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Numerical simulation of jet vane ablation effect on control force

By using advanced computational tools, we developed an engineering design procedure to determine the control force generated due to the deviation of the jet vane in the solid engine. In addition to testing the calculation data, the aim of this study is to have an opportunity of a more detailed examination of the jet vane effect on the flow in a rocket engine, followed by visualization of the processes.

Keywords: jet vane, computational fluid dynamics, thrust vector controls, solid engine.

The most frequent method of thrust vector control is the use of jet vanes (JV), which help mechanize lateral control forces (CF) and torques during jet engine operation. Jet vanes belong to the simplest devices among the variety of available controls. As a rule, JVs are mounted in solid-propellant rocket engines (SPRE) of various classes and purposes. Jet vanes are used to create considerable control forces within a relatively short period of time immediately after engine start, as the missile starts accelerating.

A CF appears once the JV airfoil portion is deflected to a certain angle [1, 2, 3]. To calculate the required CF, we need to determine the lateral surface area, engine thrust loss, and hinge moment depending on the JV turning angle. The shape of the cross-section shall be selected as well. It is difficult to obtain reliable results due to non-uniformity of the gas flow at the nozzle exit, to jet vane airfoil and to the processes of flow interaction with the JV and nozzle walls that result in formation of a complex compression shock wave pattern.

Values of drag coefficient c_x and lift force coefficient c_y are determined depending on the JV airfoil [1]. These coefficients can be calculated based on the results of testing and/or numerical simulation with CF components P_x and P_y calculated using the following formulas:

$$c_x = \frac{P_x}{\frac{\rho_a \upsilon_a^2}{2} S_p}; \qquad (1)$$

$$c_y = \frac{P_y}{\frac{\rho_a \upsilon_a^2}{2} S_p}, \qquad (2)$$

where P_x and P_y – forces acting on JV;

ρ_a – flow density upstream of JV;

υ_a – flow rate upstream of JV;

S_p – jet vane planform area.

Also, there are some empirical methods [4] related to determination of the material ablation rate under the effect of a high-temperature flow of combustion products (CP).

The most promising trend in design calculations of control forces during SPRE operation is the use of advanced computational fluid dynamics software packages. Moreover, accumulated knowledge and expertise, which allow to refine the existing design procedures, combined with off-the-shelf numerical stimulation software packages provide the possibility to implement an engineering design procedure that makes it possible to predict the SPRE operational CF value with a satisfactory accuracy.

This paper describes the method for determining the CF formed upon deflection of the JV at the beginning and at the end of SPRE operation, using an off-the-shelf numerical stimulation software package. We should note that solving this problem involves an analysis of two stationary numerical experiment setup procedures with the initial profile of the JV airfoil portion, as well as with the ablated profile reconstructed in accordance with a real airfoil portion that was kept after bench tests.

The problem was solved in 3D environment. To simplify and accelerate calculations, we developed a design quadrant with one JV. The quadrant angle was 90°.

The inlet channel and computational domain downstream of the nozzle are conditionally simulated for better problem convergence. The inlet channel is a cylindrical section created for uniform distribution of combustion products upstream of the nozzle throat area.

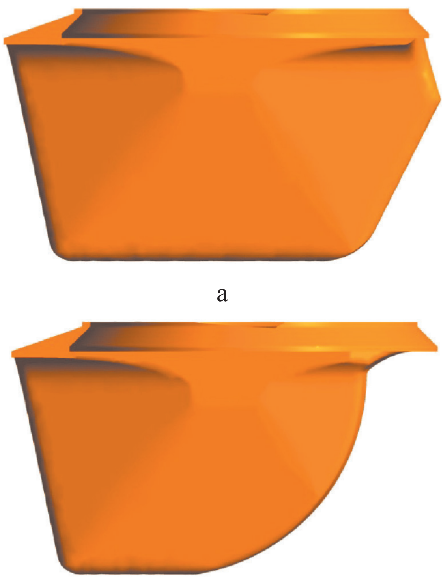
We examined the geometry only with one deflected JV airfoil portion. When analysing the model corresponding to the end of SPRE operation, in addition to the JV airfoil portion, we took into account other characteristics such as the nozzle throat area diameter and the nozzle exit diameter. Loss of material of other SPRE structural elements was not taken into account.

Fig. 1 shows schematic views of initial and finite models of the JV airfoil portion used during calculations.

As noted above, simulation was conducted in stationary conditions. The following flow parameters were selected:

• turbulence model – Shear Stress Transport (SST) model;

• heat transfer model – total energy model (compressed flow with the density being the pressure function);



a

b

Fig. 1. JV airfoil portion profile at the beginning (a) and at the end (b) of SPRE operation

• working medium – solid propellant combustion products with condensed phase.

Properties of combustion products were determined by the results of thermodynamic calculations (thermodynamic and thermal and physical characteristics of propellant combustion products). Dynamic viscosity and thermal conductivity coefficients were approximated by the Sutherland's formula [5].

For problem solving, we took into account condensed phase particles calculated in the Lagrangian model of motion, with its trajectory determined. The particle motion equation was solved with the one-directional problem formulation, and the influence of particles on gas-dynamic parameters was taken into account during thermodynamic calculation of solid propellant combustion products. Although condensed phase particles are different in diameter, they can be simulated as moving points that do no occupy any volume in an extended medium. Interaction of particles was also disregarded.

We should note that particle size distribution complied with the lognormal distribution law [6].

To describe local boundary conditions, we set a uniform inflow of combustion products with the mass flow rate and temperature in the SPRE combustion chamber, as well as the mass flow rate for condensed phase particles. The wall boundary condition was described with the help of an adiabatic surface with the particle rebound coefficient equal to zero, i.e. the condensed phase (c-phase) adhered when interacting with the wall. An open surface with standard atmospheric conditions was assumed to be the output boundary condition.

The computational domain with the specified boundary conditions is shown in Fig. 2.

Calculations were conducted with the JV airfoil portion deflected through the angle equal to 80 % of the JV deflection limit.

Table 1 contains drag and lateral force coefficients for the initial and finite profiles of the JV airfoil portion, which were determined by formulas (1) and (2).

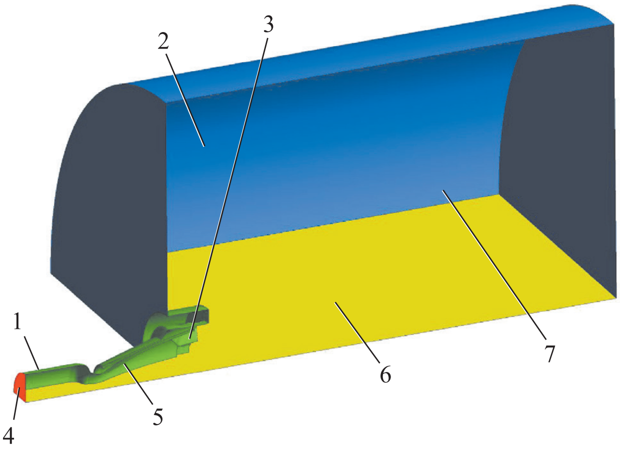


Fig. 2. Computational domain with designated types of boundary conditions:
1 – inlet channel; 2 – area downstream of nozzle; 3 – jet vane; 4 – inlet boundary condition; 5 – adiabatic wall; 6 – symmetry condition; 7 – open surface

Table 1

JV aerodynamic coefficients

JV profile	Drag coefficient, c_x	Lateral force coefficient, c_y
Initial profile of airfoil portion	0.27	0.43
Ablated profile of airfoil portion	0.27	0.26

According to Table 1, the drag coefficient for the initial and finite profiles of the JV airfoil portion at the same pressure level in the combustion chamber and the same deflection angle will be equal. At the same time, the lateral force coefficient is actually reduced by 2 times.

Fig. 3 shows pressure isolines along the structure wall, reduced relative to the pressure in the combustion chamber, measured on the logarithmic scale, for the beginning and the end of engine operation, respectively. With the JV deflected at a certain angle, the pressure acting on the structure is redistributed on the nozzle mouth and on other elements located near the installation zone (see Fig. 3).

Table 2 shows the distribution of lateral force components within the entire structure for the initial profile of the JV airfoil portion at the beginning of SPRE operation. The resultant force is assumed to be 100 %.

According to Table 2, the forces that appear on the airfoil portion exceed the final CF approximately by 25 %. The lateral force is reduced due to the pressure differential at the nozzle and protective screen. The pressure differential creates a force acting in the direction opposite to the CF created by the

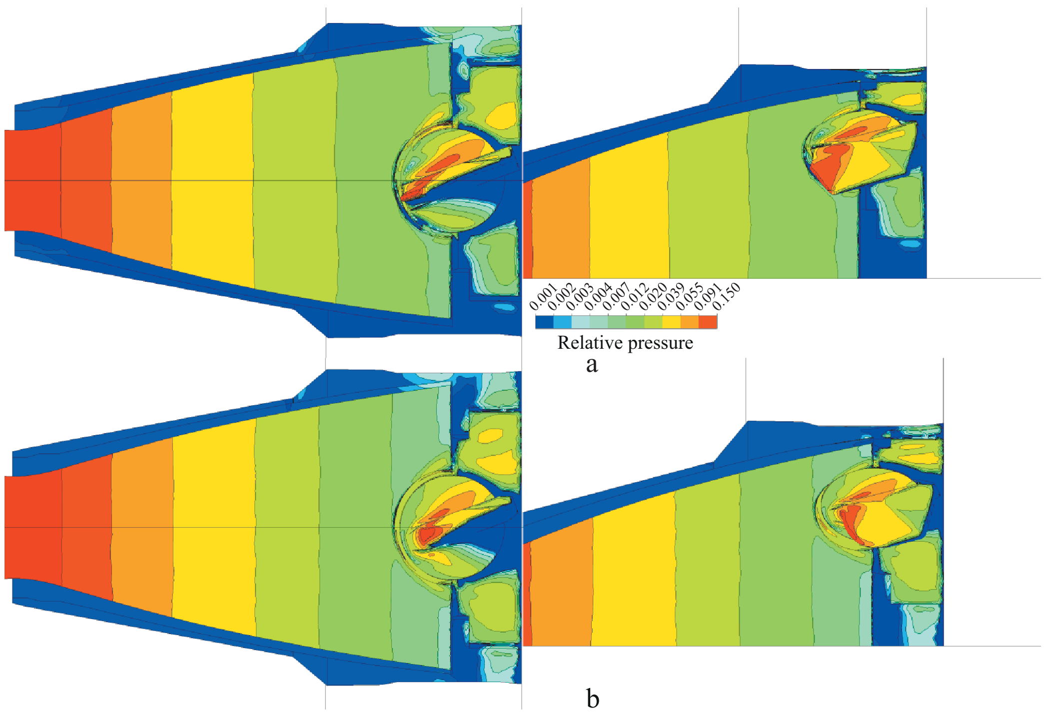


Fig. 3. Distribution of relative pressure in the structure:
a – beginning of SPRE operation; b – end of SPRE operation

Table 2

CF distribution in the structure

Lateral force created by:	CF, %
nozzle upon pressure redistribution	–13.2
protective screen downstream of nozzle exit	–16.2
tail section	0.7
scuff plate	3.9
JV airfoil portion	124.8
Total	100

JV airfoil portion and scuff plate. This reduces the efficiency of the control. At the same time, the force that appears in the tail section has no considerable effect on the final CF and is less than 1 %.

To prove reliability of the results, we compared them with experimental data acquired during bench tests (Fig. 4). The average CF value based on the bench tests at the beginning of engine operation was assumed to be 100 %. Results of numerical experiments for CF calculation turned out to be overrated, approximately by 20 %, for both the first and second design cases (see Fig. 4).

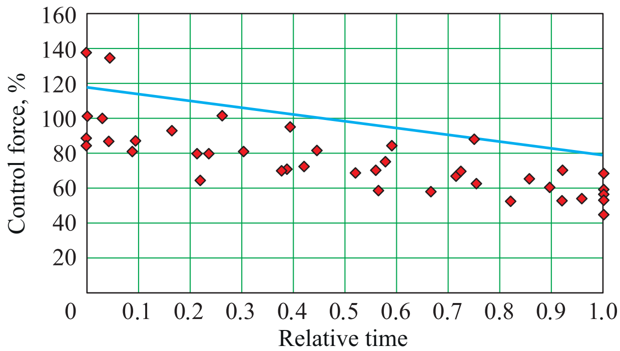


Fig. 4. Calculated vs. experimental CF estimates comparison diagram:
◆ – experimental data; —— – calculated value

Such a difference between the results of numerical simulation conducted by means of the off-the-shelf software package and experimental data may be caused by various factors such as:

• considerable spread of experimental data;

• specified assumptions in the design geometry;

• simulation of operation of only one of four SPREs with no account for mutual interference;

• specified assumptions for describing boundary conditions.

Despite the overrated CF estimate at the beginning and at the end of engine operation with the JV deflected, this method is suitable for design and checking calculations, and for the analysis of emergency situations, for example, consequences of incorrect installation of the JV on the unit under test.

Conclusions:

• we conducted the numerical study in order to determine control forces, using experimental data acquired during bench tests for the beginning (initial shape of the JV airfoil portion) and the end (ablated profile of the JV airfoil portion) of engine operation;

• results of the numerical simulation exceed experimental values approximately by 20 %, but this error is tolerable for design and reference calculations;

• the design method needs to be improved to take into account more factors and enhance the accuracy of control force calculations.

Bibliography

1. Organy upravleniya vektorom tyagi tverdotoplivnykh raket: raschet, konstruktivnyye osobennosti, eksperiment / *R. V. Antonov* i dr. Moskva-Izhevsk: NITs “Regulyarnaya i khaoticheskaya dinamika”, 2006. 552 s. (Russian)

2. *Kalugin V. T.* Aerodinamika organov upravleniya poletom letatelnykh apparatov: uchebnoe posobiye. M.: MGTU im. N. E. Baumana, 2004. 688 s. (Russian)

3. *Stolbovskoy V. N.* Matematicheskoye modelirovaniye vzaimodeystviya vnutristruynykh gazovykh ruley s dvukhfaznym gazovym potokom: dis. …kand. tekh. nauk. Tula, 2011. 134 s. (Russian)

4. *Gubertov A. M., Mironov V. V., Borisov D. M.* Gazodinamicheskiye i teplofizicheskiye protsessy v raketnykh dvigatelyakh tverdogo topliva. M.: Mashinostroenie, 2004. 512 s. (Russian)

5. *Deich M. E.* Tekhnicheskaya gazodinamika. M.: Energia, 1974. 592 s. (Russian)

6. Dvukhfaznyye mono-i polidispersnye techeniya gaza s chastitsami / *L. E. Sternin* i dr. M.: Mashinostroenie, 1980. 172 s. (Russian)

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Численное моделирование течения газа в реактивном сопле

Определены тяговые и гидравлические характеристики реактивного сопла газотурбинного двигателя с учетом геометрии внутренних конструктивных элементов и закрутки потока во входном сечении на основе результатов численного моделирования.

Ключевые слова: реактивное сопло, численное моделирование, характеристики.

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