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THE NEW CONCEPT OF THRUST VECTOR CONTROL FOR ROCKET ENGINE

Annotation. *The new concept represents a combination of mechanical and gas-dynamical control system for the thrust vector of a rocket engine, the combined application of which allows expanding functionality, improving characteristics and reliability of the flight control system of the rocket stage. Its advantages in solving various problems of controlling the flight of the space stage of a rocket are substantiated. Possible engine scheme with a combined ("bifunctional") thrust vector control system are presented.*

Key words: *rocket engine, jet engine, control and stabilization of flight, bifunctional thrust vector control system*

Introduction

Improvement of rocket and space equipment is strongly defined by further increase of rocket engine systems efficiency. In new application conditions, in particular for launch vehicles space stages, existing rocket propulsion systems (hereinafter PS) do not satisfy new requirements. Especially it's important to expand functionality of rocket PS in terms of flight control.

Following thrust vector control systems (hereinafter TVCS) are widely applied for space stages of launch vehicles which use mostly single chamber liquid rocket engines:

– auxiliary controlling nozzles which work using exhaust gas from turbopump unit

– gimbaled engine or chamber which is deflected in any direction, – so called mechanical thrust vector control system (hereinafter MTVCS)

– perturbation of supersonic flow in the nozzle, – gas-dynamic control system (hereinafter GDTVCS)

Thrust vector control system with controlling nozzles is frequently used regarding simplicity of its scheme and low latency. However such systems practically ran out of ability to handle new challenges for space rockets top stages.

Advantage of MTVCS is its ability to provide unlimitedly big control force almost without engines unit impulse loses. At the same time it requires meaningful increase of weight and size of deflecting drives and development of approaches to provide steady work of thrust

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vector control stabilization system. Where in construction layout circuit has to provide relevant spaces to place hinge nodes, steering unit and on-board power source as result engine station becomes more complex.

GDTVCS practically lacks all of the previous disadvantages because of its smaller size and weight (in comparison to mechanical system). Where in stationary engine does not require additional free spaces in construction layout circuit of engine station. High dynamic characteristics such as low latency and accuracy are important advantages of GDTVCS. Inefficiency in cases when big (more than ~ 3% of engines thrust) control forces.

New thrust vector control concept which is suggested in [1] is BFTVCS (bifunctional thrust vector control system) which represents combination of MTVCS and GDTVCS. This concept applies advantages of MTVCS and GDTVCS and lacks their disadvantages.

Objective of current article is substantiation of BFTVCS advantages, development of basics for characteristics calculation methodic and demonstration of possible schemas.

Substantiation of BFTVCS advantages.

BFTVCS will allow providing optimal efficiency characteristics for thrust vector control devices as for liquid rocket engines so as for solid rocket engines

Control devices efficiency defines control forces (in the projections on the axes of the associated coordinate system) [2]:

$$Y_P = R_i^{(\delta)}\delta,$$

where $R_i^{(\delta)}$ - efficiency of the thrust vector control devices (hereinafter TVCD); δ - state deflection of the TVCS.

Provision of optimal efficiency of TVCD is achieved through solving tasks in different parts of BFTVCS:

- guiding system implements direction and velocity control of flying object;

- stabilization system prevents random deviations from given trajectory.

During design of the launch vehicle space stage TVCD efficiency is chosen to be maximal ($\succ \delta_{\max}$):

$$R_Y^{(\delta)} \succ \frac{|M_{\Pi}| + |M_B| + |M_C|}{\delta_{\max}(x_P - x_C)}, \tag{1}$$

where $|M_{\Pi}|$ - programmatic control moment; $|M_B|$- moment to parry external perturbing influence; $|M_C|$ - moment created by control devices during flight stabilization; x_C - rockets center of the mass coordinate; x_P - control force applying point coordinate.

Regarding chosen efficiency $R_Y^{(\delta)}$ coefficients $c_{\theta\delta}$ and $c_{\vartheta\delta}$ are calculated for equation of perturbed movement:

$$\begin{aligned} &\dot{\theta} + c_{\theta\theta}\theta + c_{\theta\vartheta}\vartheta + c_{\theta\upsilon}\upsilon + c_{\theta\delta}\delta = Y \\ &\ddot{\vartheta} + c_{\vartheta\dot{\vartheta}} + c_{\vartheta\vartheta}\vartheta + c_{\vartheta\theta}\theta + c_{\vartheta\upsilon}\upsilon + c_{\vartheta\delta}\delta = M_Z \ . \\ &\delta = \delta(\vartheta, \dot{\vartheta}) \end{aligned} \tag{2}$$

Solving these equations (for given Y and moment M_Z) movement parameters $\theta, \dot{\theta}, \vartheta, \dot{\vartheta}, \ldots, \delta$ (where θ - pitch angle, ϑ - yaw angle; $\dot{\theta}$, $\dot{\vartheta}$ - coincident angular velocities of stage movement) are defined and compared with maximal allowed values. If needed efficiency of control devices is specified, the calculation is repeated until optimal efficiency conditions are satisfied.

Stability margin of rocket stage (by gain or by phase) is defined from analysis of its perturbed movement with different stability criterions.

Relatively lower latency of one circuit (GDTVCS) comparing to other one (MTVCS) is an important advantage of BFTVCS. Thus oscillations of transient response in low latency circuit of control system are practically damped before the moment when they appear in circuit with high latency. It's needed to mention that MTVCS's reaction speed has an optimum because with its reaction speed increase is followed by increase of its sensibility to high frequency random perturbations and hence random errors are increased. Also systems speed reaction increase leads to significant complication of its elements and in particular its power grow so as mass and size of engine (chamber) steer drives. As a part of BFTVCS these disadvantages are excluded because of alternative control systems combination, where GDTVS satisfies any given requirements to reaction speed and MTVSC provides maximal control forces with minimal power of drives and maximal simplicity of vectoring system in general.

Concept of BFTVCS allows providing such properties for the closed control system (rocket and stabilization automat with feedbacks) which supply suppressing of rockets body elastic oscillations. For transverse elastic waves stabilization automat measures value which includes shift of the body regarding transverse wave:

$$\theta_1 = \theta + \left(\frac{\partial y_{из}}{\partial x} \right)_{x=x_Г}, \tag{3}$$

where $\left(\frac{\partial y_{из}}{\partial x} \right)_{x=x_Г}$ - is the angle between tangent line to curved axe of rocket body in the point of measurer (gyroscope) placement and axe for solid rocket body.

Rockets body elastic oscillations create undesirable strains applied to body. Besides, oscillations create deflection of the engines thrust vector $\left(\frac{\partial y_{из}}{\partial x} \right)_{x=x_{ДВ}}$. This error in programmed angle θ (navigational errors) should be removed by stabilization automate.

The most effective way to suppress transverse elastic oscillation of rockets body is its compensation with other oscillations which have same frequency and amplitude and opposite phase. Resisting oscillations may be created if the accelerometer is used as a sensitive element for stabilization system which signal is inputted into servomechanism that implements vectoring in GDTVSC.

From similarity of equation for generalized coordinate which (q_n), characterizes rockets body self elastic oscillations,

$$\ddot{q}_n + 2\xi_n \omega_n \dot{q}_n + \omega_n^2 q_n = a_n \delta(t), \tag{4}$$

and equation for closed control system got from (4) with substitution of gain coefficients $k_{\ddot{q}_n}$, $k_{\dot{q}_n}$, k_{q_n} for negative feedback signals from sensitive stabilization system elements

$$\ddot{q}_n + 2\xi'_n \omega'_n \dot{q}_n + (\omega'_n)^2 q_n = 0, \tag{5}$$

it means that frequency of systems self oscillations (ω'_n) can be changed in comparison to circuit self oscillations (ω_n). Newly formed dynamical system has new damping ration ξ'_n which can be increased to overcritical value so it allows improving system damping (with adding feedback signals).

In (4) and (5) is indicated:

$q_n(t)$ – generalized coordinate which represents shape of rockets body self oscillations $f_n(x)$; ω_n – frequency of rockets body self oscillations; ω'_n – frequency of systems self oscillations; $2\xi'_n\omega'_n = \dfrac{2\xi_n\omega_n + k_{\dot{q}_n}}{1 + k_{\ddot{q}_n}}$; $(\omega'_n)^2 = \dfrac{\omega_n^2 + k_{q_n}}{1 + k_{\ddot{q}_n}}$.

Using such an active method of stabilization, rockets body oscillations damping is carried with creation coincident oscillation of control force from GDTVCS by the signals from measurers (acceleration, speed and deflection) which are placed at points where maximal signals can be got. These signals are used to damp oscillations which caused them. Additional feedback from high speed gyroscope is inserted to BFTVCS and GDTVCS creates transversal force which is proportionally to angular velocity of transversal oscillations of rockets body. Placement of measurers is chosen regarding closed system equation (elastic rocket body with stabilization automate)

$$\left(1 + k_{\ddot{q}_n}\right)\ddot{q}_n + \left(2\xi_n\omega_n + k_{\dot{q}_n}\right)\dot{q}_n + \left(\omega_n^2 + k_{q_n}\right)q_n = 0, \tag{6}$$

taking in account rockets body self oscillations and placement of control devices (points of application for control forces which are created by GDTVCS).

In (6) it's indicated: k_q gain coefficients of stabilization automate for generalized coordinate $q_n(t)$ and its derivatives.

Choosing correct placement for high speed gyroscope can able control forces created by GDTVCS to damp of rockets body elastic oscillations which are caused by transversal force R_Y. Damping this oscillation is as more effective as higher value of

$$R_Y f_n(x_\Gamma) f'_n(x_\Gamma)/m_n, \tag{7}$$

where R_Y - efficiency of GDTVCS; $f_n(x_Г)$, $f_n'(x_Г)$ - self oscillation shape value and value of the tangents incline to it in gyroscope placement point; m_n - reduced mass of rockets body during n-tone shaped oscillations.

As a rule low amplitudes and frequencies are taken and safe in terms of rockets body durability and allowed during multifunctional control system design because their prevention complicates construction (MTVCS). In this case ability of BFTVCS to damp any auto oscillations without complication of construction is an advantage of BFTVCS.

Thus new rocket engines thrust vectoring concept allows solving concerns of flight accuracy and construction durability. At the same time goals of guidance (provision of programmed rocket flight), stabilization (provision of steady angle movement) and active damping of rockets body elastic oscillations. Having minor mass of the drives BFTVCS and simplicity of its construction, GDTVCS allows to parry random perturbations of any frequency which influence the rocket and MTVCS provides controlling forces of any value which parry determined perturbations.

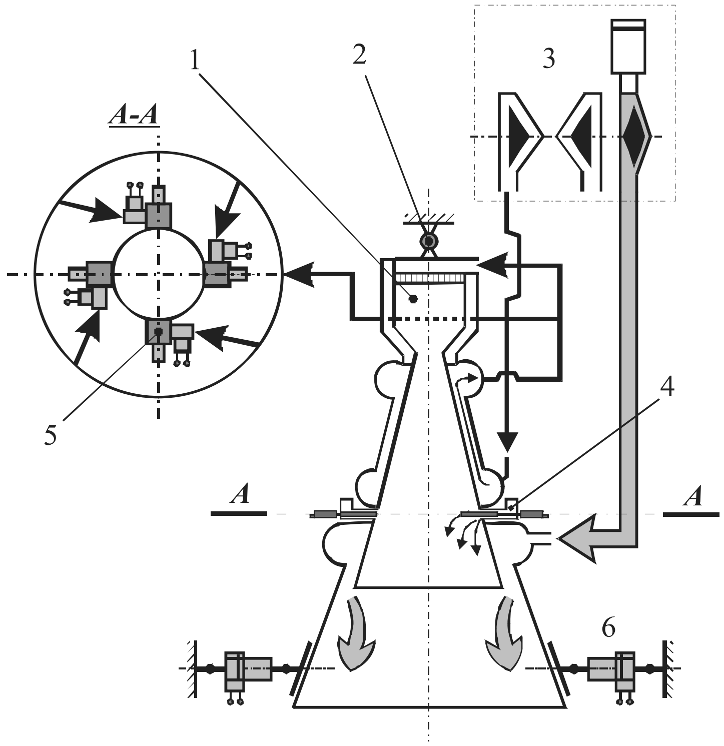
Characteristics of BFTVCS as a part of the rocket stage estimation show that exclusion of need to improve MTVCS dynamic characteristics is compensated (with mass characteristics and complexity of systems realization) by adding GDTVCS to control system. At the same time the previous advantages of BFTVCS are implemented.

Scheme of BFCS

In [3] different combinations of thrust vectoring devices as a part of BFTVCS are substantiated taking in account rockets mission, final velocity, flight conditions and etc. On fig. 1 shown scheme of liquid engine with BFTVCS which is used as a possible base of other systems in coincidence with proper usage conditions. Main traits of BFTVCS are gimbal 2; injection node 4; chamber deflection drives 6.

Deflecting drives of the chamber are placed on the nozzles edge. For nozzle with high expansion rate such a placement of drives practically prevents its deformations during perturbations of the supersonic flow (in the nozzle) and inertial loads to the nozzles wall in process of working engines chamber deflection. At the same time hinge moment in deflecting circuit is decreased regarding to deflection vector increase.

It is needed to mention that such a scheme of BFTVCS may be designed on base of solid rocket engine which, for example, has deflecting nozzle.



1 – combustion chamber; 2 – gimbal of the chamber; 3 – turbopump unit;

4 – injection nodes; 5 – control devices of the injection nodes;

6 – deflecting drives of the chamber

Fig. 1 – Scheme of the liquid rocket engine with bifunctional thrust vector control system

Conclusions

BFTVCS allows providing optimal characteristics in terms of trust vectoring devices efficiency as for liquid so as solid rocket engines.

Important advantage of BFTVCS is much lower latency of one of the circuits (GDTVCS) relatively to other (MTVCS). Thus transition response in low latency circuit of control system practically damp before they could appear in high latency circuit.

Disadvantages of the control systems which included into BFTVCS are excluded because of combination of their alternative characteristics: GDTVCS provides any preset reaction speed requirements and MTVCS provides maximal control forces with minimal power of the drives and maximal simplicity of the systems elements.

BFTVCS allows providing such properties of closed system (rocket and stabilization automate) which contribute damping rockets body transverse elastic oscillations.

In case of BFTVCS usage on the space stage of the rocket with mass center which changes during the flight it allows solving complex task of parrying high mass asymmetry of the stage and its stabilization in conditions of perturbations with wide range of frequency characteristics.

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