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Side Force Determination in the Rocket Motor Thrust Vector Control System

Nikola Gligorijević[1)]
Saša Živković[1)]
Sredoje Subotić[1)]
Stevan Kozomara[1)]
Momčilo Nikolić[1)]
Slobodan Čitaković[1)]

The side force of a thrust vector controlled (TVC) rocket depends on the rocket motor thrust and the efficiency of the applied type of a TVC system. The value of the efficiency is important in the calculating procedure of the rocket maneuvering capability. The special static test equipment is necessary to obtain the accurate values of the side force. During the research of the rocket motor and the Bumbar TVC system with jet tabs, the relation is made between the accurate but expensive test results from the complex six-component test stand (6-K), and the results obtained from the simple one-component test stand (1-K). Afterwards, on the basis of this relation, using the computational fluid dynamics program (CFD), a physical model is developed to get exactly the same relations between the characteristic parameters of the TVC system as in the tests. The successful numerical model is adjusted to predict the characteristics of some other TVC system, only on the basis of the simple test results.

The TVC system with jet deflectors is applied on the Maljutka antitank rocket. The CFD model is used to evaluate the lateral force on the basis of two simple and inexpensive types of tests on the 1-K test stand: the first, with the TVC switched ON with constant frequency during the motor work, and the second, without involving the TVC.

Key words: **rocket motor, thrust, thrust vector control, static test, side force, computational fluid dynamics method.**

Nomenclature

A_e	– Nozzle exit surface
F	– Thrust, Undisturbed thrust, Force
F_R	– Reduced thrust
F_{side}	– Side (lateral) force
h	– Distance
k	– Relation between reduced and undisturbed thrust
l	– Distance
$\dot{m}$	– Mass flow
M	– Momentum
p_e	– Pressure on the nozzle exhaust
p_0	– Ambient pressure
T	– Temperature
t	– Time
V_e	– Velocity on the nozzle exhaust
α	– Angle between the motor and the nozzle axes
α	– Angle between the plane with the nozzle axes and the plain with the axes of the transducers D_5 and D_6 on the 6-K test stand
η	– TVC system efficiency

Introduction

FOR the analysis of the guided rocket missile behavior during the flight, it is necessary to determine the actual value of the lateral force produced by the TVC system.

During the years, various TVC systems have been researched in the Department for Solid Propellant Rocket Motor Propulsion (MTI-Belgrade), based on entering the different types of barriers into the gaseous flow of combustion products [1-4]. The special attention has been directed to a system with jet tabs (interceptors, knives) mounted at the nozzle exhaust, which is applied on the Bumbar antitank missile.

In the Solid Propellant Rocket Motor Laboratory in Žarkovo, there are different kinds of test stands adjusted for thrust, pressure, temperature and other types of measuring for various assemblies or elements of rocket missiles.

A large number of tests and measurements were carried out to determine and analyse the properties of the Bumbar antitank rocket TVC system and a respective amount of knowledge has been accumulated.

During the time, different experimental methods for the TVC parameter determination have been developed.

1) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

The most accurate measurements of the lateral force that produce the rocket motor TVC system may be obtained in the static tests on a six-component (6-K) test stands that are completely statically determined. Unfortunately, they require quite complex test preparation and analysis of test results.

Design and construction of test stands in the Rocket Motor Test Center in the MTI is such that the measured results on the three-component (3-K) test stand are more suitable for the functional efficiency analysis of the opposite pairs of jet tabs than those obtained on the 6-K, test stand; it is also easier for test operators to prepare tests. On the other hand, the 3-K test stand is not completely statically determined and it is quite difficult to estimate the real equipment influence on the test results. It is known that the accuracy obtained from 3-K test stands is lower in comparison with the 6-K results.

The tests on the classic one-component (1-K) test stand are the easiest for preparation. However, with only one force transducer located in the axis of the rocket motor, it is possible to measure only the axial motor thrust and its variations produced by the TVC system, without measuring the side force.

During the Bumbar TVC system development, a good and reliable relation between test results from different test stands has been established. When a TVC system is analysed and tested, it is necessary to establish the real values and the correlation between the three characteristic values:

1. The mean undisturbed thrust of the motor (F)
2. The mean reduced thrust (F_p) for the rocket motor, when the TVC is switched ON;
3. The mean side force (F_B).

Finally, at the end of the TVC Bumbar development, it was possible to get the real values of the lateral (side) force by making only the two simple kinds of static tests with the Bumbar sustainer motor on the 1-K test stand: the first, when the TVC system is switched ON, and the second test without involvement of the TVC.

Based on the experience and the test results from the Bumbar project, a physical model for a gas-flow analysis and numerical calculations is tested and confirmed. The model is based on the FLUENT computer program for the **„Computational fluid dynamics“** (CFD). The real nozzle geometry parameters of the Bumbar sustainer rocket motor were used as well as the motor combustion and gas-flow parameters. The model had been gradually changed until it became capable of making the relations between the three characteristic parameters equal to the relations evaluated through the number of tests.

In this way, the model was prepared to predict the values of the lateral force that can produce another, different TVC system.

The relations between results from different test stands depend on the type of the thrust vector control system. In any case, the experiment is the most accurate way for defining these relations, but it is sometimes too expensive. Different rocket motors with their TVC systems need the special test stands and a large number of tests to get good results.

For this reason, the defined numerical (CFD) method is acceptable to give quite satisfactory results in the side force analysis, avoiding the high price and long-term preparation of complex tests on multi-component test stands.

For a new, quite unknown system, it is necessary to know its internal-ballistic parameters and the real geometry of the rocket motor nozzle. This model uses the test results from two simple and inexpensive types of tests: with and without turning the TVC system on. The two characteristic values have to be measured in the static tests of the rocket motor on the 1-K test stand (undisturbed thrust and reduced thrust). The third value, lateral force, will be numerically calculated using the CFD method.

The developed method that uses the FLUENT program for numerical fluid mechanics was used to calculate the TVC efficiency of the enhanced Maljutka sustainer motor.

Static tests on the Six-component test stand

A solid propellant rocket motor is defined mechanically as a rigid body with six degrees of freedom. In order to limit all of these degrees of freedom, six different connections (supports) are necessary.

The rocket motor and the test stand together make a single closed system. External forces that act on the system cause reaction forces in the system supports (connections between the motor and the test stand), where the force transducers are mounted in order to measure them.

Every six-component (6-K) test stand is designed for the research and development of a specific TVC system. Its optimization depends on the sizes of generated forces and it is not suitable for testing different TVC systems. An example of the 6-K test stand realized for the research of the POR-2 TVC system is shown in Fig.1.

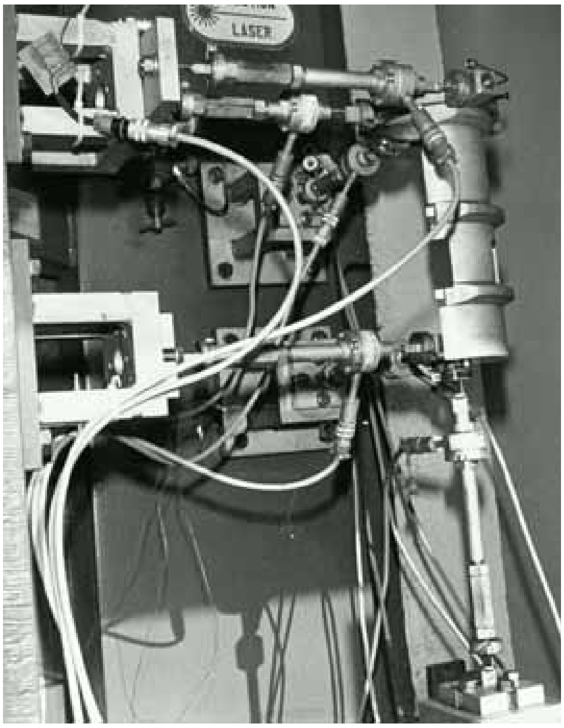

Figure 1. Six-component test stand for the POR-2 TVC system development

Measuring the lateral force generated by the rocket motor and the TVC system is a complex process that requires long-term preparation. Ideally, the static test measurements on the 6-K test stand are sufficient to get the value of the lateral force, because the system is completely statically determined.

However, the constituent elements of the 6-K test stand have to be adapted to the real geometry and structural requirements of the tested rocket motor and TVC system.

During the research and development of a rocket motor and its TVC system, it is necessary to test different versions of the rocket motor, because its elements are continually adapted and changed, until the optimal design is achieved.

Furthermore, it is usually necessary to test different kinds of the same motor, such as the test version or the original one,, alone or in combination with other elements of the missile.

During the system development, the rocket motor or TVC system elements have to be changed, and these changes affect the behavior of the test stand and the test results. It is quite difficult to perform the calibration of the sensitive test stand. Every time when the smallest change in the system is introduced, all the force transducers, mounted in the test stand supports, react. Changing the method of the rocket motor mounting on the test stand always affects the response of the force transducers. It is not sometimes possible to bring all the measured values to the baseline before the test.

For these reasons, the results obtained in the initial tests during the research and development are not completely reliable. Along with the static tests on the 6-K test stand, the similar tests and measurements are performed using the other test stands. The process of approaching the exact values of the side force is iterative and time-consuming. During this process, both the TVC system design and the measurement procedure become better.

When it is estimated that a satisfactory level of accuracy is reached in the process of measuring the lateral force on the 6-K test stand, a basis for comparison is created. After that, further lateral force measurements usually have to be performed on the three-component or one-component test stand. These measurements are easier and faster, but with less accuracy.

Six-Component Test Stand for the Bumbar TVC system

The basic measurements of the Bumbar TVC system were carried out on a six-component test stand (Fig.2). Six force transducers (one for measuring axial thrust and five for measuring the components of lateral force) are located at different places. The theoretical review of this test stand is shown in [5,6].

Figure 2. Bumbar sustainer motor on the 6-K test stand

The schematic representation of the location and layout of the measuring elements in this test stand is shown in Fig.3. The rocket motor thrust and the lateral force are determined on the basis of the data measured on one axial and five different lateral force transducers.

The main force transducer is mounted coaxially with the rocket motor, on its front side, on the floor (Fig.2 and 3). The rocket motor is mounted vertically and the transducer measures the motor thrust corrected by the gravity force due to the mass of the burned propellant.

The nozzle exhaust with the mounted interceptors is seen on the upper side of the Bumbar sustainer motor (Fig.2). When the motor is fired, the opposite pairs of interceptors periodically enter the flow of gaseous combustion products, making the alternating changes of the side force.

On the right wall of the test stand, two force transducers are mounted at a specified distance (h) between them, both with the axes that orthogonally intersect the motor axial axis. On the left wall, another two force transducers at the same distance (h) are mounted. Their axes are also passing through the motor axis at right angles. Finally, the last force transducer is mounted on the left wall, with the axis also at the right angle to the motor axis, but bypassing it on the specified distance, to make a moment.

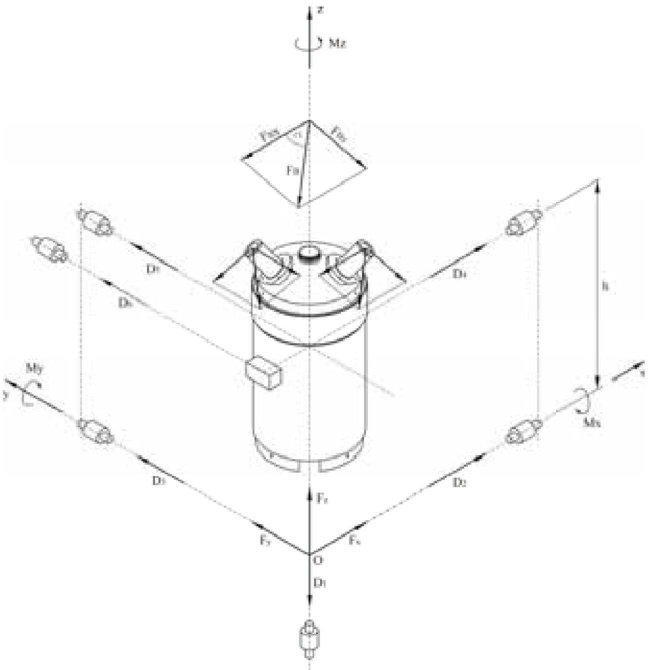

Figure 3. Force transducers layout on the 6-K test stand

Equations for Lateral Force Determination in the 6-K tests

When the Bumbar sustainer rocket motor with the TVC system is tested on the six-component test stand, the coordinate system is set so that one of the coordinate axes (z) coincides with the longitudinal axis of the rocket motor. Along this axis, in the vertical direction, the motor thrust and the gravity force act, while the position of the other two perpendicular axes (x and y) is in the horizontal plane, as in Fig.3.

In the horizontal plane, all the lateral force components can be seen as a result of the interceptor (jet tub) activities.

Force transducers directly measure resistances in test stand supports. During the static test, when the motor is burning and the TVC system is active, the whole system is in equilibrium. The condition for the equilibrium is that the sum of all external forces and resistances in the test stand supports is equal to zero, as well as the sum of moments caused by these forces. This condition is represented by six linear equations of static equilibrium [2]:

$$\sum X_i = 0 \quad D_2 + D_4 + F_x = 0 \tag{1}$$

$$\sum Y_i = 0 \quad D_3 + D_5 + D_6 + F_y = 0 \tag{2}$$

$$\sum Z_i = 0 \quad -D_1 + F_z = 0 \tag{3}$$

$$\sum M_{xi} = 0 \quad -D_5 \cdot h - D_6 \cdot h + M_x = 0 \tag{4}$$

$$\sum M_{yi} = 0 \quad D_4 \cdot h + M_y = 0 \tag{5}$$

$$\sum M_{zi} = 0 \quad -D_6 \cdot l + M_z = 0 \tag{6}$$

l − Horizontal distance between the transducers D_5 and D_6
h − Vertical distance between the transducers D_2 and D_4

The values measured by the force transducers D_1 to D_6 are enough to evaluate all the components and the resultant values of the force and the momentum, $\vec{F}_R = \vec{F}_x + \vec{F}_y + \vec{F}_z$ and $\vec{M}_R = \vec{M}_x + \vec{M}_y + \vec{M}_z$.

The lateral force consists of two equal components formed on each of the nozzles. During the test on the 6-K test table, the lateral force, in the first approximation, appears only in the horizontal plane which is perpendicular to the longitudinal axis of the rocket motor. This force, approximately, passes through the nozzle exit center (Fig.2). Its components in the x and y directions are obtained directly from expressions (1) and (2).

$$F_x = -(D_2 + D_4) \tag{7}$$

$$F_y = -(D_3 + D_5 + D_6) \tag{8}$$

The intensity of the side force is determined by the intensity of the components:

$$F_{side} = \sqrt{F_x^2 + F_y^2} \tag{9}$$

The time distribution of the side force is a combination of the measured values on the force transducers D_2 to D_6:

$$F_{side} = \sqrt{(D_2 + D_4)^2 + (D_3 + D_5 + D_6)^2} \tag{10}$$

The side force may be simply evaluated using only the values measured on the transducers mounted on one side of the test table:

$$F_{side} = \frac{F_x}{\cos\alpha} = -\frac{D_2 + D_4}{\cos\alpha} \tag{11}$$

$$F_{side} = \frac{F_y}{\sin\alpha} = -\frac{D_3 + D_5 + D_6}{\sin\alpha} \tag{12}$$

The angle (α) is defined in Fig.3.

Test Diagrams

A characteristic thrust diagram of the Bumbar sustainer rocket motor is shown in Fig.4. The TVC system is switched ON with constant frequency of jet tabs insertion.

The upper envelope curve of the thrust (Fig.4) coincides with the value of the thrust when the TVC system is switched OFF, and is called "undisturbed thrust" (F). The lower envelope of the same curve corresponds to the theoretical thrust curve in the case when the executive TVC system elements (jet tabs) were continuously in the jet of gaseous combustion products. This value is called "reduced thrust" (F_p).

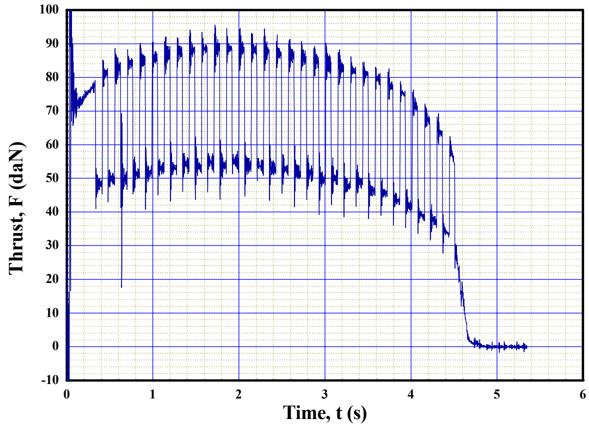

Figure 4. Bumbar sustainer thrust-time distribution

A typical diagram of the side force vs time [2] is shown in Fig.5. The curve is obtained using equation (10) and by combining results from five different force transducers.

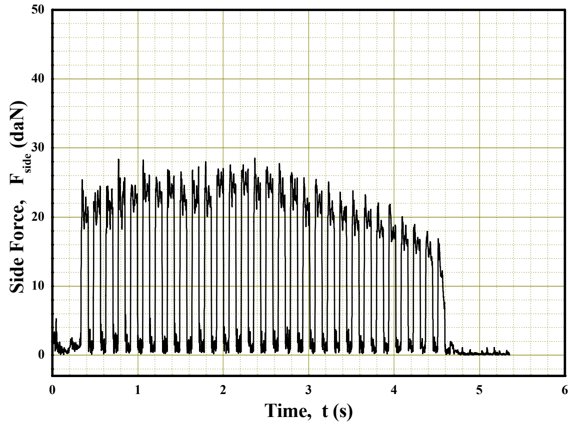

Figure 5. Bumbar rocket motor side force measured on the 6-K stand

Along with the advantages of the rocket motor and TVC system testing on the 6-K test stand, there are also certain disadvantages. If one of the jet tabs does not work well, it is not possible to recognize it by analysing the side force time distributions. All the disorders of the TVC system are transmitted to each of the force transducers.

In the diagram (Fig.5), the difference that occurs due to the effects of opposite jet tabs pairs could not be seen. The side force acts perpendicularly to the longitudinal axis of the rocket motor and it changes its own direction. The size and structure of the opposite pairs of jet tabs are the same as well as the expected intensity of the lateral force in both cases. In the diagram, one can see only the intensity but not the direction of the side force. It is not possible to identify the side force peaks that correspond to one or another pair of jet tabs. A careful analysis should recognize that the adjacent peaks of the lateral force values differ slightly in intensity, indicating that there is a difference between the force produced by the opposing pairs.

For this reason, the analysis of the opposite pairs of jet tabs is more suitable in the tests on the 3-K test stand.

Static tests on the three-component test stand

The TVC system testing on the 3-K test stand is shown in Fig.6. This structure that consists of the rocket motor, the TVC system, some other parts of the rocket and the 3-K test stand, is not completely statically defined as in the case of the 6-K one. However, when the problem of mass effects of the elements for the connection between the motor and the test stand is solved, good results for further analysis may be obtained.

In the TVC system of the Bumbar rocket, the jet tabs are entering the combustion products jet on the exhausts of two symmetrical nozzles (Fig.7), placed at an angle (α) to the axis of the motor.

Figure 6. Bumbar test rocket on the 3-K test stand

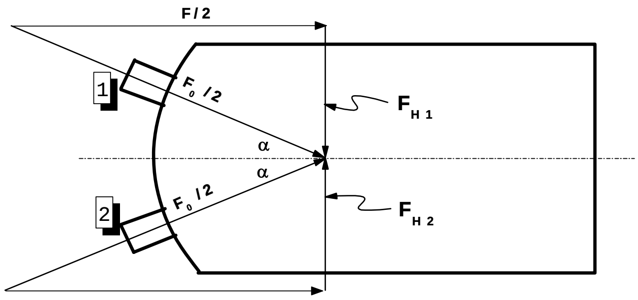

Figure 7. Thrust forming in the motor with symetrical nozzles

Fig.7 is a sketch of the motor cross section in the plane containing the nozzle axis. Ideally, the forces in the lateral direction, transversely to the axis of the motor, are reversed because of symmetry.

During the motor combustion, when the TVC system operates, the opposing pairs of jet tabs alternatively enter the jet of gaseous products, Fig.8.

Figure 8. Bumbar, the nozzle with the interceptors

The problem of the accurate measurement consists of mounting the side force transducer perpendicular to the axis of the motor, in the plane where the lateral force acts. However, it is never known exactly where the point of the lateral force action is. For this TVC type, it is known that the side force acts near the exit of the rocket motor nozzle. Furthermore, if it is not possible to place accurately the force transducer at the best site in the point where the side force acts, it is necessary to make a calibration to get the best possible result.

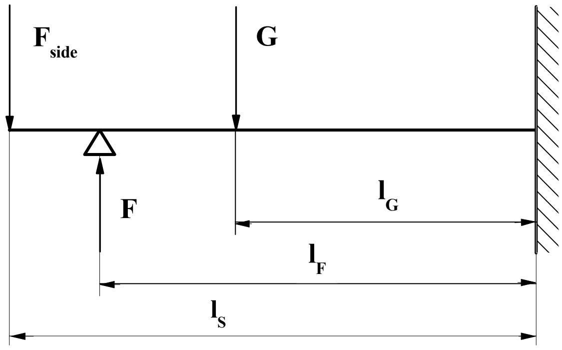

Figure 9. Approximate allocation of the forces on 3-K test stand in the vertical cros-section of the rocket motor

G – Rocket motor gravity force
F – The force in the side transducer in the vertical plane
F_{side} – Side force

An approximate scheme of the characteristic forces in the vertical plane passing through the axis of the rocket motor, is shown in Fig.9. The vertical force in the support is measured by the force transducer (F), mounted on the right angle to the motor axis. Another lateral force transducer, set in the horizontal plane, ideally measures the force that is approximately equal to zero, as a difference between symmetrical forces (F_{H1}) and (F_{H2}), shown in Fig.7. In Fig.10, a characteristic diagram of the force measured in the vertical transducer is shown. There is a clear distinction between the forces produced by the opposing pairs of jet tabs.

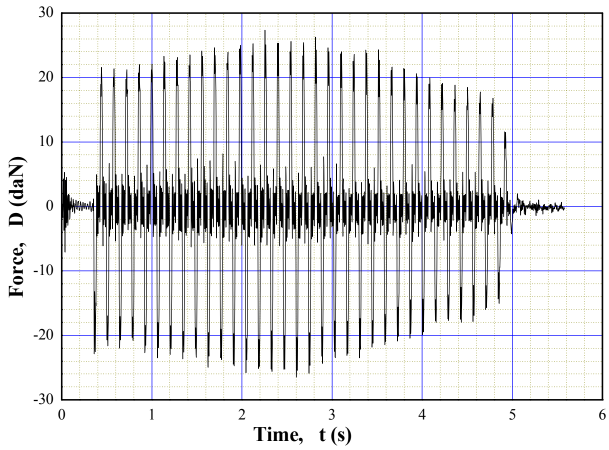

Figure 10. Bumbar rocket motor side force measured on the 3-K test stand

Mounting the rocket motor on this test stand is easier and faster. This is very important in the situations when the static tests of the motor and TVC system behavior at extreme temperatures are required. In these cases, the rocket motor has to be mounted very fast after extracting from the chamber for temperature preparation.

When the measurements on the 3-K table were realized to give approximately identical values of axial thrust and lateral forces as on the 6-K test stand, it was considered that a good calibration had been performed and the results were satisfactory. After that, it was not necessary to make further tests on the 6-K test stand.

Numerical CFD Method Development

The computational fluid dynamic (CFD) method for the gas flow processes numerical simulation has already been widely applied and proved in many branches of technology as well as in the study of rocket motor processes.

During the research of the gas dynamics phenomena in order to develop the CFD method in the area of TVC system analysis, the results of the Bumbar sustainer rocket motor tests were used.

At the end of the aforementioned iterative process of achieving the accurate measurements of the side force, combining the tests on different kinds of test stands, the following results have been achieved (Fig.11). The values of the lateral force (F_{side}), the undisturbed thrust (F) and the reduced thrust (F_R) have been quite accurately determined. The average time distributions for all three characteristic values of the Bumbar TVC system are shown. These values were used for further analysis.

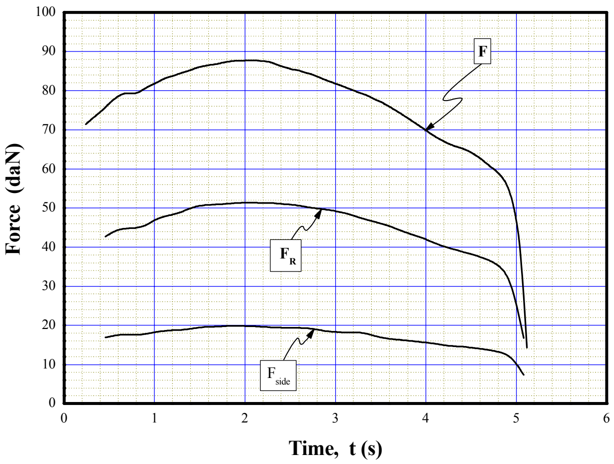

Figure 11. The mean Bumbar TVC properties vs time

At the beginning of the research, the development of the (CFD) method was based on the studying of gas dynamics phenomena [7], followed by appropriate wind tunnel tests (Figs. 12 and 13).

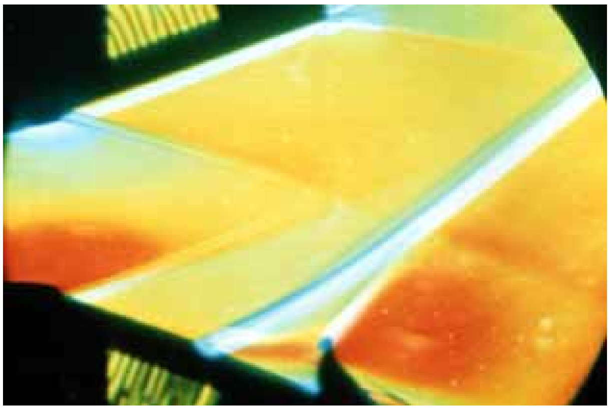

Figure 12. 2D model Wind tunnel Schliren photography of the gas flow in the rocket motor nozzle

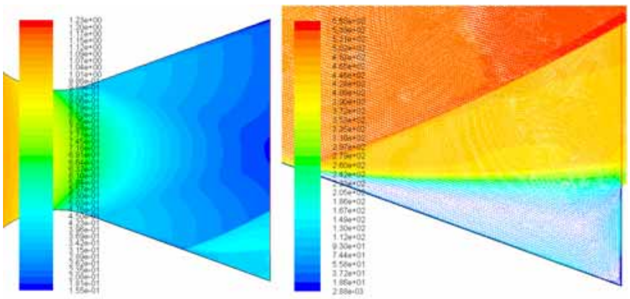

Figure 13. Contours of the density and velocity vectors from the CFD model

In the second phase of the method research, an analysis of the influence of the real geometry parameters was included. This was made with air as the working fluid (Figs. 14 and 15).

Finally, in the third phase of the model research and development, a number of real Bumbar sustainer rocket motors, with their TVC systems, were tested on the multi-component test stands (6-K and 3-K). These results have been used for the verification of CFD models. All these tests were followed by appropriate CFD simulations. The relation between three characteristic values from Fig.11 was used for the method verification in particular.

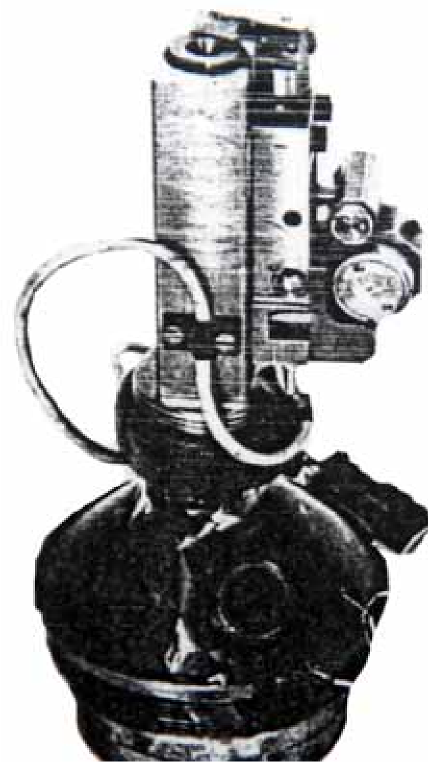

Figure 14. Test equipment for the identification of the influence of geometry parameters

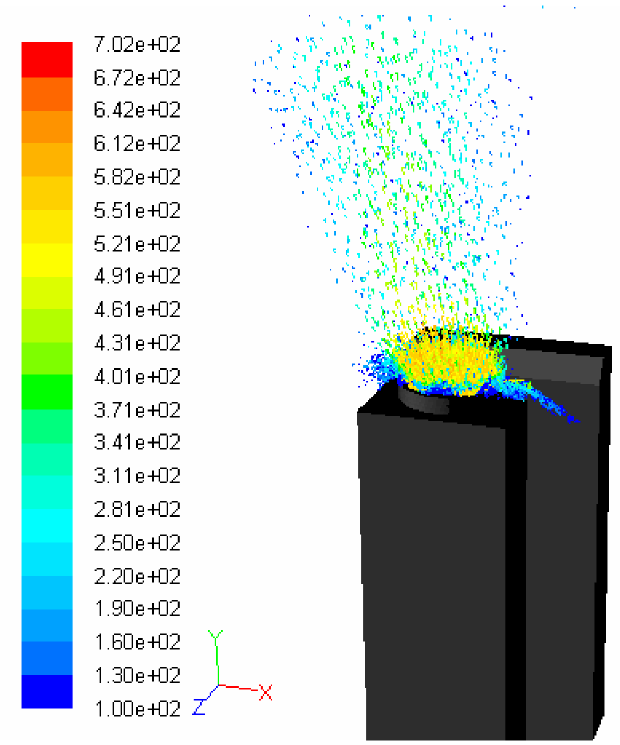

Figure 15. Velocity vectors from the CFD calculation

The exit plane of the Bumbar rocket motor nozzle, with its housing and the TVC jet tabs is shown in Fig.16.

Figure 16. Bumbar nozzle exit with the jet tabs

An example of a visual representation of the CFD flow calculations can be seen in Fig.17.

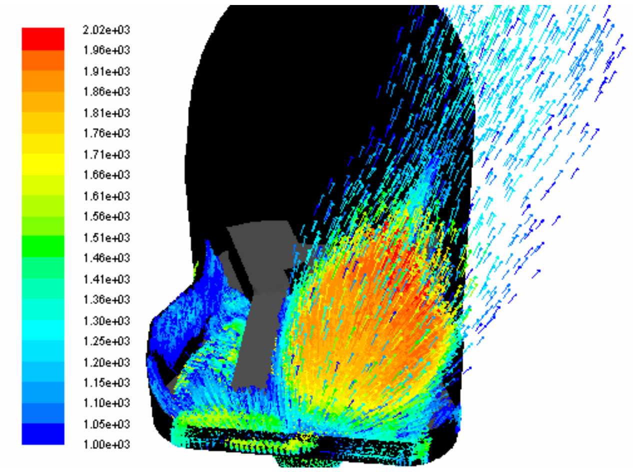

Figure 17. Velocity vectors from the CFD calculation

CFD simulation procedure

For the proper implementation of the computational fluid dynamic (CFD) method for the gas flow numerical simulation, it is necessary first to provide the correct input parameters for the calculation.

The input parameters for this calculation are:

1. Rocket motor geometry, including the combustion chamber, propellant grain and the motor nozzles.
2. Thermo-physical characteristics of the propellant,
3. Rocket motor internal-ballistic parameters,
4. Experimental results as a basis for adjusting the calculation model.

The most important thermo-physical characteristics are: combustion temperature, molecular weight, specific heat, viscosity, and thermal conductivity of the combustion products. Their temperature dependence may be obtained by thermo-chemical calculation, based on the propellant chemical composition [8].

The calculation process for the fluid flow parameters determination, like velocity field, turbulence characteristics and boundary layers is described in [9].

The basic internal ballistic parameters of the rocket motor [10,11] necessary for the calculation may be determined as it is described in [12] and [13], or they can be measured in experiments.

Also, the comparison between the experimental results and the CFD calculations is shown in [12].

The parameters of turbulence are also important and they may be obtained by a semi-empirical equation [14]. They are imported into the calculation as boundary conditions.

When all the input data are defined, the gas flow parameters may be determined: pressure, temperature, velocity, density, turbulence parameters, etc. The procedure for thrust components derivation using the CFD simulation is described in [12] in detail.

The new task - lateral force determination for the modernized Maljutka rocket

Problem definition

During the modernization of the Maljutka guided antitank rocket system, the sustainer rocket motor was also reconstructed [15]. The increase of the motor total impulse was achieved only by increasing the motor thrust, proportionally to the rocket mass increase, without changing the motor burning time. On the basis of the theoretical analysis, in these conditions, the acceleration of the missile is not changed. Its speed is approximately the same, and the range of the missile and its arrival time to the target are also very similar to the original rocket.

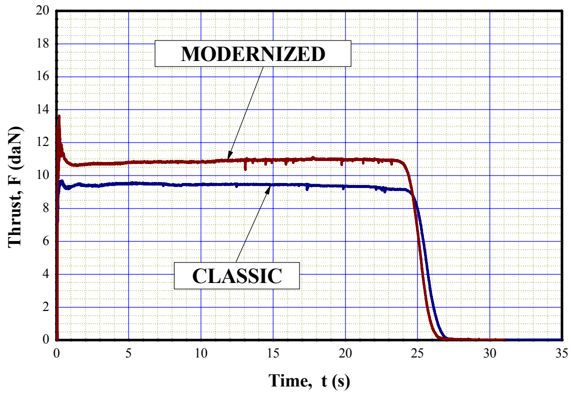

Figure 18. Thrust curves comparison for the modernized and classic sustainer motors

The curves in Fig.18 show the thrust vs time distribution for the original (classic) and the reconstructed (modernized) sustainer rocket motor. This diagram is the result of the static tests in which the thrust vector control system (TVC) was not activated.

The increase of the rocket motor thrust was realized by changing the propellant composition and grain dimensions. The TVC system itself has not been changed.

The amount of gaseous combustion products in the new, modernized motor is higher and the origin efficiency of the TVC system is changed. The relation between the motor thrust and the side force is also changed.

It is necessary to see, at first, whether the TVC system is able to work when the gas production is increased. Furthermore, in order to analyse the behavior of the missile in the flight, it is necessary to determine the actual value of the lateral force produced by the TVC system.

The Maljutka TVC system uses a dome deflector that is quite different, compared to the Bumbar TVC system with jet tabs. Long ago, this system was seriously analysed.

One of the static tests of the Maljutka sustainer motor and its TVC system on the special type of 6-K test stand is shown in Fig.19. These tests were carried out in the period when the rockets were produced serially, so it was possible to obtain a sufficient number of items for testing.

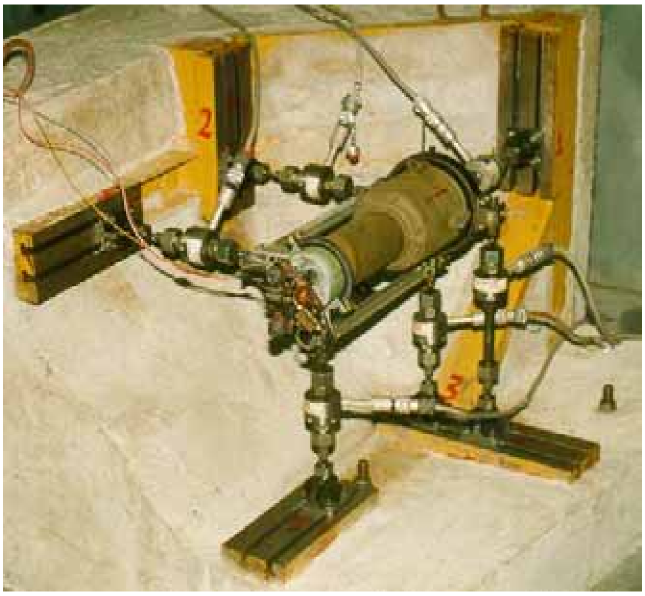

Figure 19. Maljutka sustainer rocket motor on the 6-K test stand

Today, a long time after the serial rocket production, the modernization of the stored missiles from the warehouse inventory is planned, but not their new production. In these conditions, any TVC system tests, except the necessary periodical receiving tests that verify the functionality after a certain period of storage, do not have economic justification. Required elements for any research may be provided by opening a new production line, which would be very expensive. Using the items from stored missiles would be even more expensive.

The problem is reduced to the following: the side force of the Maljutka modernized guided rocket has to be determined without performing expensive tests on the multicomponent test stands.

Two types of test results have to be used:

1. Thrust vs. time curves measured in the static tests on the one-component (1-K) test stand during the propellant grain verification, without involving the TVC system;
2. The results of thrust vs. time measuring during the TVC system functional tests using the modernized sustainer rocket motor.

The knowledge gained during the research in the area of all TVC systems, especially the Bumbar TVC system with jet tabs, has to be applied for solving the problem using the computational fluid dynamic (CFD) method.

Experiment

The static tests on the one-component (1-K) test stand were performed in the Rocket Motor Test Laboratory Center in Žarkovo, in order to evaluate the quality and internal-ballistic characteristics of the new realized propellant grain for the modernized Maljutka rocket.

These tests were done using the standard test motors, for the propellant grain verification (Fig.20). In these tests, the TVC system was not included and the values of the undisturbed thrust (F) and the pressure in the combustion chamber were measured [16].

Figure 20. Experimental Maljutka sustainer rocket motor on the one-component test stand

According to the standard procedure of the propellant grain acceptance, a number of static tests were carried out at three characteristic temperatures, without the involvement of the TVC system. The thrust vs time change was measured, and the mean values of thrust, burning time and total impulse were determined. The increase in total impulse, compared to the original motor, is evaluated.

A typical thrust vs time diagram is shown in Fig.21.

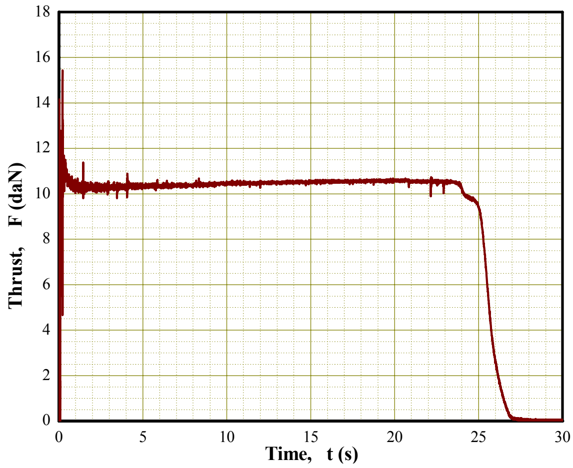

Figure 21. Maljutka, sustainer rocket motor – Thrust distribution

The second type of tests, called 'TVC functional tests' were performed on the special test stand, recommended by the licence for the Maljutka standard rocket, in accordance with the efficient acceptance procedure.

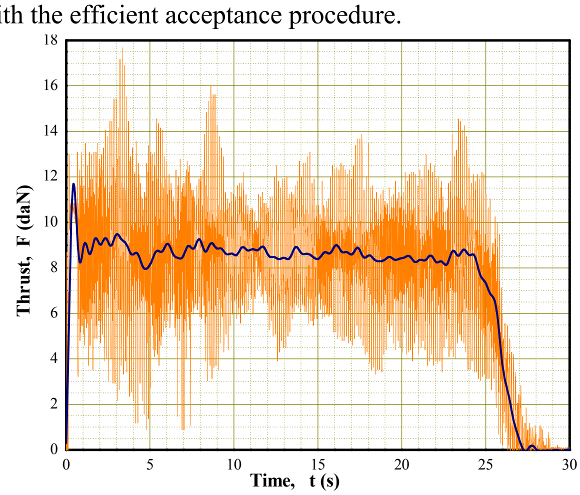

Figure 22. Maljutka, sustainer rocket motor – Reduced thrust

When the TVC system is switched ON, with a frequency of 16 Hz, the thrust-time distribution oscillates around the mean value, obtained by filtering the test curve (Fig.22).

This is actually a (2-K) test stand, and it is operated by the final manufacturer of the modernized rocket. Besides the axial force transducer, there is a lateral force transducer that measures some kind of the side force, but the measured values at that point are only usable for a qualitative, not quantitative analysis.

During the motor burning, with the TVC system switched ON (Fig.22), the average value of the thrust is called the "reduced thrust" (F_R). This quantity represents the axial component of the force produced by deflection of the jet of gaseous combustion products. This value is lower than the undisturbed value of the thrust.

In the above-mentioned two kinds of tests, with the TVC switched ON and OFF, the average values of the reduced thrust (F_R) and the undisturbed thrust (F) were determined.

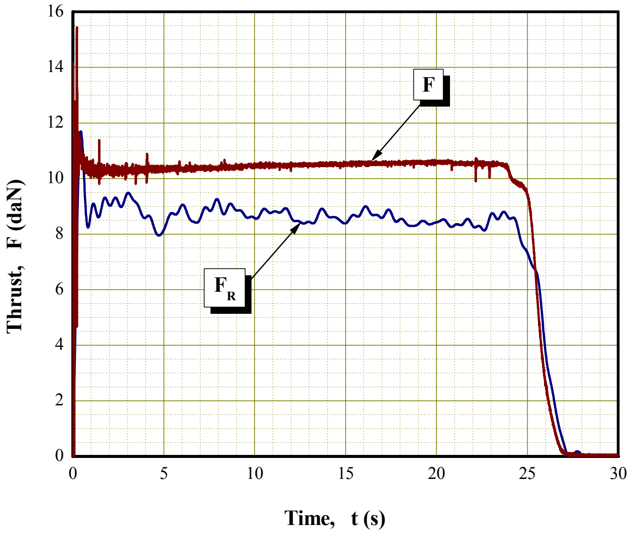

Figure 23. Comparison of the undisturbed and reduced thrust

The relation between the two values is seen in Fig.23. The mean value of this relation may be represented in the form of:

$$\frac{F_R}{F} = k < 1 \qquad (13)$$

		TVC		
	$T\ (^\circ C)$	OFF	ON	k
F_{av} (daN)	+50	11,02	8,85	0,803
	+20	10,60	8,54	0.806
	-40	9,39	7,64	0.814

The value of (k) is determined very reliably through a series of six (6) functional experiments with the TVC system switched ON (two experiments at three different temperatures, -40°C, +20°C, +50°C) and eighteen (18) static tests without involving the TVC system (six tests at all the three characteristic temperatures) [16].

On the basis of two values, F_R and F, it is possible to determine the relative decrease of the motor thrust and the total impulse due to the insertion of barriers into the combustion products jet. If the efficiency of the TVC system and the amount of losses were known, the value of the lateral force could be directly calculated. However, this is not the case, and the problem is directed to the evaluation of the TVC system efficiency (η) and system losses.

Combustion products produce thrust (F) in undisturbed conditions. If a barrier is inserted into the jet of gaseous products, the jet changes its direction, forming an angle to the axis of the motor. In this case, there is a loss due to scattering, which may be represented by the degree of TVC effectiveness. It is less than a unity. The force produced by the jet may be divided into two components, the axial force (F_R) that is equal to the reduced thrust force and the lateral (side) force (F_{side}) (Fig.24).

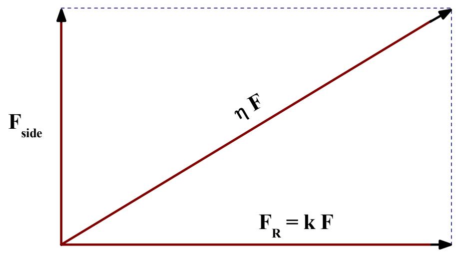

Figure 24. Thrust force components: reduced thrust and side force

The procedure of thrust and lateral forces calculation during the rocket flight was discussed in some of our earlier papers [17-19]. However, there are no precise literature data or test experience on the losses for different TVC systems. However, the efficiencies of some systems are quite different and it is not easy to estimate these values empirically. The TVC system efficiency of the reinforced Maljutka sustain motor has been estimated using the CFD simulation procedure.

Numerical side force calculation

It is said earlier that the development of the numerical (CFD) method was based on studying gas dynamics phenomena, wind tunnel tests, analysis of real geometry parameters influence, and finally the tests results of the Bumbar TVC system.

After the verification of the numerical CFD method on the Bumbar TVC system, it is applied in the analysis of the Maljutka TVC system. The gas flow of the combustion products is the same physical process in both the Bumbar and Maljutka rocket motors.

The complete analysis of the side forces for the Maljutka system, step by step, was based on the following data:

1. Complete definition of the nozzle and the TVC system geometry for the Bumbar sustainer rocket motor;
2. The test values of the undisturbed thrust vs time distribution of the Bumbar rocket motor;
3. The test values of the reduced thrust vs time distribution for the Bumbar rocket motor;
4. The test values of the side force vs time distribution for the Bumbar rocket;
5. The completely defined geometry of the nozzle for the Maljutka sustainer rocket motor;
6. The mean undisturbed thrust vs time distribution of the Maljutka rocket motor;
7. The mean reduced thrust vs time distribution for the Maljutka rocket motor, when the TVC is involved;

The special attention was paid to generate the geometric grid, whose quality is crucial for the stability and accuracy of the numerical calculation. A good experience in that area is gained through some earlier works with the heat conduction through the rocket motor [20].

The model simulation of the TVC system flow space geometry of the Maljutka rocket is shown in Fig.25.

Figure 25. Maljutka (the sustainer rocket motor) – The flow space geometry: nozzle and deflector

When the TVC is switched ON, in the space between the exhaust of the nozzle and the entrance of the deflector, the part of the gas flow that is covered by the deflector strikes onto its surface.

On the opposite side of the deflector, a pocket in the part of the deflector is opened, and a stop zone of reduced pressure and low velocity vortex flow is formed.

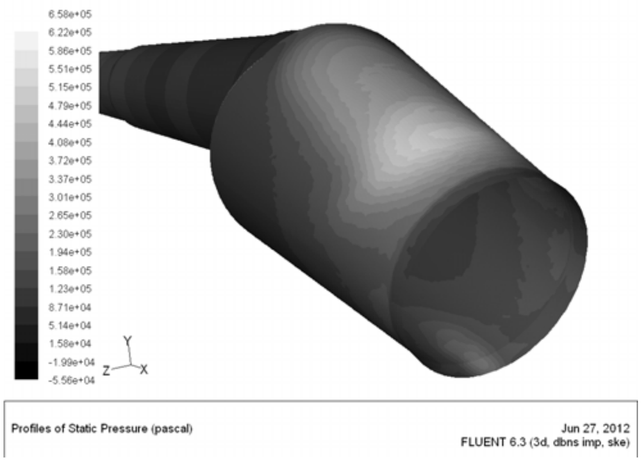

Figure 26. Profiles of the static pressure distribution in the deflector surface

A good view of this phenomenon can be seen in Fig.27 where the velocity vectors in the cross section of the flow space are shown.

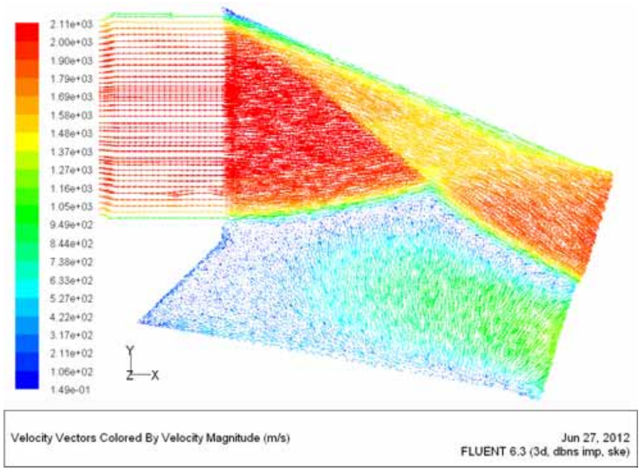

Figure 27. Velocity vectors in the cross-section plane of the deflector

The estimation of the characteristic parameters is performed as follows:

1. The basic property, motor thrust (undisturbed thrust) is calculated using a geometric model with the deflector in the axis with the nozzle. Based on the calculated flow parameters: the mass flow ($\dot{m}$), exit velocity (V_e) and the output pressure (p_e), the thrust is determined by equation (14):

$$F = \dot{m} \cdot V_e + (p_e - p_0) \cdot A_e \qquad (14)$$

   The reduced thrust and side forces were calculated on the basis of the geometric model of the deflector in the end position.
2. The side force is calculated based on the integral of the pressure on the inner surfaces of the gas flow space, in the direction perpendicular to the axis of the deflectors rotation and to the axis of the nozzle [10].
3. The reduced thrust is calculated using the indirect method defined in [10]. The classical approach was not good for determining the reduced thrust and "the principle of thrust definition" had to be used. The pressure integral on the inner contour of the gas flow domain, in the direction of the motor axis, is corrected for the value of the thrust generated in the part of the rocket motor that was not considered (in this case it was the combustion chamber).

A sufficiently close matching is achieved between the results of numerical calculations and the measured values of undisturbed and reduced thrust, thus confirming the high accuracy of the calculation model.

The calculation showed a very high efficiency of the Maljutka TVC system with the dome deflector. The degree of its efficiency is estimated at about $\eta \approx 0.95$. There is a very close agreement with the measured thrust values during the dynamic flight tests of the modernized Malutka rocket.

Conclusion

During the last twenty years, the important research and development in the area of guided rocket TVC systems have been conducted in the Department for Solid Propellant Rocket Motor Propulsion in the MTI-Belgrade. A serious experimental base is made, consisting of a number of test laboratories, equipment, test methods and knowledge.

In this paper, a part of the research is shown with the TVC systems with entering the barriers into the gas jet. Different kinds of static tests are shown with the purpose of determining the real characteristic properties of an arbitrary TVC system. The analysis and testing procedure is commented.

One of the basic tasks in the TVC system analysis is to determine the value of the side force made by the system. An example of this evaluation procedure is shown, using the long-time experience, bypassing the expensive research, equipment and tests. The numerical method for the fluid dynamic calculations is used to make the correlation between the most important TVC properties: thrust F, reduced thrust F_R and side force F_{SIDE}. Using the numerical model, it is possible to prepare conditions to make not too expensive tests only on the classic, one-component test stand, measuring only the thrust-time distribution. Just on the basis of thrust, it is possible to estimate the lateral force.

Figure 28. Maljutka sustainer rocket motor on the one-component test stand

The numerical calculation CFD model was prepared using the test results made in the period of the Bumbar TVC system research and development. In the case of the Maljutka TVC system, the same model is used to get the necessary values with the minimum number of static tests. This method has successfully reduced the cost of a very expensive procedure.

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Merenje bočne sile sistema za upravljanje vektorom potiska rakete

Bočna sila vođene rakete sa sistemom za upravljanje vektorom potiska (UVP) zavisi od potiska raketnog motora i efikasnosti primenjenog tipa sistema za UVP. Efikasnost sistema je važna za proračun manevarskih sposobnosti rakete. Određivanje tačnih vrednosti bočne sile zahteva posebnu opremu za statička ispitivanja. Tokom istraživanja interceptorskog sistema za UVP rakete Bumbar, uspostavljena je korelacija između tačno izmerenih vrednosti na skupim opitima na šestokomponentnom opitnom stolu (6-K) i rezultata dobijenih ispitivanjem na jednostavnom jednokomponentnom opitnom stolu (1-K). Kasnije, koristeći ovu vezu, i program za numeričku analizu dinamike fluida(CFD), prilagođen je model za proračun tako da se dobiju isti rezultati kao i u realnim opitima. Numerički model je zatim korišćen za proračun osobina drugog tipa UVP na osnovu rezultata jednostavnih statičkih opita.
Sistem za UVP sa deflektorima mlaza (naglavcima) primenjen je kod protivoklopne rakete Maljutka. CFD model za numerički proračun je korišćen za određivanje bočne sile na osnovu dve jednostavne i ne mnogo skupe vrste statičkih opita na jedno-komponentnom opitnom stolu: prvi, kada tokom rada motora radi i UVP sa konstantnom frekvencijom i drugi, bez uključivanja sistema za UVP.

Ključne reči: **raketni motor, potisak, upravljanje vektorom potiska, statički opit, bočna sila, numerička dinamika fluida.**

Измерение боковой силы системы управления вектором тяги ракеты

Боковые силы управляемого ракетного комплекса со системой управления вектором тяги (УВТ) зависят от тяги двигателя ракеты и эффективности применяемого типа системы УВТ. Эффективность системы важна для расчёта манёвренности ракеты. Определение точных значений боковой силы требует специального оборудования для статических испытаний. В ходе исследований интерцепторской системы УВТ для ракет Шмель, установлена связь между истинными измеренными значениями дорогих экспериментов на шестикомпонентном испытательном стенде (6-К) и результатами, полученными при испытании на простом однокомпонентном испытательном стенде (1-К). Позже, по этой ссылке и программе для численного анализа гидродинамики (CFD), модель была скорректирована для бюджета, чтобы получить те же результаты, что и в реальных экспериментах. Численная модель затем использована для расчёта свойств другого типа УВТ по результатам простых статических экспериментов. Система УВТ со струеотбойными щитами (розетками) был применён в противотанковой ракете Малютка. CFD модель для численного расчёта была использована для определения боковых сил на основе двух простых и не слишком дорогих видов статических экспериментов на однокомпонентном испытательном стенде: во-первых - когда при работающем двигателе работает и УВТ с постоянной частотой и с другой стороны - без участия УВТ системы.

Ключевые слова: **ракетный двигатель, тяга, управление вектором тяги, статические испытания, поперечная сила, численная динамика жидкости.**

Détermination de la force latérale chez le système de commande du vecteur de poussée de la fusée

La force latérale de la fusée guidée avec le système de commande par le vecteur de poussée (UVP) dépend de la poussée de moteur à fusée et de l'efficacité du système appliqué pour UVP. L'efficacité du système est importante pour le calcul des capacités de manœuvre de fusée. La détermination des valeurs précises de la force latérale demande un équipement spécial pour les essais statiques. Pendant les essais du système de l'intercepteur pour les fusées Bumbar UVP on a établi la corrélation entre les valeurs précises mesurées lors des essais coûteux sur la table d'essai à six composantes (6 – K) et les résultats obtenus par les tests sur la table d'essai simple à une composante (1-K). Ensuite, utilisant cette relation et le programme pour l'analyse numérique de la dynamique des fluides on a adapté le model de calcul afin d'obtenir les mêmes résultats comme pendant les essais réels. Le modèle numérique est utilisé pour le calcul des propriétés du second type de UVP basé sur les résultats des essais statiques simples. Le système pour UVP aux déflecteurs du jet s'applique chez la fusée antichar Maljutka. Le modèle CFD pour le calcul numérique a été utilisé pour la détermination de la force latérale à la base de deux simples et pas très coûteux tests statiques sur la table d'essai à une composante : le premier test où le moteur est en marche avec UVP à la fréquence constante et le second test où le système pour UVP n'est pas en marche.

Mots clés: **moteur à fusée, poussée, commande du vecteur de poussée, essai statique, force latérale, dynamique numérique des fluides.**