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Modeling of Spacecraft Centre Mass Motion Stabilization System

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Abstract:- The publication suggests how to significantly improve the spacecraft center of mass movement stabilization accuracy in the active phases of trajectory correction during interplanetary and transfer flights, which in some cases provides for high navigation accuracy, when rigid trajectory control method is used. 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.
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), disturbing force.

I. 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. Tis 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 missions [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.

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.

II. 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.

Problem setting. The publication suggests how to significantly improve the spacecraft center of mass movement stabilization accuracy in the active phases of trajectory correction during interplanetary and transfer flights, which in some cases provides for high navigation accuracy, when rigid trajectory control method is used. It is the simplest-to-implement method allowing avoiding more complex control methods. Improvement of control accuracy increases chances for successful implementation of the flight program. However, a significant reduction in the correcting impulse lateral error leads to reduction in fuel required for corrections, and thus increases the payload.

The publication addresses spacecraft which use high- thrust PS for correcting impulses and control at active phases. During the active phase, the spacecraft shall be exposed to disturbances caused mainly by working PS. These disturbances create components of the spacecraft center of mass velocity in the normal and lateral directions (the drift velocity), and the spacecraft center of mass stabilization system is to provide center of mass lateral drift velocities close to zero during active phases. Since the time of the active phase T, which is determined by specified velocity impulse is not known and quite limited during correction maneuvers [8, 9] and in view of the fact that a guaranteed approach evaluating accuracy is always used to solve a guidance task in practice, in this publication, we shall understand the maximum dynamic error of the transition process $\dot{y}_{\max}(\dot{z}_{\max})$ with normal (lateral) drift velocity of the spacecraft as the accuracy of spacecraft center of mass movement stabilization in transverse directions.

Consequently, our purpose is to significantly increase stabilization accuracy of the spacecraft center of mass tangential velocities (reduction of the maximum dynamic error in the drift velocity of the spacecraft in the transition process). This shall be done by synthesis of highly accurate stabilization algorithms in the rigid trajectory control system on the trajectory correction phases outside the atmosphere when using high-thrust engines.

The spacecraft center of mass movement stabilization system in the normal (lateral) plane applied in the trajectory correction phases shall be the subject of research. A high-thrust sustainer PS provided either with deviating or linearly moving combustion chamber shall be used in the correction phase to control motions of the spacecraft.

III. MATHERIALS AND METHODS

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 [9-11] 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 [9]. 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.

To improve the correction accuracy, the following additional algorithm shall be used in practice [11, 12]. 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 [13]. 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. 1) 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 0.5 s 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.

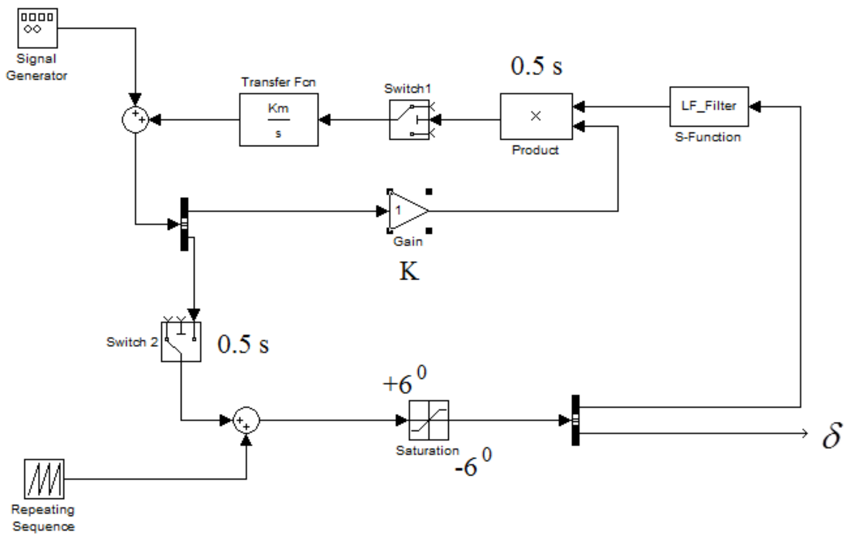

Fig. 1. Block diagram of the compensation circuit of thrust misalignment influence in the Apollo spacecraft

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 [14].

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 [15-17]. The theory was developed by G. V. Shchipanov (1939), a Soviet scientist, who formulated the task "on compensation of external disturbances" [18]. 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.

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. The publications [19-22] 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. 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 [23-29].

There is still another method to enforce implementation of invariance conditions without application of combined regulatory techniques [30]. 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 [14, 29, 31-36] 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. 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.

IV. RESULTS AND DISCUSSION

Synthesis of stabilization algorithms in the system controlling rotations of the operating device. We study motions of the spacecraft in the normal plane of the inertial coordinate system XOY (Fig. 2). The center O of the inertial coordinate system at the beginning of the active phase is the same as the center of mass of the spacecraft; the axis OX coincides with the direction of the required correction impulse $\Delta\vec{V}_{cor}$, axis OY together with axis OX form a normal plane. The angular position of the spacecraft in the normal plane is determined by an angle ϑ between axis OX of the inertial coordinate system and X- axis O_cX_c of the bound coordinate system. Control of the spacecraft in the active phase shall be done by deflection of combustion chamber of PS at an angle δ between X-axis O_cX_c of the spacecraft and X-axis of the nozzle symmetry of PS.

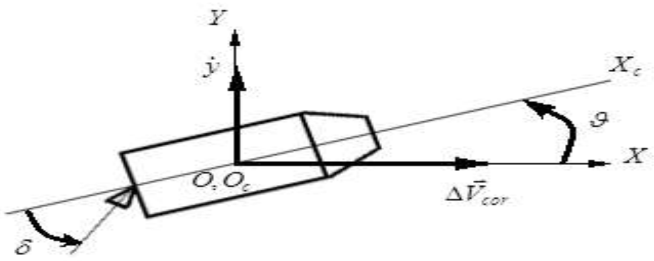

Fig. 2. Spacecraft diagram in the inertial coordinate system

The following assumptions and conditions were used in the process of synthesis of the stabilization algorithms:

1. We assume that the spacecraft is subject to disturbances in the active phase (force F and moment M), which are mainly caused by working PS (tilt and thrust misalignment). Because of their nature, these parameters shall slowly change in time throughout the active phase (except for the period from the start of PS till switching to the nominal operation mode $\approx 0.2s$). For this reason, the disturbances may be considered permanent within the active phase with a reasonable degree of accuracy:

$F = const; M = const$. We shall consider the work of the stabilization system within the entire possible range of disturbances: $0 < |F| \le F_{\max}; 0 < |M| \le M_{\max}$ (experience shows that the maximum force and moment are respectively about 0.3^0 and 3.5^0 in the equivalent deviation angles of PS).

2. The motion of the spacecraft is considered as movement of the absolute rigid body in vacuum relative to the reference trajectory in the normal plane of the inertial coordinate system.
3. A high-thrust chemical engine is used to control the spacecraft in the active phase. Control is provided by deflecting PS combustion chamber. The servo control, which deflects the combustion chamber, includes a feedback control actuator.

To stabilize the angular position of the spacecraft we shall use the information about deviation of the spacecraft body-fixed axes from the axes of the inertial coordinate system implemented in the gyro stabilized platform (CST) on board the spacecraft and the angular velocity sensors (AVS). The information on the deviation of the tangential velocities shall be taken from the accelerometers installed on CSP.

Mathematical model of the spacecraft center of mass motion stabilization system. Taking in consideration the above assumptions and suppositions we can set down a system of equations (1) describing the behavior of the spacecraft center of mass motion stabilization system under study:

$$\begin{cases} \ddot{y} - C_{y\vartheta}\vartheta - C_{y\delta}\delta = F_y \\ \ddot{\vartheta} + C_{\vartheta\delta}\delta = M_z \\ \dot{\delta} = K_{CA}(W_{AS}\vartheta + W_{CM}\dot{y} - K_{FB}\delta), \end{cases} \qquad (1)$$

where $y-$ is the center of mass drift coordinate in the inertial coordinate system; $C_{y\vartheta}, C_{y\delta}, C_{\vartheta\delta} -$ are dynamic coefficients of the spacecraft; $C_{y\vartheta} = C_{y\delta} = \frac{P}{m}$, where $P-$ is PS thrust, $m-$ is mass of the spacecraft; $C_{\vartheta\delta} = \frac{Pl}{I_z}$, where $l-$ is the distance from the gimbal assembly of PS to the center of mass of the spacecraft,

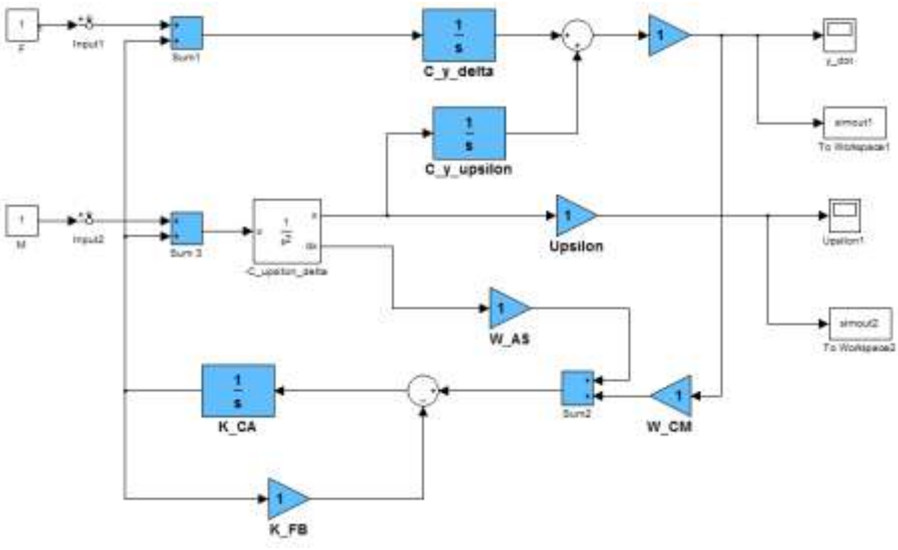

Fig. 3. Block diagram of the spacecraft center of mass motion stabilization system under study

$I_z -$ is momentum of inertia of the spacecraft relative to the axis $0z_c$ of the bound coordinate system; $K_{CA} -$ is a velocity performance index of the control actuator; $K_{FB} -$ is a control actuator feedback index; $W_{AS} -$ is a response function of the angular stabilization controller; $W_{CM} -$ is a response function of the stabilization controller through the center of mass channel.

According to the above mathematical model, a block diagram of the stabilization system under study shall be as follows (Fig.3).

In order to improve accuracy of stabilization while using synthesized algorithms, a model of a model of a standard stabilization system shall be made. It is to be used as a reference model for comparison. The standard stabilization model uses a known stabilization controller [8, 37, 38], which provides control proportionally to the angle ϑ, of the spacecraft angular rotation velocity in the normal plane $\dot{\vartheta}$, linear drift y and the drift velocity $\dot{y}$. A block diagram of the standard stabilization system is shown in Fig. 4.

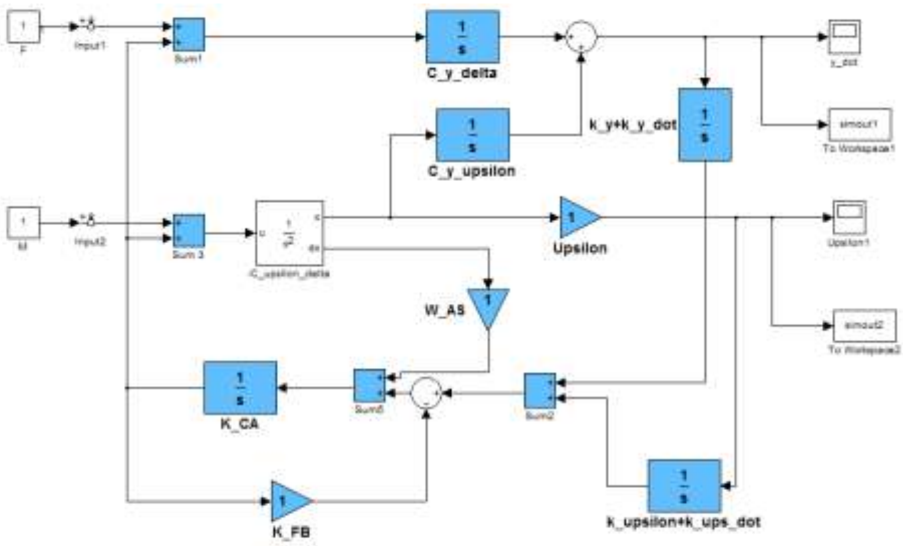

Fig. 4. Block diagram of a standard center of mass motion stabilization system of a spacecraft

Method to solve the problem. As mentioned above, usage of methods of the invariant theory [17, 18, 20, 28-31, 33] is seen as a way to improve the accuracy of the automatic regulation system. In the present case, it is not possible to synthesize the invariant stabilization system using the method of combined regulation, which is traditional for invariant systems because actual measurements of the disturbing effects are not available. However, publications [39, 40] observe that it is possible to build an invariant system without use of combined regulation methods, if we apply the principle of dual-channel impact distribution in the controlled object. The principle of dual-channel impact distribution resides in the fact that if the controlled object has two distribution channels of the same impact, we may achieve mutual compensation of the impact transferred through the above channels by selecting a respective law of control so that the regulated value becomes invariant (independent) of the said impact.

Fig. 3 shows that the controlled object under study has two channels of distribution of disturbing moment M. Therefore, we can improve the accuracy of the stabilization system by using the invariant theory principle. So we select synthesis of high-precision stabilization systems based on the principles of the invariant theory as a method helping us to solve the problem set.

V. CONCLUSION

Based upon research results we can conclude the following:

1. It is impossible to implement a center of mass stabilization system, which is absolutely invariant regarding both the disturbing force and disturbing moment.
2. It is possible to build an absolutely invariant system regarding the disturbing moment due to presence of two distribution channels in the controlled object.
3. A stabilization system, which is partially invariant regarding the disturbing moment, is the easiest to implement in practice. In order to meet the invariance conditions, a positive feedback is required from the flight control actuator with a gain in angular deviation of the object in the angular stabilization channel.

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