PRINCIPLES OF HALL THRUSTER ONBOARD MALFUNCTION DIAGNOSTICS BASED ON MAGNETIC FIELD MEASUREMENTS OF PLASMA CURRENTS

B. Rubin(1), M. Guelman(1,2), A. Kapulkin(2)

(1) *Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Technion city, Haifa, 32000, Israel,*
Email: rubin@aerodyne.technion.ac.il
(2) *Asher Space Research Institute, Technion - IIT, Technion city, Haifa, 32000, Israel*

ABSTRACT

The possibility of non-contact determination of Hall current structure in the thruster is considered in order to use this information for operational processes diagnostics during flight. The scheme of the diagnostics and the algorithm for experimental data processing are developed. Using the MHD equations, an example of interpretation of hypothetical malfunction based on data on the Hall current structure deviation from nominal is considered.

1. INTRODUCTION

Due to the growth of Hall thruster applications in different space missions the problem of Hall thruster reliability becomes more topical. Application of onboard diagnostics of thruster operation is one of the most important ways to increase the thruster reliability, because it is capable of providing information clarifying the reasons of thruster failure or degradation of its characteristics.

In recent years several spacecraft equipped with Hall thrusters included also packages for thruster diagnostics [1, 2]. In the flight experiment on SC “Express-A” [1] the correlation of Hall thruster SPT-100 operation parameters to those obtained in ground testing, as well as some aspects of thruster-spacecraft interaction, was analyzed. The SMART-1 spacecraft, launched in September 2003 is also equipped with electric propulsion diagnostics package for characterization of SPT-spacecraft interactions [2].

All experiments mentioned above intended mainly to investigate the thruster-spacecraft interactions. However, data on operational processes in Hall thruster during flight are also of great interest. In this paper one possible approach to creation of an onboard system for operational processes diagnostics in Hall thruster is considered.

It should be emphasized that the required method of diagnostics should be non-contact. Both probes, and retarding potential analyzers (RPA), which were used several times in onboard diagnostic systems, cannot be permanently placed in plasma, because it will lead to the erosion of the probe or RPA. Therefore, a measurement system based on probes or RPA cannot provide real-time diagnostic information, and a malfunction may occur during the period of time when the diagnostic information is not available.

One possible approach to SPT non-contact diagnostics, is described in [3], and is based on measurements of radio-frequency thruster radiation. The electromagnetic radiation is a potential source of important information on the finest processes in the plasma of Hall thruster. However, to understand the correlation between different spectrum patterns and the thruster malfunctions it is necessary to carry out deep experimental and theoretical studies.

The proposed approach uses non-contact determination of Hall current structure. These data may be used for operational processes diagnostics during flight. The technique, which allows performing non-contact measurements of magnitude and position of center of gravity of Hall current in the Hall thruster channel was originally proposed in Russia [4, 5, 6]. These measurements of Hall current magnitude and position of its center of gravity were carried out using inductive loops, simple detectors used to measure time-varying magnetic fields. The inductive loops (detectors) were located on the outer insulator outside the acceleration channel, and inside the inner insulator, so that non-contact measurements not perturbing the plasma in the acceleration channel were possible. This approach was also used in works [7, 8]. In these works specific power supply systems were created for fast discharge current interruptions.

The most important difference from previous works is that a stationary current value will be measured. In all works mentioned above, the current interruptions were used to investigate the Hall current. Obviously, this approach is undesirable for onboard systems, because it will be necessary to switch the thruster off to measure its parameters. The system proposed in this paper will measure a steady-state magnetic field during thruster operation, allowing real-time measurements.

Thus, the idea of the method is to determine the current value and position using the magnetic field generated by this current. The computation of magnetic field from known current distribution is called the direct problem. In our case the inverse problem, i.e. the computation of the currents configuration from the known distribution of magnetic field should be solved.

The structure of this paper is as follows. In the first part, the results of the direct problem solution and the method of Hall current self-magnetic field measurement is described. In the second part, the inverse problem solution method is presented. In the third part, the application of the experimental data on Hall current structure in the case of one possible emergency event is discussed. The possibility of identification of the malfunction using these data is shown.

1. COMPUTATION OF HALL CURRENT MAGNETIC FIELD (DIRECT PROBLEM)

The inverse problem solution method, which will be described in detail below, includes the direct problem solution algorithm. The direct problem has been solved using finite-element method.

The simulations of direct problem were performed using commercial ANSYS software. This software applies a finite-element method for the solution of electromagnetic problems.

According to the different experimental data available up to date [7, 8, 11], Hall current is 3.5-15 times higher then the discharge current. In our case the discharge current value is about 2 A, therefore the Hall current value of 10 A was chosen as a conservative estimation.

The problem of measuring the magnetic field of the Hall current is complicated because this field should be measured in the presence of a much stronger magnetic field created by the magnetic system of the thruster. To facilitate the measurements it is desirable to increase the ratio of the magnetic field generated by the Hall current to the field created by the magnetic coils in some area, where the magnetic probes could be placed. At the same time it is important not to change the configuration of the magnetic field in the acceleration channel.

The following magnetic system configuration was chosen for analysis. The cylindrical magnetic screen was modified in the area near the thruster cut, where the Hall current flows, as shown in fig. 1.

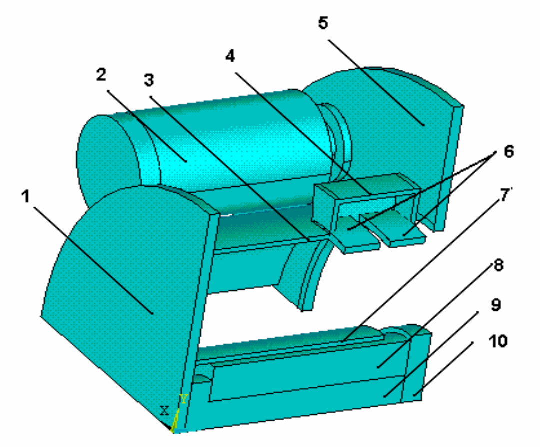

Fig. 1. Hall thruster magnetic system.
1-Backplane, 2- outer magnetic coil, 3- outer magnetic screen, 4- modified part of the magnetic screen, 5 – outer magnetic pole piece, 6 – magnetic sensors, 7 - inner magnetic screen, 8 – inner magnetic coil, 9- inner magnetic core, 10 – inner magnetic pole piece.

This modification does not perturb the magnetic field configuration in the channel. After the modification, the ratio of the Hall current field to the primary field increased in the range from a tenth of percent to several percent.

For the inverse problem solution it is important to choose the parameterization of Hall current spatial distribution. This parameterization defines the parameters which will be found during the inverse problem solution. In our case a rather simple parameterization was chosen – the stepped Gauss distribution in the axial direction and the flat distribution in the radial direction. The rectangular and stepped fits were chosen because in the 3D magnetostatic analysis in ANSYS the primitive current sources, such as coils, bars and arcs are used to represent the location of current sources. The value of current is constant in each source, therefore it is impossible to simulate a continuous current distribution. Thus, current distribution is parameterized using three parameters – the value of the current, the center of gravity axial position and the width of axial distribution. The computations of magnetic field distributions generated by the Hall current were performed for different sets of these parameters. Axial distributions of axial and radial magnetic field of Hall current components for three different current distributions are presented in Fig.2. First and second distributions differ in the current center axial location *z*; first and third differ in the width of axial distribution *dz*. In all cases current is 10 A.

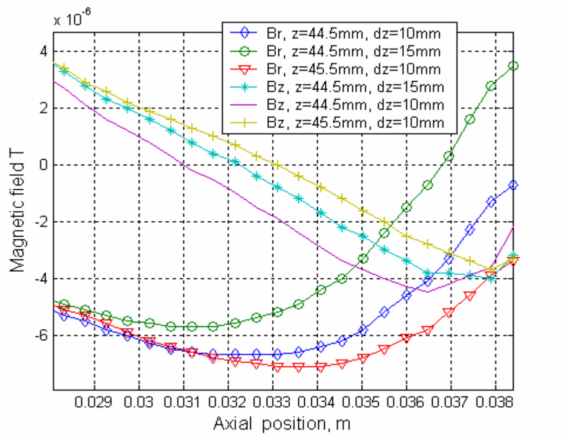

Fig. 2. Hall current magnetic field

The proposed type of magnetic sensor is a Honeywell HMC 1021D sensor. This sensor temperature range allows to operate at temperatures as high as 300 ^{0}C. The sensor includes the offset strap, which allows compensation of the unwanted magnetic field. In our case, the magnetic field created by the magnetic system in the sensor location may be compensated. Other advantages of this sensor are high sensitivity, small size and noise immunity.

An important step is to choose the positions of the magnetic sensors. The modification of the magnetic screen mentioned above allows placing several magnetic sensors in each of volumes shown in Fig.1. These data will be used in the inverse problem solution, described below. As the Hall current is azimuthally symmetric, it generates a magnetic field with a zero azimuthal component. Radial and axial field components may be measured. It is convenient to choose two points for the radial field measurements and two points for axial field measurements. The considerations for this choice are that the measured magnetic field components should be strongly influenced by the changes in the Hall current structure, while the values of these fields should be as high as possible.

2. COMPUTATION OF HALL CURRENT PARAMETERS FROM MEASURED MAGNETIC FIELD VALUES (INVERSE PROBLEM)

In works [4-8] the inverse problem solution was approximated by experiment. A current-carrying loop, simulating the drift current, was placed inside the acceleration channel, and a current in it was pulsed. Varying the loop radius, position, and current, and measuring the corresponding variations of sensor response, an approximation to the inverse problem solution was obtained. In [7] the time dependent measurements of current induced in loop antennas were computed using a numerical model.

As mentioned above, in this paper the method allowing determination of Hall current parameters without being interrupted is described. In this case the inverse magnetostatic problem should be solved.

The inverse problems for magnetostatics are ill-posed (in the sense of Hadamard) [9]. The main concern in these ill-posed problems is that the solution is unstable. The input data for the inverse problem are often obtained from experiment (as in our case) and therefore are perturbed by measurement errors. Therefore, regularization techniques are required to prevent the solution instability. Iterative regularization described in [10] may be applied in our case. According to this method, the inverse problem is formulated as an optimization problem and solved by an iterative method. The objective function is a quadratic residue between the computed magnetic field and the measured field. The residue is minimized to obtain the current distribution.

The described above parameterization of the Hall current distribution allowed to reduce the inverse problem to estimation of the set of parameters. The objective function to be minimized is the quadratic residue between the calculated magnetic field and the measured field.

At first the optimal number and locations of the magnetic sensors was determined. In the absence of experimental data the measured magnetic field values were simulated by the direct problem solution. The values of magnetic field in the presumed sensors location were averaged over the sensors size. The exact form of the objective function is

$$J = (B_{r1}^{m} - B_{r1}^{c})^2 + (B_{r1}^{m} - B_{r1}^{c})^2 + (B_{r1}^{m} - B_{r1}^{c})^2 + (B_{r1}^{m} - B_{r1}^{c})^2$$

where B_{r1}^{m}, B_{r2}^{m}, B_{z1}^{m}, B_{z2}^{m} are measured and B_{r1}^{c}, B_{r2}^{c}, B_{z1}^{c}, B_{z2}^{c} computed magnetic field values.

The minimization was performed by fitting three parameters – the total current value, axial position of the current center of gravity and axial width of the volume, where the current flows. Magnetic field values depend on the current value linearly, and on the other two parameters non-linearly. Taking into account, that the axial position and the width of the current may vary over a rather narrow range, these non-linear dependences were linearized. It introduced a maximum error not exceeding 10 % in the field values. After the linearization, the problem became a quadratic-programming problem. It was solved by different optimization algorithms, realized in MathLab. The best results were obtained using medium-scale Quasi-Newton line search algorithm and Levenberg-Marquardt algorithm. The inverse problem solution algorithm was first tested on the exact direct problem solution, the obtained results were accurate enough, especially the current value. Then the experimental data were simulated by adding the worst-case 10% error to the exact data. It increased the maximal error in the current determination to 20%, the error in axial position was within 5%. For example, for the current with following parameters – axial center of gravity position – 48 mm, axial width – 13 mm and current – 25 A, the "measured" magnetic field values, obtained by using the linearized direct problem solution are: $B_{r1} = -1.02*10^{-5}$ T, $B_{r2} = -1.20*10^{-5}$ T, $B_{z1} = 6.65*10^{-6}$ T, $B_{z2}=-5.28*10^{-6}$ T. After the "measurement" error was added, these values became $B_{r1} =-9.23*10^{-6}$ T, $B_{r2}=-1.10*10^{-5}$ T, $B_{z1} = 6.05*10^{-6}$ T, $B_{z2} = -4.78*10^{-6}$ T. The solution of the inverse problem by the Quasi-Newton method converged after 21 iterations and gave the following results – the axial center of gravity position – 47.7 mm, axial width – 11.7 mm and current – 22.8 A. The results are close enough to the direct problem input. Therefore, the proposed inverse problem solution algorithm may be applied for the experimental data processing.

The method used in this work uses simple current distributions parameterization. In future works a more complex form of parameterization will be used, which will allow to study the Hall current distribution in greater detail. More exact approximation of the direct problem solution will also be used, which will increase the accuracy of the method.

3. APPLICATION OF EXPERIMENTAL DATA ON HALL CURRENT STRUCTURE FOR MALFUNCTION ANALYSIS

As mentioned in the introduction, the information on the Hall current structure in HT may help significantly in the investigation of the reasons of thruster malfunction or degradation of its characteristics. In this section we will consider an example, which shows how the information on Hall current value in some parts of the acceleration channel may be used to understand the reason of the discharge current reduction. For more clearness we will consider the case, where the discharge and the magnetic systems are supplied from separate power sources. It is easy to transform the theoretical model to the case where the discharge and the magnetic coils are serially connected.

The reduction of the discharge current at constant magnetic field (which may be checked using the parameters of magnetic system power supply, i.e. current and voltage drop), may be caused by two possible reasons:

1) the reduction of the propellant mass flow rate, which may happen as a result of parasitic leakage in the propellant feed system;
2) the degradation of the cathode compensator, which will cause the plasma plume potential increase outside the acceleration channel, a subsequent reduction of the voltage drop in the acceleration channel and as a result – a reduction of propellant ionization.

To demonstrate the possibility to determine which of the two mentioned reasons (or both of them) caused the reduction of the discharge current, we use the known MHD one-dimensional steady set of equations, describing the process of ions acceleration taking into account ionization [12]:

$$\frac{dnV}{dx} = \beta n n_a$$

$$\frac{dnV^2}{dx} = \frac{enE}{M} + \beta n n_a V_a \qquad (1)$$

$$V_a \frac{dn_a}{dx} = -\beta n n_a$$

$$E = \frac{I_d - enVS}{\sigma S}$$

,where n - ions (electrons) number density,

V - ions velocity,

n_a - neutral atoms number density,

V_a - neutral atoms axial velocity,

I_d - discharge current,

σ - transverse to magnetic field plasma conductivity,

β - ionization coefficient,

M - ion mass,

e - unit positive charge,

E - electric field strength,

S - the acceleration channel cross-sectional area.

We shall assume that V_a is approximately constant. We also assume that over the entire acceleration channel the conductivity σ is equal to

$$\sigma = \frac{ne^2}{m\omega_e^2 \tau_{ef}} \qquad (2)$$

the so-called near-wall conductivity, where m is the electron mass, $\omega_e = \frac{eB}{m}$,

$B(x)$ - magnetic flux density (the magnetic field is assumed purely radial),

τ_{ef} - effective time of the electron scattering on the walls, which is accompanied by the loss of momentum azimuthal component.

The distribution of the magnetic flux density in the acceleration channel is approximated using the following dependence:

$$B = \frac{B_m}{\left(\frac{sha(\frac{x}{L} - c)}{shaq}\right)^2 + 1} \qquad (3),$$

where L - the length of the area under consideration,

B_m – maximal value of the magnetic flux density,

a, c, q - non-dimensional parameters, which characterize the steepness of the profile, the peak position and its width respectively.

The behavior of the ionization coefficient β in the acceleration channel is approximated by the following dependence:

$$\beta = \beta_m \left[1 - \exp\left(-\frac{|E|}{E^*}\right)\right] \qquad (4)$$

where $\beta_m = 8.8 \cdot 10^{-14}$ m^3/s .

This form of the β approximation takes into account the fact that in the locations where the electric field is high, temperature of electrons is usually also high and therefore the ionization coefficient is high as well.

The system of equations (1) may be transformed to the following form:

$$\frac{dn}{dx} = \frac{\beta n}{V_a V}\left(\frac{\dot{m}}{MS} - nV\right)(2 - \frac{V_a}{V}) - \frac{eEn}{MV^2}$$

$$\frac{dV}{dx} = \frac{eE}{MV} - \frac{\beta}{V_a}\left(\frac{\dot{m}}{SM} - nV\right)(1 - \frac{V_a}{V}) \qquad (5)$$

$$\frac{d\Phi}{dx} = -E \quad , \quad E = \frac{I_d - enVS}{\sigma S}$$

, where $\dot{m}$ – mass flow rate,

Φ – plasma potential.

Equations (5) should be accompanied by the boundary conditions. In the course of the direct problem solution, i.e. solving for the distribution of the plasma parameters, including the Hall current density, the following boundary conditions may be taken:

$$n(0) = n_0 = \frac{\alpha \dot{m}}{S V_0 M}; \qquad V(0) = V_0;$$

$$\Phi(0) = \Phi_a; \qquad \Phi(L) = \Phi_b \qquad (6)$$

, where $\alpha = \dfrac{n_0 V_0}{n_0 V_0 + n_a V_a}$,

Φ_a – the anode potential relative to the cathode,
Φ_b – the ion beam potential in the point $x=L$.
In the system of equations (5) the discharge current I_d is also unknown. Therefore, let us consider formally the boundary-value problem (5) - (6) as an eigenvalue problem. For its numerical solution let us formally add to the system (5) - (6) the condition

$$\frac{dI_d}{dx} = 0 \qquad (7).$$

A numerical solution example of problem (5) – (7) is presented in Fig.3.

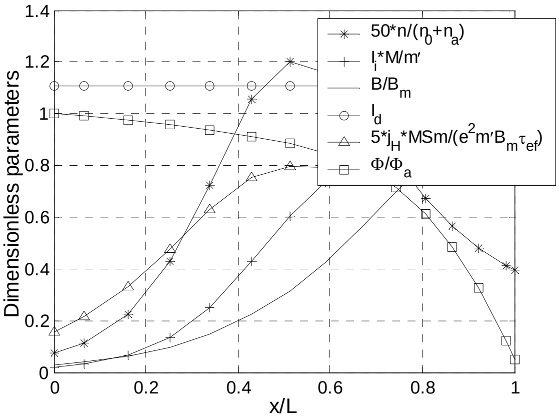

Fig. 3. Numerical solution (direct problem)

The following parameter values were used:

$\dot{m} = 2*10^{-6} kg/s$, $\alpha = 0.02$, $V_0 = 2.09*10^3$ m/s, $V_a = 1.5*10^2$m/s, $\tau_{ef} = 2.82*10^{-7}$, $B_m = 1.6*10^{-2}$ T, $L = 3*10^{-2}$ m, $\Phi_a = 300$V, $\Phi_b = 15$V, $S = 3.56*10^{-3}$m^2 , $E^* = 3.33*10^3$ V/m.

In Fig. 4 the distributions of Hall current density in the channel for different values of $\dot{m}$ and Φ_b are presented. As seen from the figure, the Hall current density is rather sensitive to variations of both mass flow rate and ion beam potential, but the degrees of this sensitivity are different. For practically equal deviations of the discharge current from the nominal value (3.9% and 3.5%) the influence of the plume potential on the Hall current density, especially in the vicinity of the thruster exit plane is significantly higher. Therefore, plotting these graphs for a sufficient number of the $\dot{m}$ and Φ_b values it is possible to determine from the results of Hall current density measurements which one of the two reasons caused the variation in the discharge current.

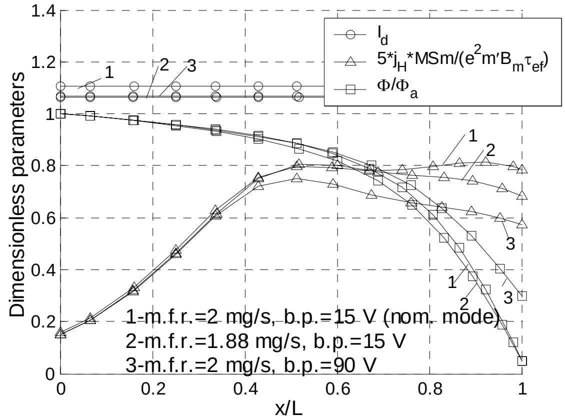

Fig. 4. Hall current density distribution

To make the process of malfunction identification more convenient, the boundary-value problem (5) – (7) was re-formulated as an inverse problem (in a certain sense): instead of (7) equation

$$\frac{d\dot{m}}{dx} = 0 \qquad (8)$$

was taken and instead of the fourth boundary condition in (6) the following condition was used:

$$\frac{en(L)E(L)}{B(L)} = j_H(L) \qquad (9)$$

where $j_H(L)$ – the Hall current density in point $x=L$.

Now $\dot{m}$ is an unknown value and at the same time $\dot{m} = \dot{m}(0)$, therefore the first boundary condition in (6) should be formally written as

$$n(0) - \frac{\alpha \dot{m}(0)}{S V_0 M} = 0 \qquad (10)$$

The examples of $\dot{m}$ and $\Phi(x)$ determination from the known values of the discharge current and the Hall current density in the point $x=L$, are presented in Fig.5. One of the curves corresponds to the determination of the "nominal solution", presented in Fig.3. The comparison of the "nominal solution" curves in Fig.3 and Fig. 5 demonstrates the good accuracy of this procedure. The second group of curves corresponds to the operation mode, when leakage of propellant occurs before branching to the anode and cathode.

It is necessary to note that in the course of the emergency situation modeling for demonstrational purposes, a relatively simple system of MHD equations was used. Remaining in the frames of the used numerical method it is not difficult to include the gradient of electron pressure term, which causes the inversion in the potential distribution in the near-anode region. It is also possible to apply different mechanisms of the cross-field conductivity in different regions of the channel. Generally speaking, for the analysis of the emergency situation of the Hall thruster in flight, it is necessary to fit parameters τ_{ef} and E^*, used in the equations for conductivity and ionization coefficient, for every thruster design, which differ in their dimensions and other characteristics. These can be obtained from ground tests.

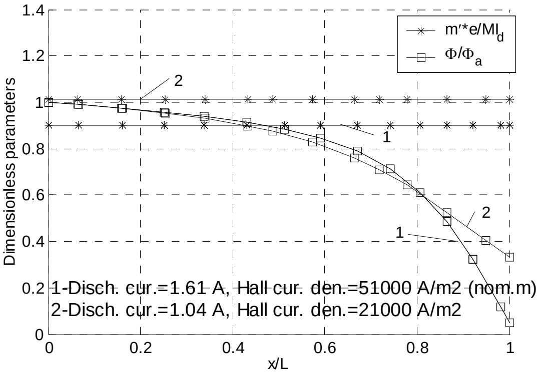

Fig. 5. Inverse problem solution

CONCLUSIONS

1. A scheme for magnetic field measurements in flight was developed. The scheme is based on the use of onboard commercial magnetic sensors, and requires only a local variation of the magnetic screen configuration. This variation does not significantly influence the applied magnetic field in the channel.
2. Numerical modeling of Hall thruster magnetic fields showed, that it is possible to estimate the Hall current density in the thruster acceleration channel, on the basis of stationary magnetic fields measurements outside the acceleration channel.
3. The scheme for Hall current parameters determination (inverse problem) based on the stationary magnetic field values measured outside the acceleration channel was developed and numerically verified.
4. The mathematical model and corresponding software for the analysis of emergency discharge current variations was developed. The model uses the information on the Hall current density current on the thruster exit plane as an input parameter. The possibility to determine which one of the two possible causes of discharge current reduction – gas leakage or cathode degradation, was demonstrated.

REFERENCES

1. Manzella, D., Jankovsky, R., Elliott, F., Mikellides, I., Jongeward, G. and Allen, D. "Hall Thruster Plume Measurements On-board the Russian Express Satellites." *IEPC Paper* 2001-044, 2001.
2. Matticari, G., Noci, G., Estublier, D., Gonzales, J., Marini, A., Tajmar, M., «The SMART-1 Electric Propulsion Diagnostic Package", *3-rd International Conference on Spacecraft Propulsion,* Paper no. 210, October 2000.
3. Kapulkin A., Kogan A., Guelman M. "Noncontact Emergency Diagnostics of Stationary Plasma Thruster in Flight", *52-nd International Astronautical Congress, 2001*. To be published in *Acta Astronautica*.
4. Demyanenko, V.N., Zubkov, I.P., Lebedev, S.V., Morozov, A.I., "Induction Method for Measuring the Azimuthal Drift Current in a Hall-Current Accelerator", *Soviet Phys. Tech. Phys*. 23 (3), March 1978.
5. Bugrova, A.I., Versotskii, V.S., Kharchevnikov, V.K., "Determination of the Radial Center of Gravity of an Azimuthal Drift Current in Accelerators with Closed Electron Drift", *Soviet Phys. Tech. Phys*. 25 (10), October 1980.
6. Barkalov, E.E., Vesselovzorov, A.N., Subbotin, M.L., "Experimental Study of the Azimuthal Electron Drift Current in Hall Accelerators", *Soviet Phys. Tech. Phys*., Vol. 35 No. 2, February 1990.
7. Thomas, C.A., Gascon, N. and Cappelli, M.A., "A Study of the Azimuthal Electron Drift in an E x B Discharge Using a Non-invasive Antenna Array", *AIAA Paper* 2003-4854.
8. Prioul, M., Bouchoule, A., Roche, S., Magne, L., Pagnon, D., Touzeau, M., Lasgorceix, P., "Insights of Hall Thrusters through Fast Current Interruptions and Discharge Transients", IEPC *Paper* 01-059, 2001.
9. Tikhonov, A., Arsenin, V., "*Solutions of Ill-posed Problems*", Moscow, Mir, 1977.
10. Begot, S., Voisin, E., Hiebel, P., Kauffmann, J.M., Artioukhine, E., "Resolution of Linear Magnetostatic Inverse Problem Using Iterative Regularization", *European Phys. J. AP* 12, 123-131, 2000.
11. Haas, J.M., Gallimore, A.D., "Considerations on the Role of the Hall Current in a Laboratory-Model Thruster," *AIAA Paper* 2001-3507, 2001.
12. Morozov A.I. and Savelyev V.V., "*Fundamentals of Stationary Plasma Thrusters Theory, Reviews of Plasma Physics*", edited Kadomtsev B.B., Shafranov V.D., Kluwer Academic Publishers, pp. 203-390, 2001.