УДК 629.78.533.6.013:621.45

N. S. PRYADKO, N. P. SYROTKINA, E. L. TOKAREVA

INCREASING THE EFFICIENCY OF COMBINED CONTROL OF THE ROCKET ENGINE THRUST VECTOR

Institute of Technical Mechanics
National Academy of Sciences of Ukraine and the State Space Agency of Ukraine,
st. Leshko-Popelya, 15, Dnipro, Ukraine, 49005; e-mail: sinatal@ukr.net

Рішення нових завдань управління космічним ступенем ракети вимагає вдосконалення виконавчих органів регулювання вектора тяги ракетного двигуна з метою зменшення енерговитрат на управління, спрощення їх конструкції, підвищення їх динамічних характеристик і надійності.

В результаті попередніх досліджень, в яких брали участь автори даної роботи, була запропонована і обгрунтована нова концепція управління вектором тяги – біфункціональна система, заснована на комбінації механічної і газодинамічної систем управління вектором тяги двигуна. Таке рішення щодо вдосконалення органів управління вектором тяги дозволило реалізувати переваги складових подсистем, виключивши їх недоліки.

У даній роботі зроблено акцент на недоліки нової концепції системи управління вектором тяги двигуна, а саме – наявності в конструкції системи приводів повороту елементів двигуна, які мають велику масу.

Запропоновано та обґрунтовано нове рішення по виключенню цього недоліку шляхом передачі функції приводів (на поворот елементів двигуна) газодинамічній системі.

Показано, що при цьому велика сила, що повертає двигун щодо шарніра, створюється газодинамічною системою в імпульсному режимі, що виключає великі втрати енергетики (при роботі газодинамічної системи) на поворот двигуна. Стабілізація ступені ракети здійснюється керуючими силами малої амплітуди і високої частоти, що створюються газодинамиічною системою управління. Таким чином біфункціональна система управління вектором тяги трансформується в цілком газодинамічну, тільки з шарнірним вузлом для повороту елементів двигуна (в досліджуваному варіанті цей елемент – камера згоряння двигуна). Виключення приводів зменшує масу системи управління вектором тяги, підвищує її надійність, уможливлює повне відпрацювання динаміки системи управління вектором тяги космічного ступеня ракети в земних умовах, оскільки відсутня необхідність повороту двигуна при його відпрацюванні. Втрати енергетики на управління вектором тяги (втрати питомого імпульсу двигуна) запропонованої системи не перевищують втрат економічної механічної системи (поворотом двигуна).

Решение новых задач управления космической ступенью ракеты требует совершенствования исполнительных органов регулирования вектора тяги ракетного двигателя с целью уменьшения энергозатрат на управление, упрощения их конструкции, повышения их динамических характеристик и надежности.

В результате предшествующих исследований, в которых принимали участие авторы данной работы, была предложена и обоснована новая концепция управления вектором тяги – бифункциональная система, основанная на комбинации механической и газодинамической систем управления вектором тяги двигателя. Такое решение по совершенствованию органов управления вектором тяги позволило реализовать преимущества составляющих подсистем, исключив их недостатки.

В данной работе сделан акцент на недостатке новой концепции системы управления вектором тяги двигателя, а именно – наличии в конструкции системы приводов поворота элементов двигателя, обладающих большой массой.

Предложено и обосновано новое решение по исключению этого недостатка путем передачи функции приводов (на поворот элементов двигателя) газодинамической системе.

Показано, что при этом большая сила, поворачивающая двигатель относительно шарнира, создается газодинамической системой в импульсном режиме, что исключает большие потери энергетики (при работе газодинамической системы) на поворот двигателя. Стабилизация ступени ракеты осуществляется управляющими силами малой амплитуды и высокой частоты, создаваемыми газодинамической системой управления. Таким образом бифункциональная система управления вектором тяги трансформируется в целиком газодинамическую, только с шарнирным узлом для поворота элементов двигателя (в исследуемом варианте этот элемент – камера сгорания двигателя). Исключение приводов уменьшает массу системы управления вектором тяги, повышает ее надежность, делает возможным полную отработку динамики системы управления вектором тяги космической ступени ракеты в земных условиях, поскольку отсутствует необходимость поворота двигателя при его отработке. Потери энергетики на управление вектором тяги (потери удельного импульса двигателя) предложенной системы не превышают потерь экономичной механической системы (поворотом двигателя).

Solving new problems of rocket space stage control calls for improving rocked engine thrust vector control actuators in order to reduce energy consumption for control, simplify their design, and improve their dynamic performance and reliability.

As a result of previous studies, in which the authors of this work took part, a new bifunctional thrust vector control system based on a combination of a mechanical and a gas-dynamic thrust vector control system was proposed and substantiated. That solution on thrust vector control improvement made it possible to realize the advantages of the constituent subsystems, while eliminating their disadvantages.

This paper focuses on the drawback of the new concept of thrust vector control, which consists in the need for heavy-mass drives to rotate engine components.

The paper presents and substantiates a new solution on eliminating the above drawback by transferring the function of the rotary drives to the gas-dynamic system.

In doing so, the large force that rotates the engine on the hinge is produced by the gas-dynamic system in a pulsed mode, thus eliminating large energy consumption (during the operation of the gas-dynamic system) for engine rotation. The rocket stage is stabilized by control forces of small amplitude and high frequency produced by the gas-dynamic control system. So the bifunctional thrust vector control system is transformed into a system that is entirely gas-dynamic, except that a hinge joint is used to rotate engine components (in the case under study, the combustion chamber). The elimination of drives reduces the mass of the thrust vector control system, increases its reliability, and allows one to carry out its complete dynamic testing under terrestrial conditions because there is no need to rotate the engine during its operational development. The thrust vector control energy consumption (engine specific impulse loss) of the proposed system does not exceed that of an economy mechanical system (where the trust vector is controlled by engine rotation).

Keywords: *rocket engine; mechanical system; impulse force; gas dynamic system; bifunctional thrust vector control system.*

Introduction. Modern rockets carry out more and more complex flight programs, for example: sequential space different mass object launching on near-earth orbits, short-time maneuvers during the payload element dilution, cargo transportation (partially separated or supplemented), etc. [1]. During the space rocket stage flight its mass, central and dynamic characteristics can vary in a wide range. As a rule, such a stage has a large diameter and a small length, which may cause its own dynamic stage motion instability [2]. In such cases, for solving the tasks of ensuring the required rocket stage characteristics of controllability and stabilization, a significant regulation range expansion and a speed increase of the engine thrust vector (TV) control system are required. This is due to the increase in energy consumption for rocket stage flight control, the design complexity of the TV control system, the need to take measures to ensure the required control system reliability. An capability analysis of the existing engine TV systems shows the difficulty in solving problems of the space rocket stage control with a large mass asymmetry arising in flight (for example, by separating part of the payload). So, for an instantaneous change in the mass center of the space rocket stage, for example, when an asymmetrical separation (addition) of the payload occurs, the mass rocket stage asymmetry is compensated either mechanically (changing the inertia tensor with mass moving) or gas-dynamic (creating a compensating moment, for example, with steering engines). Such mass asymmetry compensation is associated either with constructive difficulties of implementation (in the first case), or with large losses of the engine energy (fuel) [2, 3].

The effective above task solution of the rocket stage control requires the improvement of the executive regulating bodies of the rocket engine TV. Important components of such tasks are: minimizing the energy consumption for TV control, design simplifying of the executive bodies regulating the thrust vector, improving the reliability of both the executive bodies and the whole stage control system.

For stage designing, the efficiency of TV control elements is chosen to be maximal ($\succ \delta_{max}$):

$$R_Y^{(\delta)} \succ \frac{\left(|M_P| + |M_E|\right) + |M_S|}{\delta_{\max}\left(x_R - x_C\right)} \tag{1}$$

where $|M_P|$ is the program control moment; $|M_E|$ – the moment parrying external deterministic disturbances; $|M_S|$ – the moment developed by the control units in the stabilization flight process, determined taking into account the required accuracy provision, speed operation features, oscillation of transient processes (in the control system), etc.; $\tilde{o}_{\tilde{N}}$ – coordinate of the rocket mass center; $\tilde{o}_R$ –coordinate of the application point of the resulting controlling force; $\delta_{\max}$ – max deflection angle.

For the control problem solving according to the chosen efficiency $R_Y^{(\delta)}$ the coefficients $\tilde{n}_{\theta\delta}$ and $\tilde{n}_{\vartheta\delta}$ [3], for the equations of perturbed motion (in the "pitch" guidance plane) are calculated:

$$\begin{aligned} &\dot{\theta} + \tilde{n}_{\theta\theta}\theta + \tilde{n}_{\theta\vartheta}\vartheta + \tilde{n}_{\theta v}v + c_{\theta\delta}\delta = Y \\ &\ddot{\vartheta} + c_{\vartheta\dot{\vartheta}} + c_{\vartheta\vartheta}\vartheta + c_{\vartheta\theta}\theta + c_{\vartheta v}v + c_{\vartheta\delta}\delta = M_Z , \\ &\delta = \delta(\vartheta, \dot{\vartheta}) \end{aligned} \quad (2)$$

the solution of which (for given force values Y and moment M_Z) the motion parameters $\theta, \dot{\theta}, \vartheta, \dot{\vartheta}, \ldots, \delta$ are determined (where the trajectory inclination angle θ to the starting horizon, ϑ is the pitch angle; $\dot{\theta}$, $\dot{\vartheta}$ – corresponding angular velocities of the stage moving) and compared with their maximum allowable values. If it's necessary, the control body effectiveness is refined, and the calculation is repeated until their optimum efficiency is achieved for maintaining the stage along a given trajectory and parrying disturbances acting on the stage. The coefficients $\tilde{n}_{\theta\theta}$, $\tilde{n}_{\theta\vartheta}$, $\tilde{n}_{\theta v}$, $\tilde{n}_{\vartheta\dot{\vartheta}}$, $\tilde{n}_{\vartheta\vartheta}$, $\tilde{n}_{\vartheta\theta}$, $\tilde{n}_{\vartheta v}$ [3].

In general, the effectiveness of rocket engine thrust vector control should be understood as their constructive perfection, loss of energy (specific engine impulse) for thrust vector control, and the thrust vector control system reliability.

New design approaches to the efficient executive rocket engine thrust vector control bodies (TVCB) were formulated in papers [4] – [7]. A bifunctional thrust vector control system (BTVCS), based on a combination of a mechanical thrust vector control system (MTVCS) and a gas-dynamic thrust vector control system (GTVCS), was proposed and substantiated there.

The MTVCS is based on turning engine element (for example, a nozzle element or a whole nozzle, an engine chamber or an engine as a whole) relative to a hinge (various design depending on the rotary element design). The liquid rocket engine (LRE) turn relative to the cardan joint attached to the rocket body can be attributed to the most widespread MTVCS of the space rocket stage.

The MTVCS static characteristics are determined with the lateral control force

$$Y = Đ\sin\delta$$

where P – the engine thrust; δ – the engine rotation angle. From the point of view of ultimate goal achieving of the rocket stage flight program (for example, the final speed), it is possible to consider a decrease in the thrust module on an amount $\Delta Đ = Đ(1-\cos\delta)$ due to the thrust vector deviation at an angle δ (to create a control effort Y) with the engine power losses, which must be compensated by additional fuel reserves. These losses can be expressed also in terms of the engine gas-dynamic quality factor

$$\hat{E} = \frac{Y}{\Delta Đ} = \frac{\sin\delta}{1-\cos\delta}$$

which characterizes the thrust vector control efficiency $R_Y^{(\delta)}$ by turning the engine.

The mass of the MTVCS calculated according to the drawings can be approximately represented as the following components,

$$m = m_{ê} + m_{f} + m_{d}$$

where $m_{ê}$ is the cardan joint mass; m_{f} – mass of fasteners; m_{d} – drive mass.

These static characteristics compared with other thrust vector control systems (for example, steering engines) are fundamental. As for the dynamic characteristics of MTVCS, its relatively slow speed should be noted (due to the relatively large inertia of the turning elements; in determining the dynamic characteristics, the mass of the combustion chamber $m_{\tilde{N}\tilde{N}}$ is also included into the inertia mass). At the same time, the speed of such a system is optimum, since with increasing speed the system sensitivity to the high-frequency components of random perturbations increases that ultimately leads to the system error increase. This is also connected with the complication of problem solution (at low system speed) of the rocket stage stabilization (in the case of its static instability [3]). It should be also noted that the speed increase for MTVCS is connected with the need of the rotation system design complication, increase the power, weight and dimensions of the rotational drives, taking additional measures to ensure the required reliability of the rotation system [2, 4]. The static characteristics of the gas-dynamic system (GDTVCS) are determined with the lateral and axial components of the control force ($Đ_{õ(ó)}$) that occur in the nozzle when a supersonic flow is disturbed with an obstacle on the wall. In this case, it is necessary to distinguish the disturbance by a liquid (injection) and a solid obstacle on the wall. The components of the control force (P_x projection on the axis x ; $P_y \equiv Y$ – on the axis y) arising from injection (blowing or injection) into the supersonic part of the nozzle can be determined by various methods (in particular, differential and integral) [8]. The differential method requires a certain skill in constructing the excessive perturbed pressure field on the nozzle wall and is used mainly to determine the coordinates of the application point of the control force and to calculate the force and heat loads on the nozzle wall. In the outline design for determining the static characteristics of TVCB, as a rule, the integral method is used, based on the experimental dependences of the control force on the obstacle size (the operation fluid consumption during injection or the size of the solid obstacle). In particular, for a common method of the thrust vector control with injecting fluid into the nozzle control force components are determined with a simple ratio

$$Đ_{õ(ó)} = k_{õ(ó)} I_{i} \dot{m}_{i}$$

where $k_{x(y)}$ is the gain (respectively, for the axial "*x*" and lateral "*y*" components of the control force) depends on the geometric characteristics of the injection units (nozzle diameter, set angle relative to the nozzle axis, location of the injection section along the nozzle length, etc.); I_{i} specific impulse of the injected working fluid; $\dot{m}_{\text{i}}$ – injected working fluid consumption. For a solid obstacle the solid obstacle magnitude (height, lateral dimensions, shape, etc.) that obstructs the supersonic flow is the specific impulse and the working medium consumption at the gain.

The GTVCS dynamic characteristics are mainly determined with the characteristics of the working fluid feed system (or solid obstacle) into the supersonic flow of the engine nozzle. In the first approximation the gasdynamic link – the formation of a perturbed flow pattern on the nozzle wall – can be considered inertia-free one (with a small delay ~ 10^{-3} s) [8].

Specific impulse losses in thrust vector control with a gas-dynamic system, in particular when a liquid or gas is injected, are determined by the working fluid consumption for creation a control force, and also depend on many factors (in particular, on the geometric obstacles characteristics in the nozzle gas flow, on characteristics of incoming and injected flows, etc.). When the thrust vector control is realized with moving a solid interceptor into a supersonic flow, the specific impulse loss for control is determined mainly by the losses in the shock waves of the perturbed zone on the nozzle wall and, as estimates show, these losses are an order smaller than ones at injection. A disadvantage of interceptor control (compared to injection) is the need to protect it from the aggressive action of the incident nozzle gas flow, which is indirectly connected with additional losses of the engine specific impulse for interceptor control.

Fig. 1 shows a block diagram of a rocket stage control system with guidance and stabilization subsystems. According to the mentioned principle of the control system decomposition, the “inertial” (with low speed) of MTVCS acts as a guidance subsystem, and the “dynamic” (with great speed) GTVCS is used as a stabilization system.

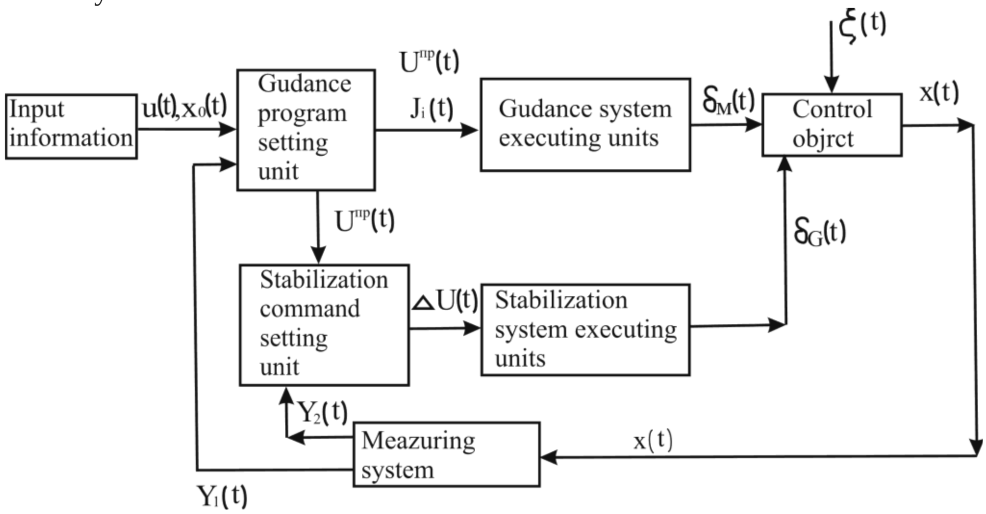

Fig. 1

The block diagram includes the following control functions: $\text{u}(\text{t})$– a predetermined rocket stage guidance program; $\text{x}_0(\text{t})$– initial one-time guidance commands (for example, on the separation of the rocket stage, the payload part separation, etc.); $\text{U}^{\text{P}}(\text{t})$– program formed by the guidance system; $\text{Y}_1(\text{t}), \text{Y}_2(\text{t})$– the actual values of the corresponding motion parameters (1 – guidance, 2 – stabilization) of rocket stages, coming from the navigation system; $J_i(t)$ – distribution of one-time guidance commands; $\Delta U(t)$ – control commands supplied from the stabilization command generation device to the control machines of the control bodies GTVCS; $\delta_{M(G)}(t)$ – deviation of the TVCB (index "M" – for MTVCB, "G" for GTVCB); $x(t)$ – output characteristics of the rocket stage; $\xi(t)$ – disturbances acting on a flight in the trajectory active part.

The specified guidance program $u(t)$, $x_0(t)$ is fed to the device for generating guidance commands $U^P(t)$ and one-time commands $J_i(t)$, which by changing the position of the MTVCS control bodies $\delta_i(t)$, determine the motion characteristics $x(t)$ of the rocket stage. At the same time, the command $U^P(t)$ is given to the device for generating stabilization commands, and after comparing with the signal $Y_2(t)$ received from the navigation system, it is issued as a signal to the control machines of the GTVCS controls that set the angle $\delta_G(t)$ corresponding to the stabilizing control.

The disturbances $\xi(t)$ acting on the rocket stage change the output signal $x(t)$. The modified signal is transmitted via feedback channels $Y_1(t)$, $Y_2(t)$ for the correction of control signals to the MTVCS and GTVCS system. The stabilization signal $\Delta U(t)$ is formed after the $U^P(t)$ and $Y_2(t)$ signal processing in the generating stabilization command device. This signal is mainly determined by random disturbances (internal and external) acting on the rocket stage, and, as a rule, has a relatively small amplitude and high frequency. Its value feeding the executive bodies of the stabilization system GTVCS is determined in the generating stabilization command device from the condition of ensuring minimal losses of the specific engine impulse for thrust vector control, taking into account the signal $U^P(t)$ that runs the rocket stage guidance program.

With all the new concept advantages of thrust vector control the rocket engine, there is a drawback in it - this is the presence of complex mass and energy-intensive drives for turning engine elements.

After analyzing the characteristics of subsystems BTVCS (declared in patents [9 – 11]), it was concluded about the possibility of further improving its characteristics. In particular, a solution was found [12], excluding from its composition the drives in the MTVCS. However, the disadvantage of such a solution was the large energy losses of the engine against the mass asymmetry of the rocket stage. Such a parry is associated with the rotation of the engine (its thrust vector) at an angle that creates the shoulder of the vaporizing mass asymmetry of the moment, that is, in fact, taking the engine thrust vector action the line in the center of rocket stage mass. According to the mention patent (with the absence of a hinge and engine turning function) in the control system the parrying moment is created by a large perturbation of the supersonic flow in the nozzle, which is connected (as it's shown above) with large losses of energy (specific impulse) of the engine. In [5], it was shown that parrying the mass asymmetry of the space rocket stage (in case of the payload part separation) by steering engines or a large perturbation of the supersonic flow in the engine nozzle can be associated with large losses of specific engine impulse. This requires additional reserves of fuel, acting as an additional payload at the first stage of the rocket.

These specific impulse losses can be practically eliminated by reducing the time for creating a large control force (disturbing the gas flow in the nozzle by a large obstacle on the nozzle wall) to a single-moment large disturbance necessary for combining the thrust vector line of the engine with the center of the rocket stage mass and then "zeroing" large governing effort. After a one-time action, the engine thrust vector changes due to the conservation law of the angular momentum and as a result the engine turning in the cardan joint on the required angle to compensate for the asymmetry moment. After getting the required “compensating” rotation angle of the engine thrust vector, the rocket stage movement is stabilized only by small high-frequency control forces created by a small obstacle on the nozzle wall. To implement such a method, it is necessary to leave the hinge, in contrast to the solution of [12], while excluding the motor rotation drives. And in order to implement the decision on large losses elimination of the engine specific impulse for thrust vector control, it’s necessary to introduce a retainer (stopper) of its predetermined position into the design of the hinge assembly. GTVCS realizes the drive function in such a thrust vector control system design. The variety of possible GTVCS implementations (blowing, injection, interceptor, and their combinations) does not change the fundamental approach to creating a moment-inducing mass asymmetry, since the engine rotation in the hinge is accomplished with a large perturbation of the supersonic flow in the engine nozzle, “zeroed” after a single-step (step-by-step) creation of the parrying moment asymmetry. The perturbations of practically any magnitude (for example, caused by a nuclear explosion) are parried in the same way.

For working out such a thrust vector control system of a high-altitude rocket engine (with a large expansion degree nozzle) under terrestrial conditions, it is not necessary to work out the engine rotation characteristics (or its elements) due to the absence of these rotation elements. This greatly simplifies test bench equipment, which can be brought to a simple gas-dynamic pipe. The absence of mechanical drives in the thrust vector control system reduces its mass, improves reliability. Such a thrust vector control system has a small loss of the specific engine impulse for thrust vector control. The small perturbations of the supersonic flow needed to create control forces that stabilize the movement of the rocket stage are comparable in energy costs to the energy consumption for generating efforts by engine turning in the cardan joint.

In fig. 2 there is a circuit of the thrust vector control system as part of a liquid rocket engine, demonstrating the new above describing solution for improving the combined thrust vector control efficiency. The LRE includes a combustion chamber (CC) 1, set on the hinge 2, relatively to which the engine rotates, the nozzle 3 with an annular gap 4 for blowing into the nozzle the generator gas extracted with the gas generator 5 and taken (through line 6) behind the turbine 7 of turbo pump

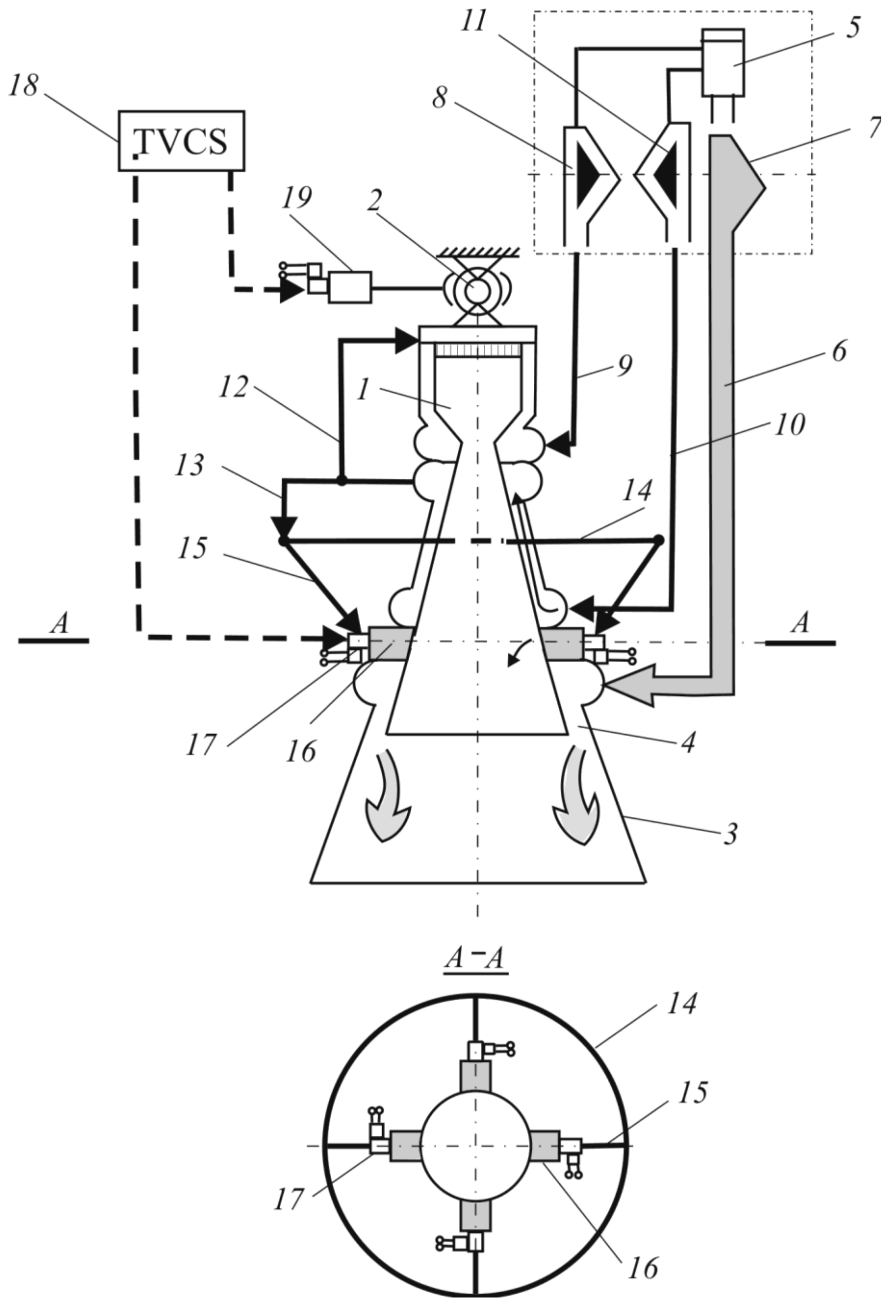

Fig. 2

unit. Fuel taken from the pump 8, on the main 9 enters the nozzle head of the CC. Oxidizer, selected (line 10) from the pump 11, after cooling the nozzle along the line 12 enters the nozzle head of the CC. Along line 13 the heated oxidizer (after cooling the nozzle wall), enters the collector 14 and then goes on line 15 to the thrust vector control units 16 (adjustable nozzles). The fuel injector into the nozzle are controlled by the drives 17 according to commands from the thrust vector control system 18.

The thrust vector control system operation is as follows. If it is necessary to create a large control force amount, TVCS 18 commands the actuators 17 of adjustable nozzles 16 through which a large flow of the fuel injected is fed the nozzle 3 (its value is determined by the TVCS based on the thrust vector control solving problem). The lateral force created at injection, rotates the CC on the required angle, and the hinge is fixed (for example, with a hydraulic lock 19) with a given deflected CC position. This turns off the TVCS channel, initiating a large control effort amount. Small in size lateral forces (required for rocket stage stabilization) are created by units 16 according to commands from the TVCS with the required amplitude and frequency of the generated efforts.

Conclusions. A new solution was proposed and substantiated on improving the bifunctional thrust vector control system of the rocket engine by eliminating of the element engine rotation drives and replacing them with the impulse force of the required size created by the gas-dynamic system. It is shown that the implementation of such an approach to the engine thrust vector control allows at the energy loss for thrust vector control (specific engine impulse), comparing with the loss of the efficient mechanical TVCS, to reduce the mass of the thrust vector control system, to increase its reliability and to realize relatively easy the dynamic fully test of the thrust vector control system of the space rocket stage in terrestrial conditions (without turning the engine in the pressure chamber).

1 *Degtyarev A. V.* Sixty Years in Rocketry and Cosmonautics (*in Russian*). Dnipropetrovsk: ART-PRESS, 2014. 540 pp.

2 *Igdalov I. M., Kuchma L. D., Polyakov N. V., Sheptun Yu. D.* Dynamic Design of Rockets. Problems in the Dynamics of Rockets and Space Stages Thereof (*in Russian*). Dnipropetrovsk: Dnipropetrovsk National University, 2010. 254 pp.

3 *Kolesnikov K. S.* Rocket Dynamics (*in Russian*). Moscow: Mashinostroyeniye, 1980. 376 pp.

4 *Kovalenko T. A., Sirotkina N. P., Kovalenko N. D.* Bifunctional thrust-vector control system of launch vehicle space stage engine (*in Russian*). Teh. Meh. 2015. No. 1. Pp. 42–54.

5 *Kovalenko N. D. , Sheptun U. D., Kovalenko T. A., Strelnikov G. A*. The new concept of thrust vector control for rocket engine. System Technologies. 2017. No. 6(107). Pp. 120–127.

6 *Kovalenko T. A., Syrotkina N. P., Sheptun Yu. D.* On the adaptation of bifunctional systems of liquid-propellant rocket thrust vector control to modern methods and systems of space rocket stage flight control. Teh. Meh. 2017. No. 3. Pp. 45–52.

7 *Kovalenko N. D., Kovalenko T. O., Sheptun Yu. D.* Separate control in response to launch vehicle stage motion parameter disturbances (*in Russian*). Proceedings of the VIth Internatinal Conference "Space Technologies: the Present and the Future" (May 23–26, Dnipro, Ukraine). Dnipro: Yuzhnoye State Design Ofice, 2017. P. 39.

8 *Kovalenko N. D.* Rocket Engine as a Rocket Flight Control Actuator (*in Russian*). Dnipropetrovsk: Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the National Space Agency of Ukraine, 2003. 412 pp.

9 Method for liquid-propellant rocket engine thrust vector control and liquid-propellant rocket engine for its implementation *(in Ukrainian*): Patent for Invention 103528 Ukraine: IPC F02K 9/00. No. a 201114384; filed Dec. 5, 2011; published Oct. 25, 2013, Bul. No. 20. 16 pp.

10 Liquid-propellant rocket engine thrust vector control system with turbine exhaust gas afterburning in the combustion chamber (*in Ukrainian*): Patent for Utility Model 94862 Ukraine, IPC 02 K 9/00. No. a 2014 04258; filed Apr. 22, 2014; published Dec. 10, 2014, Bul. No. 23. 9 pp.

11 Method for liquid-propellant rocket engine thrust vector control and a liquid-propellant rocket engine for its implementation (*in Ukrainian*): Patent for Invention 105214 Ukraine: IPC F02K 9/56, F02K 9/82. No. a 2011 12467; filed Oct. 24, 2011; published Apr. 25, 2014. Bul. No. 8. 8 pp.

12 Method for thrust vector control of a liquid-propellant rocket engine with a propellant component feeding turbopump assembly and a liquid-propellant rocket engine based thereon (*in Ukrainian*): Patent for Invention 107270 Ukraine: IPC F02K 9/00. No. a 2013 06211; filed May 20, 2013; published Dec. 10, 2014, Bul. No. 23. 11 pp.

Received 25.04.2019,
in final form 12.06.2019