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A. LAZURENKO[1], V. VIAL[1], A. BOUCHOULE[1], P. LASGORCEIX[2], C. LEGENTIL[2], L. ALBAREDE[2], M. DUDECK[2], L. JOLIVET[3], M. PRIOUL[4]

[1] *GREMI Laboratory, Orleans University, France*
[2] *Aerothermique Laboratory, CNRS, France*
[3] *CNES, France*
[4] *SNECMA Moteurs, France*

TRANSIENT BEHAVIOR OF THE PPS®-1350 THRUSTER IN AN EXTENDED RANGE OF OPERATION MODES

Engineering model of the PPS®-1350 Hall-effect thruster was tested in an extended operation domain: mass-flow rate 2–7.5 mg/s, discharge voltage 250–1000V. Transient behavior of the thruster was studied at each operation point. Oscillations of the discharge current, anode potential and cathode potential were analyzed, particularities are presented.

hall thruster, PPS®, discharge current, discharge voltage, oscillations, Fourier transform

Introduction

Hall thrusters (HT) currently find their application in the space propulsion technology for station-keeping. Also, in the SMART-1 moon mission a PPS®-1350 HT serves for primary propulsion [1]. For the prospective applications a HT operation in the extended range of operation modes would be welcome. Operation modes with high thrust, moderate specific impulse could be useful for a spacecraft orbit transfer. Operation modes with high specific impulse, low thrust could offer an increase of spacecraft lifetime or reduction in spacecraft mass.

There is a number of works devoted to the HT investigation in the wide range of mass flow rates, discharge voltages [2 – 4]. But, until now little attention has been paid to the thruster oscillating behavior when discharge parameters differ significantly from standard ones. Apparently, oscillations are not the main factor limiting HT operation at these operation modes. Nevertheless, a high level of discharge parameter oscillations could prevent the thruster from effective operation. Therefore, it is interesting to study this problem in more details.

Oscillations of different frequency families are present in HT [5]. Oscillations related to the neutral and ion dynamics fall into the range of < 1 MHz. They have the greatest impact on thruster performance. On the other hand these oscillations are relatively well understood, also due to the results of numerical simulation (e.g. [6]). Therefore, subsequent analysis of experimental data is greatly facilitated. Oscillation of 1 MHz and higher are related to the electron dynamics in HT [7]. This question represents a rather complicated physical problem and it is not well-studied up to now. Here, we will limit our study to frequency lower than 1 MHz.

1. Apparatus and procedure

A PPS®-1350 engineering model, developed by SNECMA, was chosen for the investigation in the wide range of operation modes. This thruster has a nominal discharge voltage $U_d = 350$ V, a total xenon (Xe) flow rate $\dot{m} = 5{,}3$ mg/s, a thrust $F = 89$ mN [8]. It is equipped with a standard flight-version LaB_6 cathode. At the present studies anode mass flow rate was varied between 2,31 mg/s and 7,4 mg/s with discharge voltages up to 1000 V and discharge powers not higher than 3,2 kW. At each operating point the magnetization coils current were adjusted to reach the minimum of discharge current.

PPS®-1350 characterization was carried out at French national PIVOINE facility [9]. It consists of a cylindrical stainless steel chamber of 2,2 m in diameter and 4 m in length, equipped by cryopumps providing a pressure $1{,}5\cdot10^{-5}$ Torr (corrected for Xe) at mass flow rate of 5,5 mg/s. The corresponding pumping speed for Xe is 70000 l/s. Thrust stand is of compensatory type with measurement accuracy of $\pm$ 2,5 mN.

The main discharge was powered by two power supplies connected in series. Another power supply was used to pre-heat the cathode. Internal and external magnetization coils were connected in series and powered by an additional commercial power supply. Accuracy of voltage and current measurement is ± 1,0%.

Anode and cathode were fed by Xe through the independent lines with MKS flow controllers. Accuracy of flow rate measurements is ±5,0%. Cathode mass flow rate was set to 10% of the anode one.

Discharge parameters oscillation measurement scheme is presented in fig. 1. Discharge current oscillations were detected at two points: near the anode ($\sim I_{d\_a}$) and near the cathode ($\sim I_{d\_c}$). Tektronix P6021 current probes were used for this purpose. These probes allow for measuring a current alternating component in the range of frequencies 300 Hz – 6 MHz. Anode (V_a) and cathode potentials (V_c) relative to the facility ground were measured by Tektronix P5100 probes with a frequency pass band up to ~20 MHz for the voltage range of interest.

The probes were connected to the Tektronix TDS3054 four entrances oscilloscope allowing for 10000 points in each signal recording. Simultaneous acquisition of signals from all four probes was therefore enabled. For each PPS®-1350 operating point oscillation samples were taken in single-shot mode. These recordings were stored in the oscilloscope memory and then transferred to the computer for further processing.

Standard techniques of signal processing were applied. To define a frequency the recordings were Fourier transformed. Level of the measured parameter oscillations was estimated by calculation of its standard deviation:

$$\sqrt{\sigma^2} = \left(\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2 \right)^{1/2}, \qquad (1)$$

where x_i – measured values;

$\bar{x}$ – mean value;

N – number of measurement points.

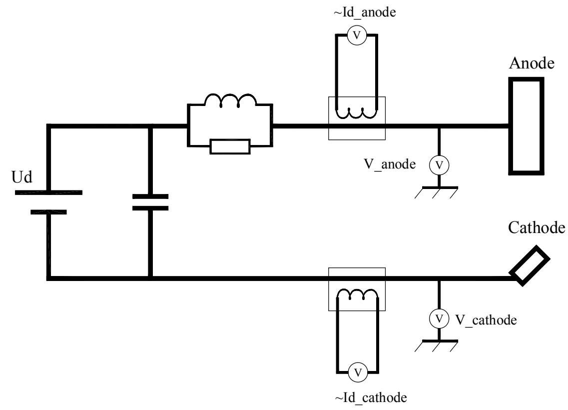

Fig. 1. Measurement scheme of discharge parameters oscillations

2. Results and discussion

The interest of measuring discharge current oscillations in two points is explained by the considerations that these oscillations can comprise information on different processes. Anode discharge current I_{d_a} is the current of electrons appearing mostly as a result of ionization. Therefore it reflects the processes in the ionization zone. Cathode current I_{d_c} serves for the ion beam neutralization and for sustaining main discharge in the thruster. Therefore it is greatly influenced by the processes of ion-electron interaction at the exit of the thruster and also, in the case of ground testing, possible interaction with the chamber walls.

The difference between I_{d_a} and I_{d_c} reveals while comparing their amplitude. For the most number of operating points I_{d_a} oscillations are stronger than oscillations of I_{d_c} (fig. 2). It could be an effect of interaction between the outcoming ion beam and ambient plasma in the vacuum chamber. Presented in the chamber electrons participate in neutralization of the ion beam. Therefore, leaving the cathode electron current is smoothed. Its maximum value is lower than the corresponding value of the anode current, but in the minimum it is higher to deliver more electrons for the plume neutralization. This effect should be studied more in details because it is important for the ground HT testing.

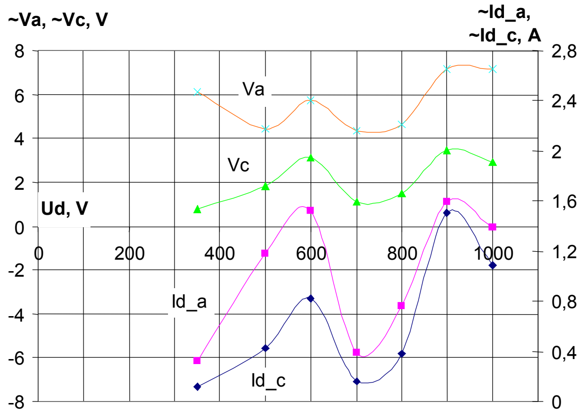

Fig. 2. Oscillation level of anode and cathode current, anode and cathode potential for $\dot{m}_a$ = 2,31 mg/s

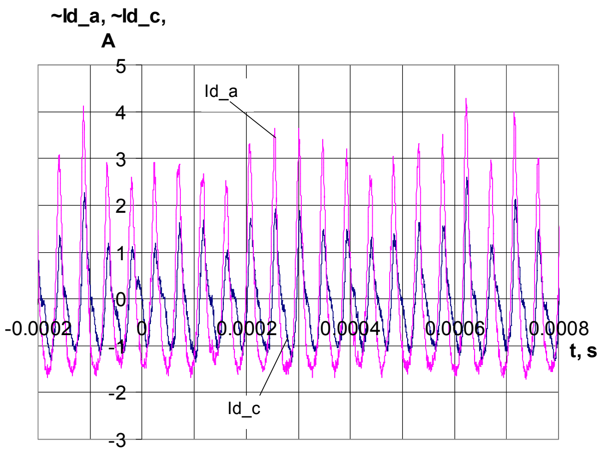

Fig. 3. Example of the current oscillations for $\dot{m}_a$ = 2,31 mg/s, U_d = 600 V

There is not any statistically significant dependence of the oscillation level on the mass-flow rate. In contrast, dependence on discharge voltage for the fixed mass flow rate has particular points. For each mass flow rate the oscillation level is maximum at the discharge voltages U_d = 400 – 600 V (see fig. 2). At these points the oscillations are pulsed, with the well-shaped peaks (fig. 3). Origin of this particularity is not well understood.

Several frequency families could be generally recognized in the oscillations spectra, grouped in three ranges: 10 – 16 kHz, 20 – 35 kHz and 40 – 45 kHz. Higher frequencies > 50 kHz are sometimes observed but their contribution to the spectra is small. Typical results of Fourier transform of the signals are presented in fig. 4. The low-frequency oscillations 10 – 45 kHz are related to the ionization front oscillations due to the processes of neutral depletion and filling in the accelerating channel. These oscillations are also termed as a “breathing” mode [5].

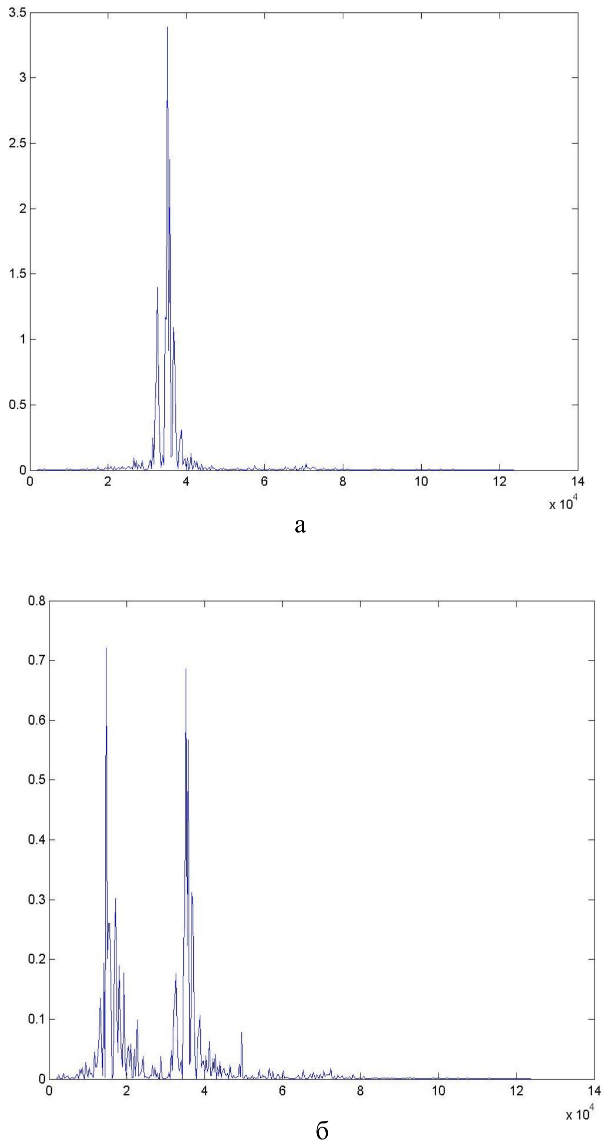

Fig. 4. Power spectrum density for $\dot{m}_a$ = 6,01 mg/s, U_d = 450 V: a – I_{d_a} spectrum; b – I_{d_c} spectrum

Anode current always shows the frequencies 20 – 35 kHz, which smoothly transit down to 10 – 16 kHz for $U_d \leq 200$ V. Frequencies of 10 – 16 kHz generally appear in the signals of cathode current and potentials oscillations. Contribution of these frequencies to the spectra is dominant for low discharge voltages $U_d \leq 300$ V. Their contribution is also significant for the standard and higher mass flow rates $\dot{m}_a \geq 5$ mg/s. This difference in spectra between anode current from one side and cathode current and potentials from the other is to be attributed to the interactions with the ambient plasma in the chamber.

Contribution to the spectra of the frequencies 40 – 45 kHz is weak, and they probably represent harmonics of frequency 20 – 23 kHz.

Frequencies 20 – 35 kHz tend to increase with mass flow rate (fig. 5). It could be understood taking into account that they are associated with neutrals dynamics in the accelerating channel. These frequencies could be approximated as [5]:

$$f \cong \frac{(V_n V_i)^{1/2}}{L_i}, \qquad (2)$$

where V_n – neutral velocity;

V_i – ion velocity;

L_i – ionization layer length.

For a constant discharge voltage we can suppose a constant ionization layer length L_i and a constant potential drop in it. This means that ion velocity in the ionization layer is constant: $V_i = \text{const}$. Then the frequency depends on neutral velocity, which in the first order approximation is proportional to the square root of the anode temperature: $V_n \sim \sqrt{T_a}$. Anode temperature increases with the heat losses; the last could be expressed in terms of discharge current I_d and anode resistance R_a: $Q_a = I_d^2 R_a$. Discharge current in HT is proportional to anode mass flow rate $\dot{m}_a$. Employing all these relationships one can deduce:

$$f \sim \sqrt{V_n} \sim (T_a)^{1/4} \sim \sqrt{I_d} \sim \sqrt{\dot{m}_a}. \qquad (3)$$

For example, for $\dot{m}_a = 4{,}62$ mg/s and $\dot{m}_a = 2{,}31$ mg/s we obtain according to (3) the ratio of corresponding frequencies 1.41 whereas the measured value is 1,45.

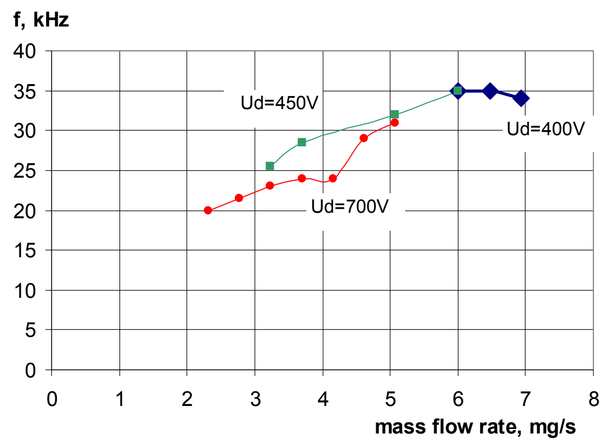

Fig. 5. Evolution of the frequency 20 – 35 kHz with mass flow rate

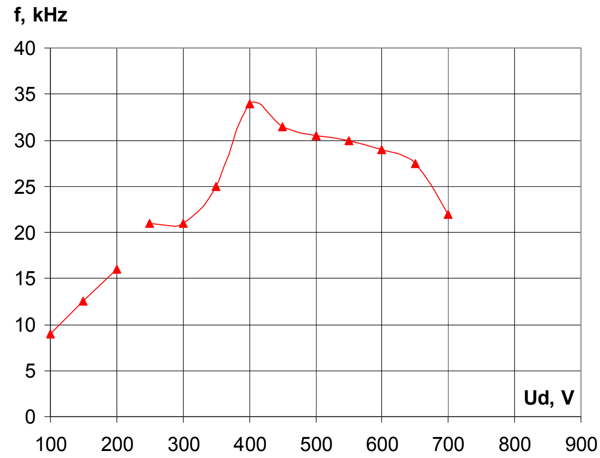

Fig. 6. Evolution of the frequency 20 – 35 kHz with discharge voltage for $\dot{m}_a = 3{,}7$ mg/s

Evolution of the frequencies 20 – 35 kHz with discharge voltage is not so trivial (fig. 6). At the range of low discharge voltages (up to ~400V) the frequency increases and then decreases. Discharge power increases with discharge voltage at fixed mass flow rate. Therefore the power dissipated in the anode increases, and, as in the previous case of the increasing mass flow rate, neutrals velocity should increase. As can be seen in fig. 6, from the certain value of discharge voltage this increase of the neutrals velocity is compensated by the other processes. Relationship (2) suggests that it could be changes in the ionization layer length. Further analysis requires consideration of more complex physical phenomena and it is out of scope of this paper.

For the most number of operating points where the high-level pulsed oscillations are observed (see fig. 2, 3) the thruster efficiency reaches a local maximum. But several points fall out from this tendency, suggesting that other factors can interfere. There was not found any other direct correlation between oscillations and thruster performance. It is probably due to the optimization of each operating point by magnetic field, and therefore the oscillations properties are close to the optimum ones.

Conclusions

Analysis reveals the particularities of the oscillation properties evolution with mass flow rate and discharge voltage for the PPS®-1350 thruster. It was shown that the main frequency in the range of 20 – 35 kHz increases with mass flow rate. Its evolution with discharge voltage is more complicated, showing the maximum at the voltages ~400 V. A lower frequency of 10 – 16 kHz can appear in cathode current, anode and cathode potentials, and for low voltages in anode current. Performance increasing at the operating points where the maximum oscillations level is observed seems very interesting and requires additional studies. From the experimental results it follows that oscillation level does not limit the thruster operation under high discharge voltages, provided that magnetization currents are optimized.

Acknowledgments

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Рецензент: д-р техн. наук проф. А.И. Оранский, Национальный аэрокосмический университет им. Н.Е. Жуковского «ХАИ», Харьков.