The electromagnetic problems of interplanetary spacecraft communication

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Abstract. The results of the radio frequency emission measurements from the ground-based experiments using electric propulsion engine applied to electromagnetic compatibility evaluation of spacecraft radio communication. The report presents the way of looking at the electromagnetic compatibility problem based on experimental and theoretical investigations of the physical foundation of the electromagnetic field generation by the electric propulsion engines. The approach under review allows evaluating the electromagnetic performance characteristics depending on thruster construction and engine operating modes.

1. Introduction

The results of the radio frequency emission measurements from the ground-based experiments using electric propulsion engine are applied to electromagnetic compatibility evaluation of spacecraft radio communication (Fig. 1). The report presents the way of looking at the electromagnetic compatibility problem based on experimental and theoretical investigations of the physical foundation of the electromagnetic field generation by the electric propulsion engines. The approach under review allows evaluating the electromagnetic performance characteristics depending on thruster construction and engine operating modes.

The electromagnetic environment produced by the different plasma propulsion systems have been compared for interference immunity evaluation of space radio communication. In accordance with the experimental and theoretical results, the operating modes of electric propulsion engines with electromagnetic waves generation have been discriminated. The approach under review allows revealing the electromagnetic radiation characteristics depending on construction and operating modes of plasma propulsion engines.

The frequency range of 500 MHz – 40 GHz has been examined to resolve the space communication problem under plasma propulsion action. The problem is related with interference radiation and electromagnetic wave interaction in exhaust plasma flows created by electric propulsion engines. The fundamental electronic analogs of electric propulsion engines as interference radiation contributors have been developed from the electron beam initiation of microwave oscillations in the different plasma propulsion regions. As such contributors of electromagnetic radiation, the regions with electron acceleration along the magnetic field and accelerating anode layers with electron drift in crossed electric and magnetic fields can be represented. Non-stationary electric fields and low-frequency plasma turbulence with intense electric field oscillations can be initiating factor of microwave radiation. Currently the attention has been focused on hollow cathode discharges as contributors of wideband microwave radiation of electric propulsion engines with closed-drift electrons.
2. The results of ground-based tests

At present, stationary plasma thrusters (Fig. 2) are among most developed types of electric propulsion engines used to correct and stabilize the orbits of geostationary communication satellites and solve problems of space transport. The interference radiation is defined at the typical operating modes of plasma engines. The increased radiation is exhibited with anode layer formation in a plasma acceleration chamber. Beside of the short-time radiation non-stability, the long-term variations of thruster radiation intensity due to abnormal erosion of dielectric walls of an accelerating chamber are observed for the stationary plasma thruster. Theoretical and experimental studies of the processes of plasma acceleration in SPTs [3–4] have revealed a wide range of instabilities resulting in the excitation of electromagnetic oscillations both inside and outside the generated plasma flows. Studies of these instabilities allow one to better understand mechanisms of plasma acceleration and the effect of oscillations on the efficiency of plasma thrusters. The particular importance is to study oscillations related to specific features of the dynamics of the electron component during plasma acceleration.

Figure. 1. The radio communication of the interplanetary spacecraft [1]
The experimental investigations of the stationary plasma thruster (fig. 2) is concerned with unstable electron dynamics in plasma thrusters and the possible contribution of microwave oscillations to both the anomalous electron transport across the magnetic field and the formation of the electron distribution function. The microwave measurements have been fulfilled in the frequency range of 1-10 GHz corresponding to the Langmuir frequencies in the different regions of thruster plasma flow. The significant stage of the basic research is the determination the efficiency of conversion the plasma waves into electromagnetic radiation. As a result, the distributions of electromagnetic fields nearby a spacecraft are available that it is required for the evaluations influence of the radiated interference influence on the radio equipment. As applied to electric propulsion engines, the conversion by the high-frequency plasma waves scattering at low-frequency fluctuations of a non-equilibrium plasma flow.

The investigations included the measurements of both microwave plasma fields and electromagnetic radiation emitted by the plasma thruster due to wave transformation. The methods for measuring the spectral and energy parameters of microwave oscillations with plasma acceleration were described in [5]. The two-line microwave probe was used for the local measurements of the plasma oscillations in both the wear-wall region of the accelerating chamber and the region of capturing the electrons from the cathode into the magnetic field. The microwave radiation measurements were produced by wide-band dipole antennae displaced from the plasma thruster. In order to obtain data on microwave oscillation parameters, the method was used by performing the calibration measurements with the standard sources of plasma microwave noise and electromagnetic radiation under the conditions similar to those with thruster tests.

The measurements of plasma microwave fields have given the information on the absolute values of the fluctuation energy density and its distribution along the path of the microwave probe. In the exhaust plasma flow, the maximum values of the energy density of plasma microwave fields attains $10^{-7}$-$10^{-6}$ J/m$^3$ MHz, which is five orders of magnitude higher than the thermal level.

The distribution of the microwave field along the exhaust plasma flow is characterized by maximum of the oscillation energy density in the cathode region. Here, as is evident from the experiment, the beam-plasma instability is most important for the generation of the microwave oscillations. In the near-wall region of the accelerating chamber, the microwave energy density is order of $10^{-8}$ J/m$^3$ MHz, that is significantly less than the energy density in the plasma flow. That allows us to assume that the generation of microwave oscillations is originate in the unstable region of the plasma flow and can be extended due to the electron motion through the transverse magnetic field in the accelerating chamber.

The most intense oscillations in the microwave spectrum are observed in the frequency range of 1.5-2.5 GHz corresponding to the high-frequency oscillations produced by the electrons coming out of the cathode. The electromagnetic radiation spectrum is located in the more wide range of frequencies up to 3-3.5 GHz due to the formation of microwave radiation field from the contributors with the different electron densities. The maximum of microwave radiation spectrum is observed in the frequency range outside the bands of the prospect space radio communication. This makes it reasonable to conclude that the operation of the plasma thruster do not impact spacecraft communication systems.

The intensity of microwave oscillations is related with the regime of the plasma flow formation on the magnetic field in the accelerating chamber. This result can be explained by increasing the potential drop accelerating electrons in the cathode region of the exhaust plasma flow. The microwave excitation is non-steady-state process when envelops of electromagnetic radiation and microwave plasma fields have the
shape of pulses with duration up to 100-200 µs and different degree of cross-correlation at the chosen frequencies.

Reliable relationship is obtained between the propulsion parameters of the thrusters and the intensity of both microwave radiation and low-frequency oscillations in the acceleration region of the discharge. It is shown that realization of the stationary operating modes of the turbulent plasma acceleration in a high-current MPD thruster is limited by the excitation of the large-scale ion-sound turbulence in the plasma flow. Under stationary operation conditions in an MPD thruster with external magnetic field, the turbulent plasma acceleration is restricted to the anomalous anode heat evolution and is most pronounced in the limiting regimes of the thruster operation. The microwave radiation is a precursor of the thermal destruction of the propulsion design and can be used for the characterization of MPD limited operating modes.

3. The results of ground-based tests
The radiated emission characteristics have been investigated in the course of ground-based tests of the promise types of the electric propulsion engines [5‒9]. In respect of their electromagnetic compatibility with spacecraft radio equipment the follow types of the engines are presented:
• plasma thrusters with closed electron drift referred to the Stationary Plasma Thruster (SPT) and the Anode-Layer Thruster (TAL);
• magnetoplasmadynamic (MPD) thrusters with applied magnetic field known as Butt-end Hall Thrusters (BHT) and with self-magnetic field known as Steady-state High-current Thrusters (SHT);
• electrostatic thrusters with ionization chambers and electron bombardment used as Plasma-Ion Thrusters (PIT).

Figure 3. Summarized spectral performances of plasma engines interference radiation:
1–TAL (Bi, two-stage version), 2–PIT (N, ionization chamber), 3–BHT (N, high-voltage operating modes), 4–BHT (Li, limited operating modes), 5–SPT (Xe), 6–SHT (Li)

4. Space communication under plasma propulsion interference
The limitation on the space communication length by plasma propulsion interference has been estimated by the procedures deduced from signal to noise relations. As the noise immunity efficiency in space communication channels under the different radiated interference, usually the energy potential of radio line
is induced this is equal to relation between the actual signal power at the radio amplifier input and the minimum signal power required for resistance radio line operating. The minimum signal power is determined by noise level at on-board radio equipment input, that are the inherent noise of instrumentation and the interference radiation of plasma propulsion engines. At present time the highly sensitive receivers are used for space radio communication when the main contributor of radiated interference is produced by plasma thruster operation.

5. Analysis of excitation of microwave oscillations in the plasma flow

The theoretical models of beam-plasma interaction in the exhaust plasma flow were used for description of microwave processes and evaluation of their parameters. The scattering of electrons by microwave electric field oscillations as analog to interparticle collisions appears to be efficient in the electron dynamics formation. The experimental data obtained on the intensity and spectra of microwave oscillations allow examining qualitatively the corresponding mechanisms for the anomalous transverse plasma conductivity in the magnetic field of the accelerating chamber. The generation of the microwave oscillations in the cathode region leads to the mixing of different electron groups in the unstable plasma flow.

The processes of oscillation excitation in the SPT are usually analysed under the assumption that the electron dynamics in the acceleration channel can be described in the drift approximation [4]. In the microwave range, the drift approximation is inapplicable, because the characteristic frequencies of the microwave processes significantly exceed the electron cyclotron frequency. The drift approximation is also violated due to the non-uniform distributions of the magnetic field and electron density in the plasma flow outgoing from the SPT; in this case, the characteristic scale lengths of microwave perturbations do not exceed the electron cyclotron radius \([10–11]\).

The frequency range of the microwave instability developing in the SPT corresponds to the high-frequency branch of electron oscillations calculated from the electron density and the magnetic field behind the edge of the acceleration channel. For the magnetic field strength measured in [10], the electron cyclotron frequency in this region of plasma flow is \(\leq 100\text{MHz}\). If the electron plasma frequency \(\omega_{pe}\) is much higher than the electron cyclotron frequency \(\omega_{Be}\), then the spectrum of the high-frequency branch of electron oscillations can be represented as [10]:

\[
\omega_{1}(\theta) = \omega_{pe} + (\omega_{Be}^{2}/2\omega_{pe}) \sin^{2} \theta, \tag{1}
\]

where \(\theta\) is the angle between the magnetic field and the propagation direction of the plasma wave.

We will take into account specific features of the electron dynamics behind the edge of the acceleration channel, the inhomogeneity of the plasma flow, and variations in the topology of the magnetic field in the
zones of microwave generation. The choice of the beam–plasma model of the source of microwave oscillations is based on the experimentally established correlation between the frequency of excited oscillations and the electron plasma frequency calculated from the electron density in the zones of microwave generation.

Analysis of the mechanism of the plasma flow instability resulting in the excitation of microwave oscillations is based on the assumption of a two-component electron velocity distribution function in the zones of microwave generation. Such a distribution is formed by the fast electron beam accelerated in the cathode sheath and slow (thermal) electrons produced due to various processes (electron-impact ionization, electrons scattering from plasma oscillations, and secondary electron emission from the construction elements of the SPT). An electron beam with a transverse (with respect to the magnetic field) velocity of \( V_\perp = (2e\Delta U_C/m_e)^{1/2} \), where \( \Delta U_C \) is the cathode voltage fall, forms in the region of the cathode-compensator.

According to the measurement results [11], the value of the cathode voltage fall \( \Delta U_C \) is 30–35 V, which corresponds to an electron beam velocity of \( V_\perp = (3.5–4.2) \times 10^8 \text{ cm/s} \). This velocity exceeds the thermal electron velocity \( V_{Te} = (5–9) \times 10^7 \text{ cm/s} \) calculated from the measured values of the electron temperature in the plasma flow.

The density of the electron beam can be estimated from the discharge current and the electron velocity in the region of the cathode-compensator. Taking into account the distribution of the emission current in the acceleration channel and outgoing plasma flow, we find that the electron beam density is \( n_b = (2–3) \times 10^{10} \text{ cm}^{-3} \). The density \( n_0 \) of thermal electrons in the plasma flow in the region of the cathode-compensator is \( (1–2) \times 10^{11} \text{ cm}^{-3} \). The spread in electron velocities in the beam \( \Delta V_\perp \) can be determined from the electron temperature in the region of the cathode-compensator. Taking into account that this temperature is \( \leq 10 \text{ eV} \), we find that the relative velocity spread in the electron beam is \( \Delta V_\perp / V_\perp = 0.1-0.3 \).

Let us consider the mechanism of saturation of microwave oscillations related to the finite time of the beam-plasma interaction in the axially inhomogeneous region of the flow. Such saturation manifests itself as the azimuthal electron beam shifts toward the edge of the acceleration channel. The relationship between the frequency and phase velocity of oscillations excited in the inhomogeneous region can be written as [12]:

\[
\omega_1 = \omega_{pe}(z) \left[ 1 + (3/2) \left( V_{Te} / V_{ph} \right)^2 \right].
\]  

(2)

Assuming that, in a steady-state plasma flow, the frequency of excited oscillations remains unchanged, we find that, as azimuthal electron beam shifts by a distance \( \Delta z \), the phase velocity changes by a value of

\[
\left| \Delta V_{ph} \right| = \frac{\Delta z}{L_{pe}} \left( V_{\perp} / V_{Te} \right)^2 V_z.
\]

(3)

The development of beam-plasma instability and excitation of microwave oscillations in the plasma flow are possible if the change in the phase velocity of oscillations does not exceed the velocity spread \( \Delta V_\perp \) in the electron beam. The length of the region in which this condition is satisfied is

\[
\Delta z = \Delta L_{pe} \left( V_{\perp} / V_z \right)^2 \left( V_{Te} / V_{\perp} \right)^2,
\]

(4)

where \( \Delta L_{pe} \) is the inhomogeneity scale length of the plasma flow and \( V_z \) is the longitudinal component of the electron beam velocity. Taking into account the longitudinal shift of the azimuthal electron beam, the characteristic growth time of microwave oscillation can be written as

\[
\Delta \tau = \left( \Delta L_{pe} / V_z \right) \left( V_{Te} / V_{\perp} \right)^2.
\]

(5)

Taking into account the growth rate of beam–plasma instability on the high-frequency branch of electron oscillations [13]:

\[
\gamma_1 \approx \left( n_b / n_0 \right)^{1/2} \left( V_{\perp} / \Delta V_{\perp} \right)^2 \omega_{pe}(z)
\]

(6)

and oscillation growth time (5), we represent the amplification factor of initial thermal fluctuations in the plasma flow, we represent the amplification factor of thermal fluctuations in the plasma flow \( \Lambda_1 = \ln(W_1 / W_0) \) in the form:

\[
\Lambda_1 = \left( n_b / n_0 \right)^{1/2} \left( V_{\perp} / \Delta V_{\perp} \right) \left( \Delta L_{pe} \omega_{pe}(z) / V_z \right) \left( V_{Te} / V_{\perp} \right)^2.
\]

(7)
For the parameters of the plasma flow and the electron beam behind the edge of the acceleration channel, the amplification factor of thermal fluctuations is $10^3$–$10^4$. For the energy density of thermal fluctuations calculated from the electron temperature, $W_0 = 10^{-8}$–$10^{-7}$ J/(m³ MHz), we find that the energy density of microwave oscillations excited in the plasma flow is $10^{-5}$–$10^{-4}$ J/(m³ MHz), which agrees with the results of measurements.

It follows from the oscillations spectra measured that, in the frequency range of 10–100 MHz, one can consider the development of plasma flow instability on the low-frequency branch of electron oscillations. For waves propagating across the magnetic field, one should take into account the contribution of ions to the excitation of oscillations. Therefore, the minimum frequency of excited oscillations corresponds to the lower hybrid frequency of $\approx 5$ MHz. Analysis of the plasma flow with the azimuthal electron beam makes it possible to determine conditions for excitation of oscillations in the frequency range of 10–100 MHz.

**Conclusion**

The main result of the theoretical and experimental studies of the problem is that the electromagnetic interference radiation of the electric propulsion engines must be taken into account with spacecraft communication design. According to the estimates, the electromagnetic interference can disturb the long-range communications at the spacecraft separation more than 10000 km from a ground-based radio transmitting station.

For low-orbit earth satellites the interference radiation is found to have an insignificant effect on radio communications. The thruster interference radiation could potentially impact radio retranslating equipment of geostationary satellites with low-energy potential of space radio receiver lines.

Under space conditions, the interference excitation of the interference radiation can be associated with the interaction of exhaust plasma flows produced by the electric propulsion engines with the space plasma. In this connection, it should be carried out the complex of space and ground-based radio tests of the plasma thrusters to resolve the spacecraft systems electromagnetic compatibility.

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