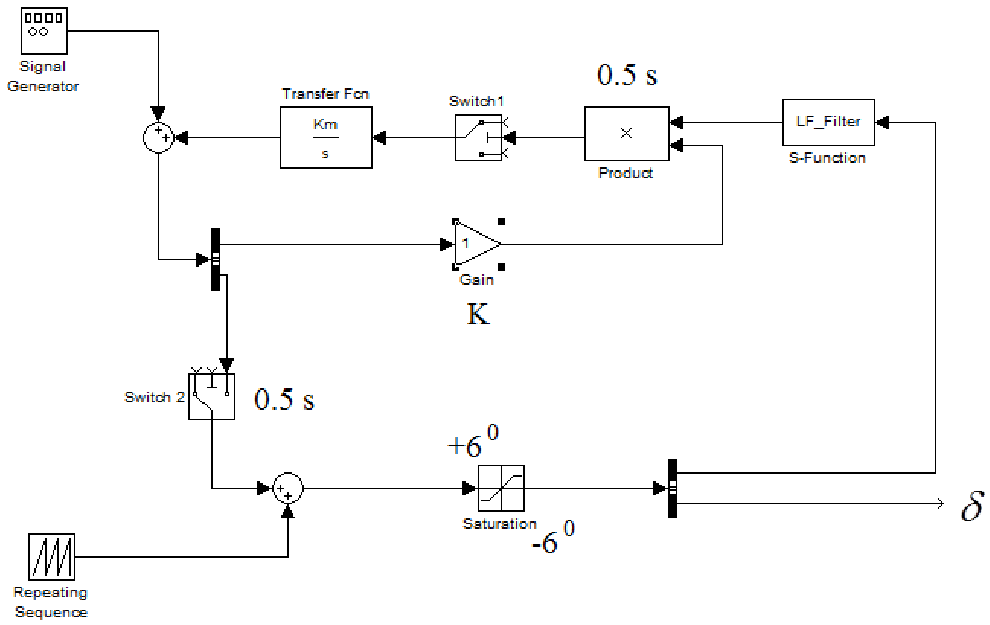

Fig. 2. Block diagram of the compensation circuit of thrust misalignment influence in the Apollo spacecraft

One of the problems inherent in the synthesis of invariant control systems, is the ability for the implementation of such systems in most cases through the use of the deviation control principle, as the simplest one and most widely used in practice (Fig. 3). The publications [17-20] consider the possibility of constructing an invariant deviation control system with one adjustable parameter including an inertial element and a servo control with feedback. The general provisions of the invariant theory prove that no absolutely invariant system can be implemented in this case because this requires that the circuit with feedback should have an infinitely great gain.

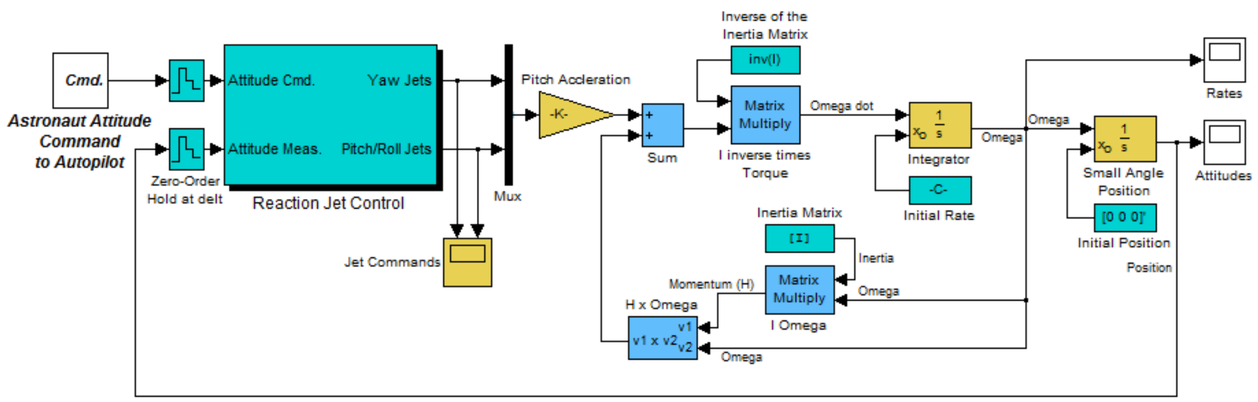

Fig. 3. The Lunar Module Digital Autopilot Design (from MATLAB library)

As a rule, most invariant control systems are based on the use of the information about external influences. Such control systems belong to the class of combined regulatory systems. In particular, the combined systems constitute the majority of invariant systems [21-27].

There is still another method to enforce implementation of invariance conditions without application of combined regulatory techniques [28]. This method is based on the dual-channel principle, which means that in order to ensure the absolute invariance of some adjustable value towards external influence, invariance with respect to the above influence should be ensured between the point of influence application and the measuring point. To implement such a system, it is necessary that two influence distribution channels should be present in the controlled element.

However, the referred task, i.e. stabilization of the spacecraft center of mass movement in the active phase provides no possibility to measure disturbing influence, and the two influence distribution channels exist in the controlled element only for one of the disturbances, namely, for the disturbing moment. Therefore, this publication proposes a way to build a highly accurate stabilization system. We suggest that the requirements to comply with the conditions of invariance should be replaced with conditions of partial invariance when considering implementation of the invariance system. This method shall enable the synthesis of a highly accurate stabilization system, where the drift velocity of the spacecraft is a partially invariant value in respect to the disturbing moment and forces influencing the spacecraft in flight.

The concept of partial invariance in this case means that the invariance conditions for drift velocity shall be met regarding external influences themselves, and not their derivatives.

Meeting the conditions of partial invariance significantly reduces interaction between the angular stabilization channels and the center of mass movement stabilization channel, which is present in the known (applied in practice) stabilization systems [12, 27, 29-34] and does not allow significant improvement of stabilization accuracy of the spacecraft drift velocity.

In order to improve the accuracy of the synthesized algorithms, we propose the application of self-configuring elements, which turn the operating device and X-axis of the spacecraft at angles recorded at the end of the previous active phase before a new active phase begins. The use of the above self-configuring elements in the synthesized invariant algorithms produces the maximum effect in increasing of the dynamic accuracy of tangential velocities stabilization as compared to similar techniques in the existing systems. This is due to the fact that the dynamic error of drift velocity in the synthesized algorithms, shall be largely determined by the initial conditions of the transition process due to the partial invariance of the algorithms proposed, which with the help of the mentioned self-configuring elements, can approach the values corresponding to the established mode as close as possible.

Conclusion. The publication provides analysis of stability of the synthesized control algorithms, proves availability of stability margins in partially invariant systems sufficient for practical implementation.

We propose an algorithm for selection of parameters of the stabilization controller, which facilitates minimization of maximum error during stabilization of the tangential velocity of the spacecraft center of mass while ensuring adequate stability margins in the system.

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