Investigation of the thrust vector angle stability of the stationary plasma thrusters

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R. Gnizdor[1], A. Komarov[2] S. Pridannikov[3] and K. Savchenko[4]

FSUE EDB Fakel, Kaliningrad, 236001, Russia

Abstract: angle of Thrust Vector Deviation is one of the main parameters of stationary plasma thrusters. The requirements for the value of this parameter are set in the specifications. This requirement for flight models is checked during acceptance tests. Of great importance is the stability of the angle of the thrust vector deviation in the resource, as well as stability with changes in the operating mode of the thruster. This article presents the results of the determination of the TVD angle of resource and acceptance tests SPT-70, SPT-100, SPT-140, which were conducted in EDB Fakel. The results of the two methods for measuring the angle of TVD (with separate and simultaneous determination of the axial and lateral components of the thrust vector) are compared. The results of the determination of the angle of thrust vector deviation confirming the stability of this parameter to the change in the operating mode of the thruster are given.

Nomenclature

Ft = *thrust vector;*
Fax = *axial component of thrust vector;*
Fβ = *thrust vector component in plane β (plane β is the plane passing through the geometrical axis of the thruster and the middle of the distance between cathodes);*
Fα = *thrust vector component in plane α (plane α is the plane passing through the geometrical axis of the thruster and perpendicular to plane β);*
α = *thrust vector angle component in plane α;*
β = *thrust vector angle component in plane β;*
αo = *angle of thrust vector deviation from the thruster axis;*
Δα = *correction κ thrust vector angle component in plane α;*
Δβ = *correction κ thrust vector angle component in plane β;*
φ = *angle of thruster mounting;*
Id = *discharge current;*
Ud = *discharge voltage;*
Uti = *readout of the thrust measurement device;*
ε = *sensitivity of the measuring system;*
TVD = *thrust vector deviation*

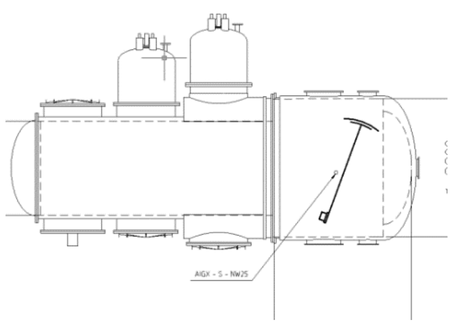
[1] Senior Researcher, Design department.
[2] Design engineer, Design department, Komarovfc.Anton@yandex.ru.
[3] Deputy Head of Department, Design department.
[4] Head of Department, Test department.

I. Introduction

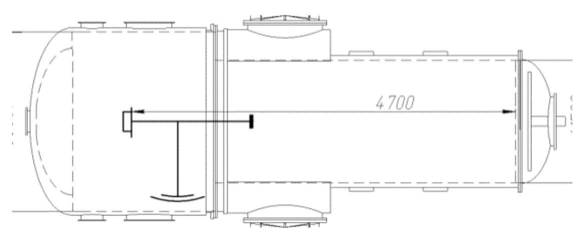
Angle of Thrust Vector Deviation (TVD) is one of the main parameters of the stationary plasma thrusters. The requirements to the thrust vector value are set in the specifications. This requirement for particular thrusters is validated during the acceptance test. The compliance to these requirements in the process of the thruster long-time operation will be validated if its TVD angle remains stable. If the thruster is to operate in several modes, then the question resolution about the TVD angle stability becomes actual as the current and discharge voltage are changed. Investigation of the TVD angle stability during a long-time operation has been carried out based on the measurement results of this parameter which were obtained in the process of the life test of the SPT-70, SPT-100, SPT-140-type thrusters. Two measurement methods were used. According to the first method, the TVD angle was calculated based on the measurement results of the axial and two mutually perpendicular lateral constituent parts of the thrust vector on two different thrust measuring devices. According to the second method, the thrust TVD angle was calculated based on the measurement results on one thrust measuring device that allows either axial or lateral constituent parts of the thrust vector to be determined during one test. The statistical analysis of the measurement results shows that the thrust TVD angle remains stable with a 90% probability in the process of the long-time operation for all the types used. For particular thrusters the thrust vector deviation angles from its average value are in the cone with a half-angle of 0.25 °. The thrust vector angle stability depending on the operation mode has been validated during SPT-100, SPT-140 and SPT-230-type thrusters testing. If the current and discharge voltage are changed, then the deviations from the thrust vector angle values, which correspond to the nominal operation mode for this thruster types, do not exceed ± 0.15°.

II. Method of thrust vector measurement

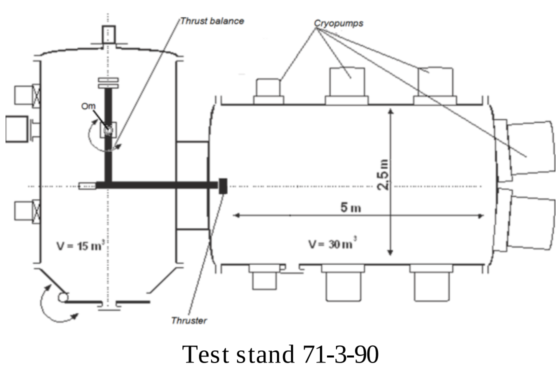
Measurement of the TVD angle was carried out at the vacuum test benches of the EDB Fakel. Thrusters with a size of 100 mm or less were tested on stands with a vacuum chamber volume of 20 m3 (stand 33-7-11A and 33-5-9). These stands are equipped with a thrust balance for separate measurement of the axial and lateral components of the thrust vector. Thrusters with the sizes 140 and 230 mm were tested in vacuum chambers with a volume of 45 m3 (stand 71-3-90) and 120 m3 (stand KVU-120) see figure 1. These stands are equipped with a thrust balance, which makes it possible to determine the axial and lateral components of the SWT angle in one measurement (without opening the vacuum chamber). The diagrams of the listed stands and thrust balances are shown in Figure 1. The pressure in the vacuum chamber did not exceed 2.00E-04 Torr (the gauge was calibrated by air).



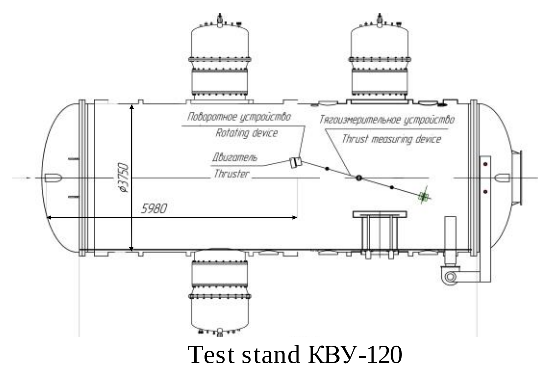
Test stand 33-7-11A



Test stand 33-5-9



Test stand 71-3-90



Test stand КВУ-120

Figure 1. Schematic view of the stands

A. Thrust vector measurement

To determine the TVD angle, a reactive method for measuring thrust was used. Thrust balances were built on the principle of torsion balance[1,2]. The TVD angle was determined as the ratio of the lateral and axial thrust vector components. The lateral component was measured in two mutually perpendicular directions. To determine the lateral component of the thrust in two mutually perpendicular planes, the load measuring device is equipped with a rotary mechanism that allows the motor to rotate around the axis of the anode block. In this case, depending on the type of thruster, two methods of determining the thrust vector were used. The first measurement of the axial and lateral components of the thrust vector was carried out separately, at different stands (stands 33-7-11A and 33-5-9) in Figure 1.

When measuring by the first method, the thrust was located on the thrust balance so that the measured component of the thrust vector created the greatest torque. I.e. the line connecting the line of action of the force was perpendicular to the line connecting the axis of the thrust balance to the thruster, see figure 2. With this approach, the other two components do not create torque moments. According to the second method, the TVD angle was determined from the results of measurements on one thrust balance, which makes it possible to determine both the axial and lateral components of the thrust vector in the course of one test. The thruster is positioned so that the force line is directed at an angle to the beam of the thrust balance, but does not pass through the axis of rotation of the thrust balance, see Figure 3. The method with a separate measurement of the axial and lateral components of the thrust vector was used for thrusters with a size of 50-100 mm.

When using the second method, the thruster was located on the thrust balance so that the thrust vector was directed at an angle of ~ 45 degree to the line that connects the thruster to the axis of the thrust balance see Figure 3. With this approach, the torque is generated by all components of the thrust vector, and the readings of the thrust balance depend on the angular position of the thruster. The axial and lateral components are determined from the readings of the thrust balance recorded at four different angular positions of the thruster.

For thrusters with sizes 140 and 230 mm, a second method was used, with simultaneous measurement of the axial and lateral components of the thrust vector. Therefore, the resource tests of the SPT-140 thruster are characterized by a greater frequency of measuring the TVD angle. A typical picture of the readings of a load-measuring device with a joint measurement of the axial and lateral components of the thrust when the motor rotates around the axis is shown in Fig. 4. The vertical axis shows the readings of the load-measuring device in gram-force. As can be seen from Fig. 4, the time dependence of the readings of the load-measuring device when the motor rotates has a shape close to the sinusoidal with an amplitude of ~ 5% of the reading of the load-measuring device. This amplitude includes inaccuracies in the thruster mounting, mechanical zero maintenance caused by the rotation of the motor and the difference in the magnitude of the torque that is determined by the angle of the TVD and the angular position of the thruster.

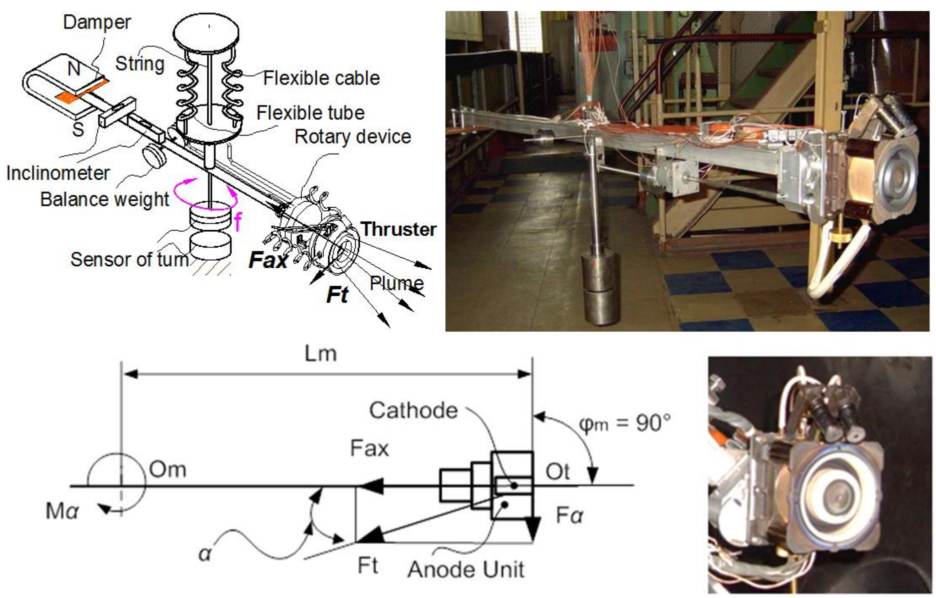


Figure 2. Scheme of measurement and appearance of the thrust balance for determining the lateral component of the thrust with the installed TDD-100.

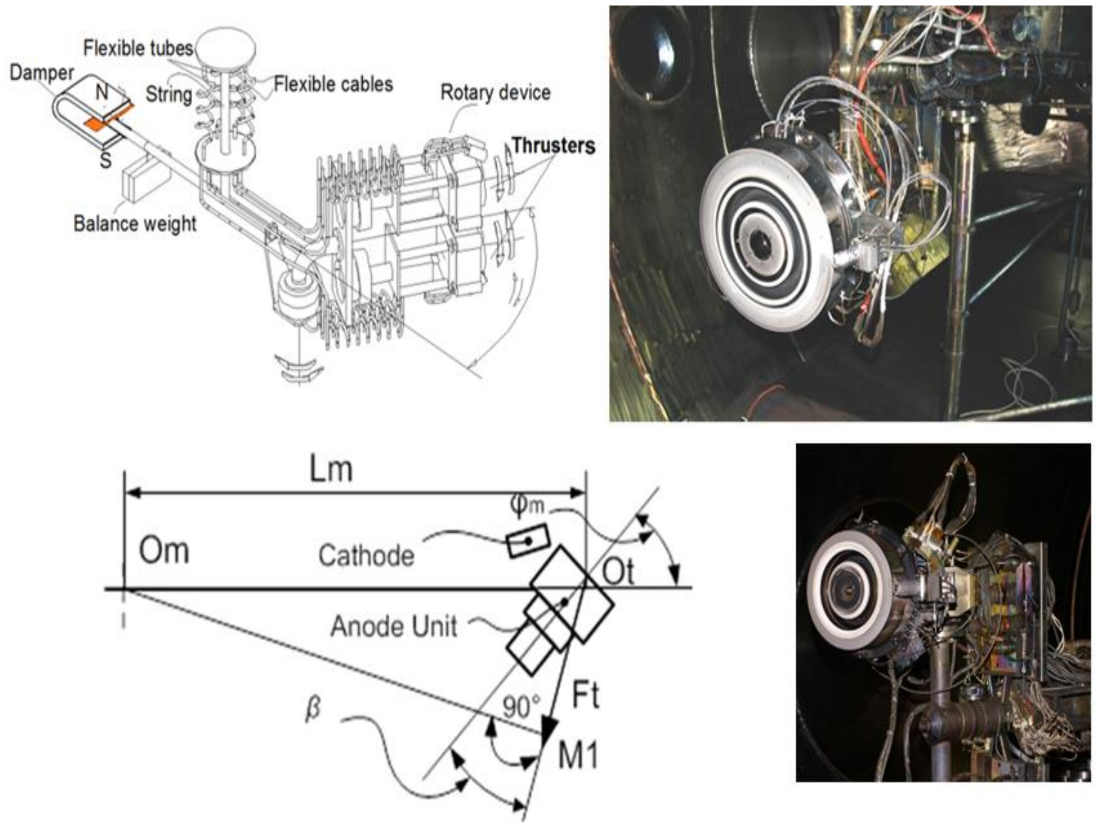


Figure 3. Schematic representation and appearance of thrust balance with joint measurement of the axial and lateral thrust component with the installed thruster SPT-140.

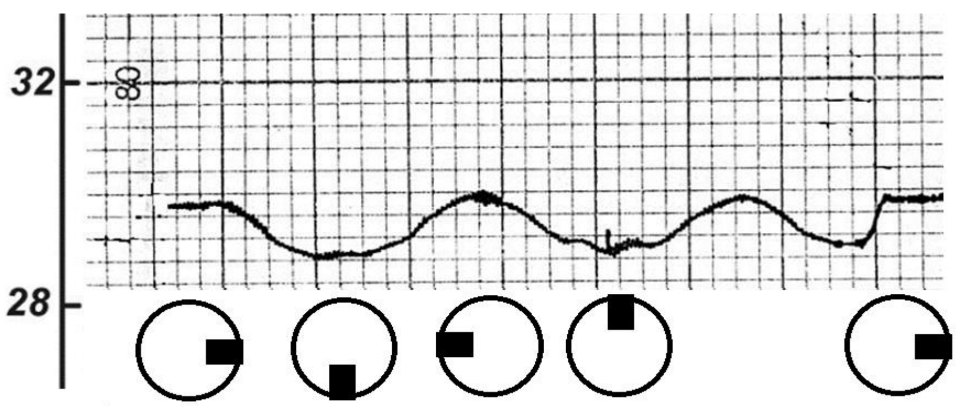


Figure 4. Changing the readings of the thrust balance when the motor rotates around the axis.

B. Corrections to the test results

The main feature of determining the lateral component of the thrust vector is its small value. So with the value of the axial component of the thrust vector 100 mN and the angle of deviation of the thrust vector 30 ', the lateral component does not exceed 0.87 mN. When measuring such small quantities, it is important to take into account all parasitic contributions introduced by various inaccuracies. When determining the lateral component of the thrust vector, the following corrections were made to the experimental data: correction for the accuracy of the motor installation on the load-measuring device, the response of the load-measuring device to the rotation of the switched-off motor, the correction for the "zero thermal drift", which was determined from the readings of the load-measuring device before and after switching-off thruster. The error in measuring the thrust vector for the method with a separate measurement of the axial and lateral components of the thrust was 10 angular minutes, for the other method 15 minutes, which corresponds to other load-measuring devices of the same type[3].

C. Coordinate system

To determine the position of the vector in space, a coordinate system was introduced, formed by two mutually perpendicular planes, the axis of the motor being the line of intersection. These planes were conditionally designated α and β. The coordinate system adopted to determine the vector was different for different thrusters. For the SPT-70 and SPT-100 thrusters, the β plane passed through the Cathode and the axis of the anode block, see figure 5. For the SPT-140 thrusters, the β plane passed through the gas feed and the axis of the anode block, the azimuthal position of the cathode being varied and being 90 degrees for SPT-140 No. 1 and 30 degrees for SPT-140 No.2. For convenience, the results of measuring the thrust vector for SPT-140 thrusters were transferred to the conventional coordinate system with the plane β passing through the cathode β. Component α was recalculated using the formula $\alpha' = \alpha\cos(\varphi) - \beta\sin(\varphi)$ $\beta' = \alpha\sin(\varphi) + \beta\cos(\varphi)$, where φ is cathode position. The coordinate system for motors with a size of 50-100 mm is shown in Figure 5.

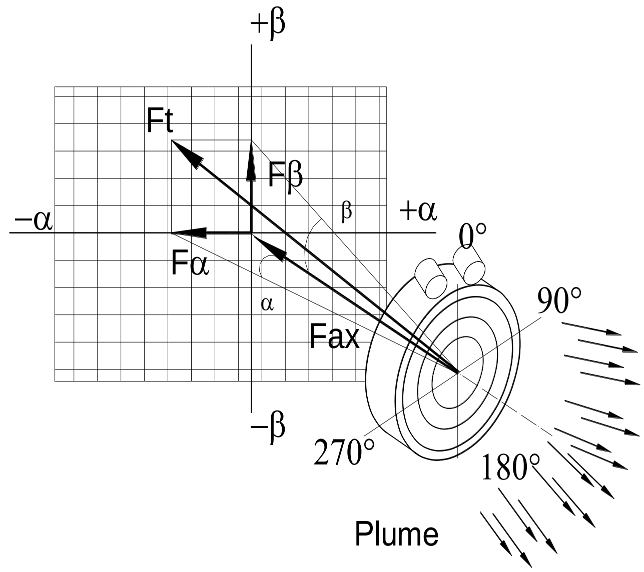


Figure 5. Accepted coordinate system

III. Brief information about factors

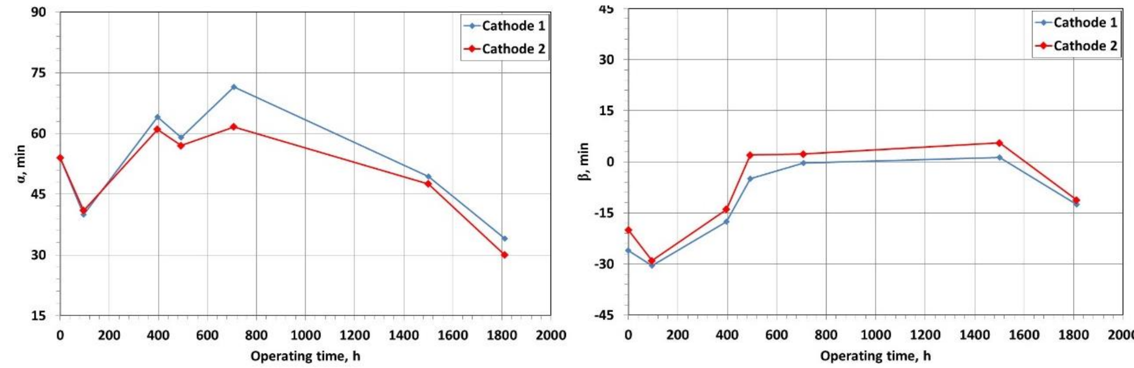
When developing the first SPT thrusters, a significant deviation of the thrust vector was a significant problem. Approximately every tenth thruster was rejected by this criterion. To reduce the variation in the angle of deflection of the thrust vector, a study was conducted in which it was determined that the main reason for the deviation of the thrust vector from the axis of the thruster are the azimuthal irregularities introduced at the stage of thruster manufacturing: the uneven flow through the anode-gas distributor, the alignment accuracy when installing the anode-gas distributor, no uniformity of the magnetic field[4]. Later it was revealed that the angle of deviation of the thrust vector is also affected by the asymmetric position of the cathode.

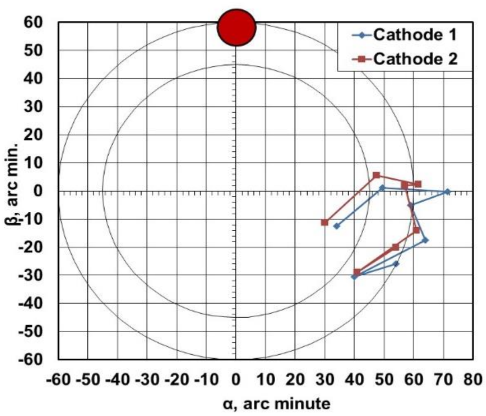
All these factors do not depend on the resource run-time or on the operating mode of the thruster. The only exception is the azimuthal uneven flow, which can change in case of anode contamination. In addition to the listed list of irregularities and asymmetries, during the resource tests of SPT-140, azimuthal uneven erosion of the discharge chamber was detected.

IV. Thrust vector stability in life test

A. Results of TVD measurement

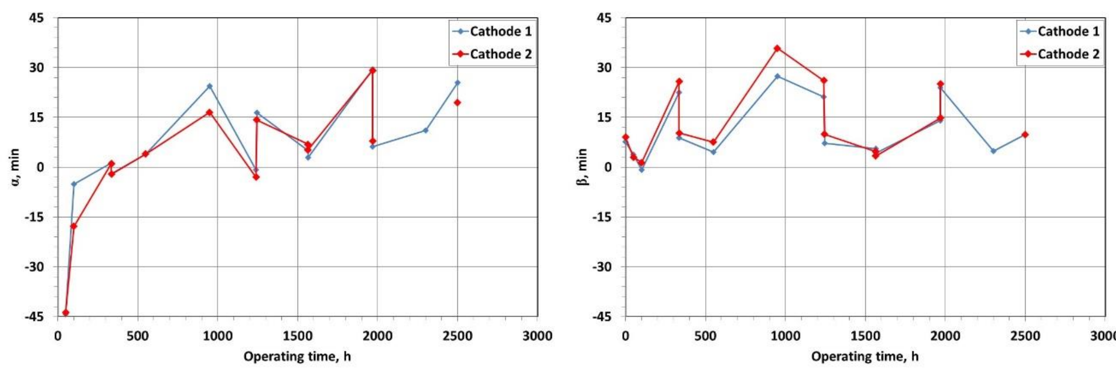
The results of measuring the TVD angle for the SPT-70 thruster are shown in Fig. 6. The table with the main statistical data is also given there. Similar data for the thrusters SPT-100 and SPT-140 are given in Figures 7 and 8. As can be seen in Figure 8, when the thruster is dismantled and assembled (the time points are marked with black lines), the results of measuring the angle of the TVD change. In the intervals between work with the thruster, the vector is stable. In the intervals between the openings, the change in the angle of the thrust vector did not exceed 15 angular minutes. This corresponds to the measurement error. In the future it will be shown that the effects of uneven erosion on the angle of the TVD were not detected. This suggests that the change in the angular velocity of the thrusters of SPT-70 and SPT-100 thrusters in the resource is most likely caused by the measurement technique, in which the thruster was dismantled.

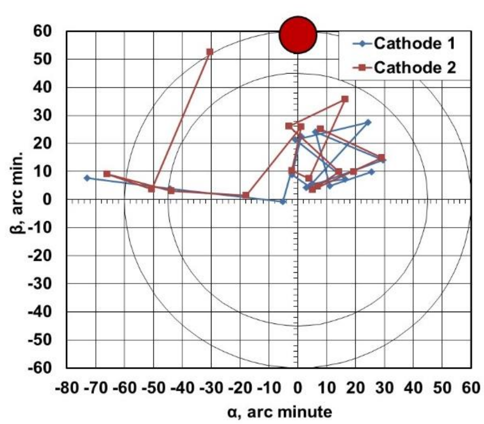




	α	β	α0
Maximum	71,50	1,20	71,50
Minimum	34,00	-30,50	36,22
Range	37,50	31,70	35,28
Standard deviation	13,19	12,40	11,80
Expected maximum	92,68	24,26	91,40
Expected minimum	13,57	-50,14	-

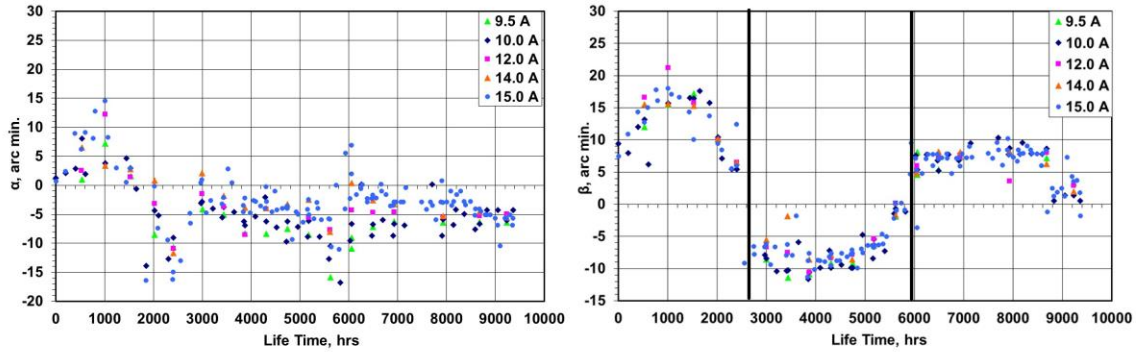
Figure 6. Stability of the TVD angle in life tests of SPT-70.

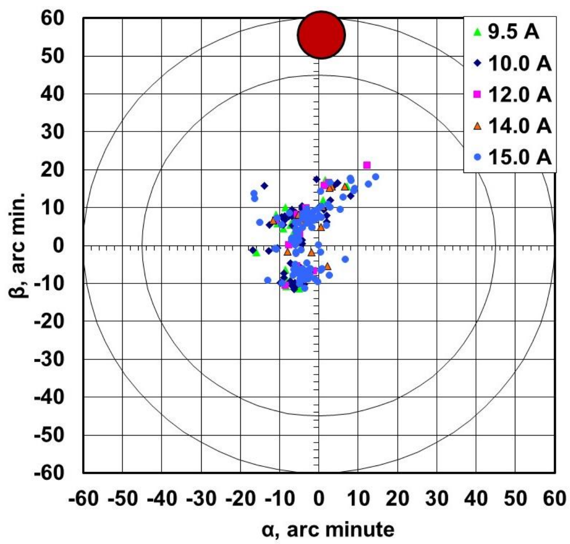




	α	β	α0
Maximum	29,50	27,40	73,39
Minimum	-73,00	-0,80	5,10
Range	102,50	28,20	68,29
Standard deviation	26,61	8,70	18,53
Expected maximum	79,89	37,09	78,64
Expected minimum	-79,75	-15,12	-

Figure 7. Stability of the TVD angle in life tests of SPT-100.





	α	β	α0
Maximum	21,19	16,76	24,46
Minimum	-11,62	-14,55	0,12
Range	32,81	31,31	24,34
Standard deviation	8,33	4,95	3,76
Expected maximum	27,54	18,54	21,27
Expected minimum	-22,48	-11,16	-

Figure 8. Stability of the TVD angle in life tests of SPT-140.

B. Erosion non-uniformity impact Analysis

The most convenient object for studying the effect of uneven erosion on the TVD angle is SPT-140. First, in the resource tests of these thruster, the method for determining the TVD was used, which does not require the opening of a vacuum chamber. This made it possible to carry out comparatively frequent measurements of the angle of the TVD (approximately every 100 hours). Secondly, of all the thrusters that passed the life tests, it is precisely for thrusters with the 140 mm type that the greatest unevenness of erosion is characteristic. To assess the effect of uneven erosion, the results of the measurement of erosion of two SPt-140 thruster, which were tested in EDB Fakel, were analyzed. The results of the determination of erosion in the output part of the discharge chamber with an azimuthal pitch of 15 degrees were used. It was assumed that the influence on the angle of the TVD is exerted only by that part of the uneven erosion, which has a period of 360 degrees. Fourier analysis of erosion measurements results on the determination of the amplitude and phase of the first harmonic was performed. Based on the results of the analysis, the amplitude and azimuthal position of the erosion maximum were determined, which for the sake of clarity were projected on the α and β planes. Note: In the determination of erosion, the azimuth angle is measured from the gas supply of the thruster. Therefore for analysis the standard coordinate system for SPT-140 was used, in which the plane β passes through the gas supply. The amplitude of the first term of the Fourier series was 0.1-0.3 mm. Based on the results of the analysis, the azimuthal drift of the mean maximum of the erosion zone was identified in the process of resource tests. The results obtained were compared with the drift of the angle of TVD . The result is shown in Figure 9. As can be seen from Figure 9, a weak relationship is observed between the maximum erosion area and the angle of the TVD . At the same time, changes in the TVD angle of outstrip changes in erosion in time, therefore the azimuthal unevenness of erosion should not be considered as a factor affecting the angle of the TVD in the life time.

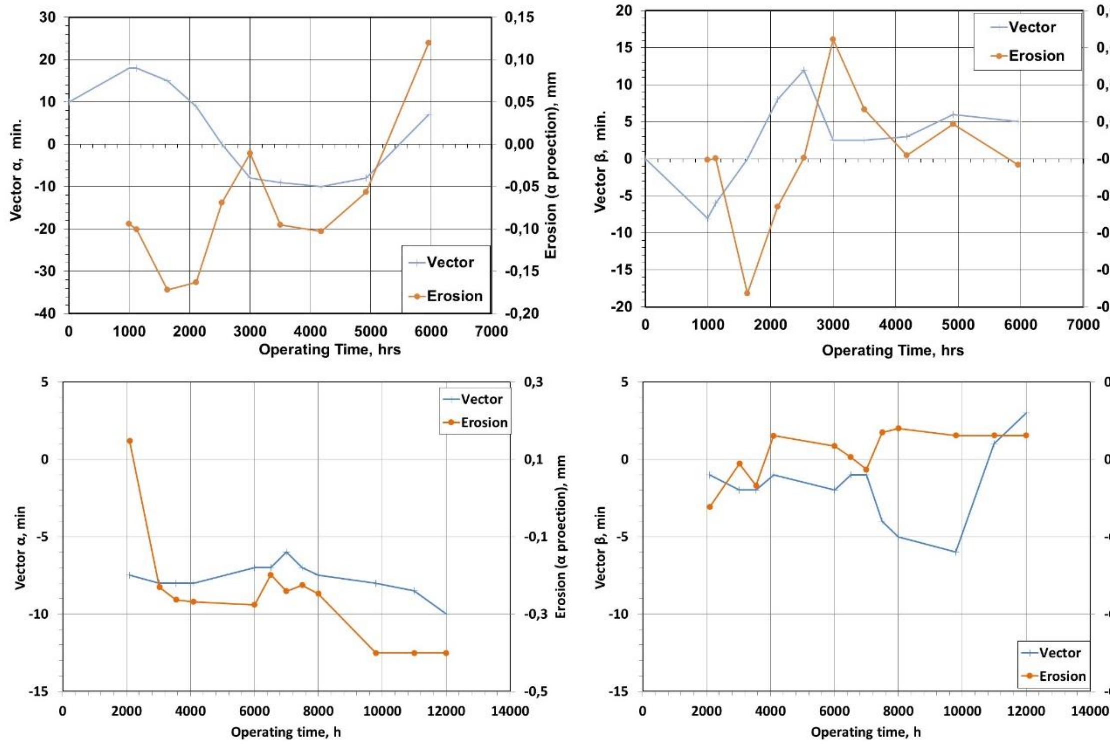


Figure 9. Comparison of the azimuthal position of the maximum of the erosion zone and the TVD angle

C. Stability to change of operating mode

An important indicator of the quality of construction for modern electric rocket thrusters is multi-mode. The requirement of stability of the TVD angle for changing the regime is especially important for thrusters, whose functions include performing both orbit raising station-keeping tasks. This is primarily the thrusters with a size of 140 and 230 mm. For the SPT-140 thrusters, the range of the discharge current is 8-16 A. There are problems for which a range of 2-16A is required. Similar requirements for the width of the operating ranges are required for the SPT-230 thruster. The change in the operating mode of the motor is due to the change in current and the discharge voltage. These factors do not relate to factors affecting the angle of deviation of the thrust vector, therefore, the dependence of the angle of deviation on the thruster operating mode is not expected. For the analysis, the results of the preliminary tests of the SPT-230 thruster and the average results of the acceptance tests of the SPT-140 thrusters were used. When carrying out the acceptance tests of SPT-140, there are no modes, with the same values of the discharge current and different values of the discharge voltage. Therefore, for these thrusters, the stability of the angle of the TVD to the change in the discharge is not given. The stability of the rotational angle to the mode change for the SPT-140 and SPT-230 thrusters is shown in Figures 10 and 11. As can be seen from Figures 10 and 11, the angle of the TVD is independent of the discharge current that is not in accordance with title[5]. Single tests of the SPT-230 thruster give grounds to believe that when the discharge voltage changes, the angle of the TVD changes with a coefficient of ~ 2arc min / 100 V. However, in order to confirm this and to determine the trend in changing the angle, more thrusters are required to be tested.

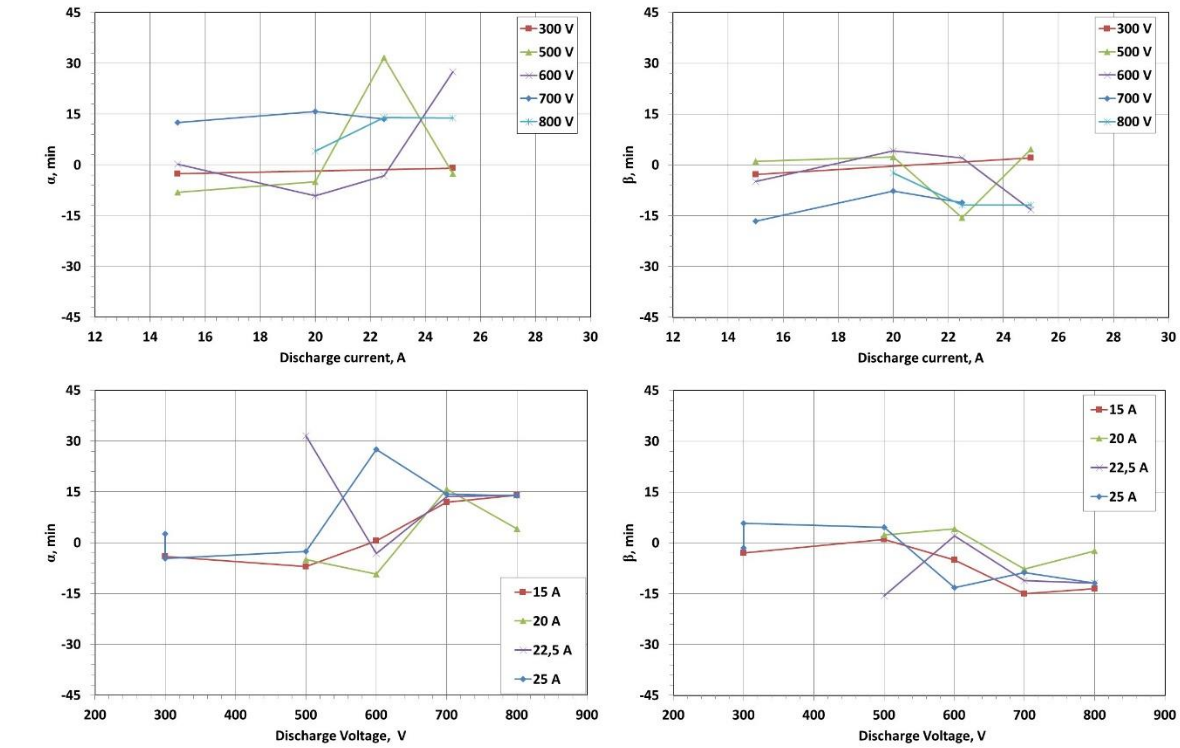


Figure 10. Thrust vector of SPT-230 in different operating modes10

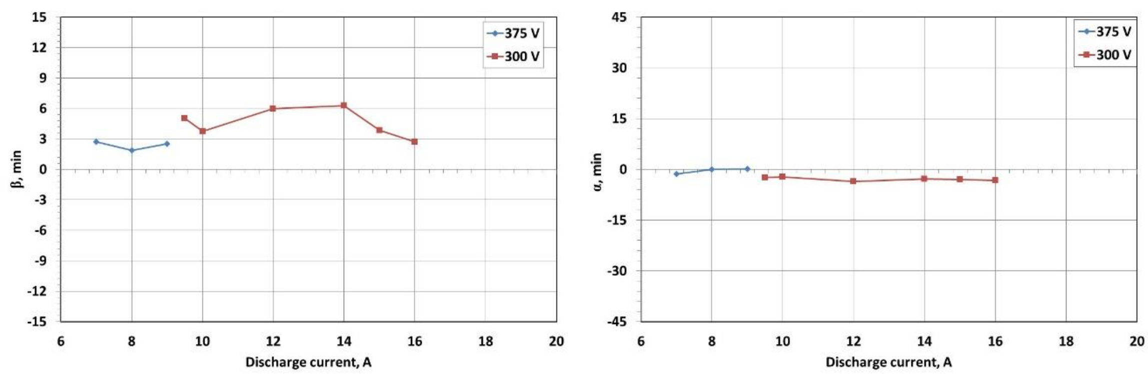


Figure 11. Thrust vector of allSPT-140 thrusters in different operating modes (acceptance test data)

V. Conclusion

The results of testing the thruster with a size of 70, 100 and 140 mm are analyzed. It is determined that the results of measuring the thrust vector depend on the repeatability of the test conditions. The abrupt changes in the angle of the TVD in the resource are connected with the change in the test conditions. The stability of the angle of the TVD under the representative conditions of the tests is confirmed by the resource tests of the thruster SPT-140. Theoretical prerequisites for the instability of the angular rotation angle of thrusters of other sizes are absent.

The stability of the angle of SWT to the change in the discharge current in the range 7…16 A is confirmed by a series of acceptance tests of thrusters with a size of 140 mm. The modes of conducting acceptance tests do not allow to determine the stability of the angle of the TVD to the change in the discharge voltage. Single tests of SPT-230 show the dependence of the components α and β on the discharge voltage. The coefficient of proportionality is approximately 2 arc. min / 100V.

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