Heavy Plasma NAPALM Propulsion Simulation Code

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Abstract— The NAPALM project addresses a new and revolutionary space propulsion system, able to deliver a very high specific impulse through a new working fluid and accelerator principle for the electric plasma thruster. The new motor will impressively exceed, by between ten and sixty percent, the vacuum specific impulse of all existing electric and thermo-electric rocket engines. The accomplishment is based on a new working medium, comprised of relatively high-mass gasified nanoparticles that will be accelerated up to very high kinetic energies. While all current electric thrusters are only able to deliver up to 15,000s specific impulse, the new thruster is expected to deliver between 18,000 and over 30,000s specific impulse. This extraordinary property will increase in the equal amount the deliverable ideal velocity during an interplanetary mission. This increased exit velocity conveys into an equal amount of propellant saving, for any equivalent mission performance. Within the range of low thrust levels, a particularly efficient application of the new thruster is in the attitude control of orbital spacecraft, which will save large amounts of propellant, in comparison to the chemical attitude control units and to other existing electrical thrusters. Additionally, the NAPALM thruster will deliver an absolute thrust of more than 0.1 Newton for every mass flow rate of 1 milligram/second and thus an absolute vacuum thrust exceeding 18 Newton is expected.

Keywords—plasma engine; electric propulsion; nano-materials

I. INTRODUCTION

Electric propulsion uses externally provided electrical power either from the Sun or from nuclear or thermodynamic conversion thermal engines, to accelerate the working fluid to produce useful thrust. There is no fundamental limit to the exhaust velocity that we can obtain with an electric rocket. However, the power may grow to the point where further acceleration is pointless. There is therefore an optimum exhaust velocity, and hence an optimum specific impulse.

All current limitations of the plasma-electric propulsion systems are set by the maximum achievable temperature of the plasma. Because the thermal energy of the plasma particles is converted into a directed axial movement by a diverging magnetic field (magnetic nozzle), the performance of any kind of engine in this category is directly connected to the maximum amount of electromagnetic energy transferable to the plasma through RF waves. This amount is limited by the maximum temperature set by the properties of the RF wave, the physical properties of the plasma, the surrounding installations, etc. This limit is the ‘maximum absorption potential’ or for short MAP.

The best way to improve these performances is to increase the power efficiency. By introducing nanoparticles into either an accelerating electromagnetic field, or into the heated plasma (at an order of 10\textsuperscript{7} Kelvin) the MAP will increase by an order of magnitude, as determined by the density, temperature, size and physical properties of the nanoparticles. Alternatively, in another ICRF heater chamber, with modified RF waves to match the optimal absorption rate of the mixture, electromagnetic energy will be further transferred to the plasma until reaching its new MAP. Through this process the engine will become much more efficient than all its predecessors. This theory was enforced by preliminary calculations of this project, in which it is shown that the energy absorption of the particles is directly related to the total specific impulse and therefore to the overall efficiency.

There is no distinct information on the international level regarding any previous proposals to use dense nanoparticles within plasma or ion space motors. The only existing information is in doping of polymers with carbon nanoparticles for using those polymers as a plasma source for thrusters. The carbon nanoparticles have the only role to prevent overheating and melting of the polymer through radiation heating [4].

The schematic diagram (Fig. 1) illustrates not only the evolution of the working fluid, but also the basic structure of the engine. As ionizing gas enters the plasma generator, an RF wave is applied to it in such a way that it creates a helicon discharge within the gas and creating plasma.

Figure 1. Working scheme of the NAPALM thruster


The helicon tests will primarily focus on developing a plasma source to produce a dense target for the ICRF experiments.

As it is well known in the art [5], [6], [7], [8], that the helicon source is most efficient at plasma production when the RF frequency ($\omega_{hp}$) is near the lower hybrid frequency ($\omega_{LH}$), for conditions under the antenna.

Another important aspect of the concept is plasma heating by electromagnetic waves at the Ion Cyclotron Range of Frequencies (ICRF). Computer simulations will help designing an ICRF antenna for maximum absorption of RF power into the plasma in the resonance area.

The improved propulsion system will make satellite orbit management more cost efficient and pull manned deep space missions into the realistic side of space exploration (this topic will be further discussed in the objectives part of this project). Furthermore it will give a sustainable foundation for further research in the field of space propulsion.

II. NUMERICAL ALGORITHM

A computer program was created, with the objective of calculating the electric and magnetic field vectors, induced by a two element, helical antenna array, in any point in space and time.

The applied voltage excitation is a cosine wave for both antenna elements, with a phase shift between them for time coupling. The elements have a relative angle displacement of 90 degrees. The obtained electric field inside the antenna array is rotational in both space and time, which corresponds to experimental data publicized by researchers in the field of plasma generation. The computer program will be the first and a key element in the simulation algorithm of gas ionization and plasma heating for the purpose of antenna geometry optimization. The program is based on the algorithm written by Sergey N. Makarov [2].

![Figure 2. Geometry of the studied antennas](image)

A helicon discharge is an excitation of plasma by helicon waves induced through radio frequency heating. The physical mechanisms that give these discharges high ionization efficiency are not yet understood well enough that an optimal plasma source can be designed. This paper addresses one of these problems, that of antenna coupling and frequency tuning. Almost all early experiments employed the so-called Nagoya Type III antennas, characterized by straight conductors collinear with the DC magnetic field. Since helicon waveforms are helices that rotate in both space and time, one can couple better to them with antennas that are themselves helices or with antenna fields which rotate in time. Physical representations are shown in 2D and 3D in Fig. 2(left) respectively Fig. 2(right).

With this geometry the fields obtained are rotating in space, but in order to achieve rotating fields in both space and time we need to use multiple helical antennas, forming an antenna array. By rotating the second element of the array and adding a corresponding phase shift to the excitation voltage, a rotation of the field in time will be obtained. We shall find that rotation in time is the stronger mechanism, enabling us to force the generation of helicons of either $m > 0$ or $m < 0$ polarization.

We can see in Fig. 3(left) respectively Fig. 3(right) the geometry of such an antenna array generated by the present program. Linear helicon waves have circularly polarized eigenmodes with variable 3D electric fields.

![Figure 3. Geometry generated by the code](image)

At any instant of time, the E-vectors therefore lie on a twisting ribbon, as the simulations will show further in this text.

The method of moments (MoM) used in this text relies on RWG (Rao-Wilton-Glisson) edge elements [1]. First, the surface of the antenna is divided into separate triangles as shown in Fig.2. Each pair of triangles having a common edge constitutes the corresponding RWG elements (Fig.4). The surface electric current on the antenna surface is a sum of the contributions over all edge elements with unknown coefficients. These coefficients are obtained from the moment equations, which are a linear system of equations with the impedance matrix $Z$.

The basis function:

$$f(r) = \begin{cases} \frac{l}{2A^+} \cdot \rho^+(r), & r \text{ in } T^+ \\ \frac{l}{2A^-} \cdot \rho^-(r), & r \text{ in } T^- \\ 0, & \text{ otherwise} \end{cases} \tag{1}$$

The edge element approximately corresponds to a small but finite electric dipole of length $d=|\mathbf{r}^+ - \mathbf{r}^-|$, where $l$ is the edge length $A^+$ is the area of the triangle $T^+$. Vector $\mathbf{\rho}^\pm$ connects the free vertex of the triangle $T^+$ to the observation point $r$. Thus the division of the antenna structure into RWG
edge elements approximately corresponds to the division of the antenna current into small elementary electric dipoles. In this sense, the impedance matrix describes the interaction between different elementary dipoles. The surface current density on a perfectly electrically conducting structures is given by an expansion into RWG basis functions over $M$ edge elements:

$$J = \sum_{m=1}^{M} I_m f_m$$  \hfill (2)

, where $I_m$ form the vector $\mathbf{I}$, which is the unique solution of the moment equation

$$Z \cdot I = V \hfill (3)$$

, where $V$ is the voltage excitation vector and $Z$ the impedance matrix, quantitatively is given by

$$Z_{mn} = l_m \left[ j \omega \left( A_{mn}^- \cdot \rho_m^+ + A_{mn}^+ \cdot \rho_m^- / 2 \right) + \varphi_{mn} - \varphi_{mn}^- \right]$$

Indexes $m$ and $n$ correspond to two edge elements; $l_m$ is the edge length of element $m$. The expressions for vector $\mathbf{A}$ and scalar $\phi$ has the form:

$$A_{mn}^\pm = \frac{\mu}{4\pi} \left[ \frac{1}{2A_h} \int \rho_m^\pm(r') g_m^\pm(r') d'S' + \frac{1}{2A_h} \int \rho_m^-(r') g_m^+(r') d'S' \right]$$

$$\varphi_{mn}^\pm = -\frac{1}{4\pi j \varepsilon} \left[ \frac{1}{4A_h} \int g_m^\pm(r') d'S' + \frac{1}{4A_h} \int g_m^+(r') d'S' \right]$$

$$g_m^\pm(r') = \frac{e^{-jk'c_m^\pm - r'}}{r_m^c - r'}$$

The radiated electromagnetic signal of the obtained surface currents can be found by a number of approaches. In this application we are generally interested in the value of the electric field $E$, and the magnetic field $B$, at any spatial point.

The approach used in this program is the so-called dipole model, where the surface current distribution for each RWG element is replaced by an infinitesimal dipole, having an equivalent dipole moment (eq. 2). The total radiated field is then obtained as a sum of all these contributions of infinitesimal dipoles.

$$m = \int_{c_m^-}^{c_m^+} l_m f_m(r) d'S = \int_{c_m^-}^{c_m^+} f_m(r) d'S = l_m l_m (r_m^- - r_m^c)$$

The radiated electric and magnetic fields of an infinitesimal dipole located at the origin are expressed at a point $r$:

$$E = \frac{1}{4 \pi \varepsilon_0} \left\{ \frac{\omega^2}{c^2 r^3} \mathbf{p} \times \mathbf{r} + \left( \frac{1}{r^3} - \frac{i \omega}{c^2 r^5} \right) \mathbf{3} \mathbf{r} \cdot \mathbf{p} \right\} e^{j \omega t/c}$$

$$B = \frac{\omega^2}{4 \pi \varepsilon_0 c^3} \mathbf{p} \times \mathbf{r} \left( 1 - \frac{c}{i \omega r} \right) e^{j \omega t/c}$$

, where $r=|\mathbf{r}|$, $\mathbf{p}$ is the dipole moment. The total electric and magnetic field at a point $\mathbf{r}$ are obtained as a sum over all edge elements:

$$E(r) = \sum_{m=1}^{M} E_m \left( r - \frac{1}{2} (r_m^c + r_m^-) \right)$$

$$H(r) = \sum_{m=1}^{M} H_m \left( r - \frac{1}{2} (r_m^c + r_m^-) \right)$$

To account for a voltage source a feed model was introduced into the antenna structure. An antenna is usually fed by a transmission line through two electrically close terminals. This means that an ideal voltage generator is connected across a gap. The simplest way to describe the gap field, which is ideally suited for RWG edge elements, is the so called delta-function generator. It assumes a gap of negligible width, $\Delta$:

$$E = -\Delta \varphi = \frac{V}{\Delta n_y}$$  \hfill (6)

When $\Delta$ tends to 0 then $E$ becomes infinite, to correct this we use the delta-function approximation:

$$E = V \delta(y)n_y$$

$$V = \int E_z \, dy$$

A control experiment was used to compare the data from the simulation with the data from the experiment [3]. The simulation gave a good representation of the processes described in the experiment [3]. It also explains the asymmetries in the generated plasma. The antenna geometry needs to be optimized in order to create a symmetric radiated helical wave. Simulations have shown that even the feeding point on the antenna is influencing the form of the helical wave and the polarization of the field. Below (Fig. 5) we can see the representation of the excited helicon wave, projected to a plane perpendicular to the antenna’s axis. Here we can see the rotation of the $E$ field, along the antenna axis, where the evolution of the wave is shown for a half period of the excitation voltage. The second row represents the waveform of the antenna geometry from Fig.5 and the first row shows a
more symmetric waveform of a second antenna that was modified with the help of this program.

In the next figure (Fig.6) the rotation in 3D space of the \( \mathbf{E} \) field is shown for a different antenna configuration, where the second row of arrows (green) show the polarization of the field, note the circular polarization inside the antenna.

III. CONCLUSIONS AND FURTHER DEVELOPMENT

A computer program was created, with the objective of calculating the electric and magnetic field vectors, induced by a double-element, helical antenna array, in any point in space and time. The applied voltage excitation is a cosine wave for both antenna elements, with a phase shift between them for time coupling. The elements have a relative angle displacement of 90 degrees. The obtained electric field inside the antenna array is rotational in both space and time, which corresponds to experimental data published by researchers in the field of plasma generation. The purpose of this work was to develop the computer program and to present the results of the computer code exploitation. The plasma generation theory is considered as known by the reader and the reader is assumed as being familiar with the fundamentals of the field. The program developed is mainly based on the algorithm written by Sergey N. Makarov [2].

The expertise of the team from the National Institute for Physics of Lasers and Plasma in manufacturing plasma generators is considerable and offers a strong certitude that the present project has a good material means for development. Taking into account the prevalent fundamental character of the NAPALM engine, which aims mainly to morphological, structural or functional modelling of nanomaterials for practical applications, the plasma productivity is no more a challenge.

The study of some important and still unclear aspects bound up with the synthesis of these heavy plasmas and particularly with the in-situ modelling of their functional properties will complete the activities performed by the group that performs the NAPALM project.

Proprietary experimental sets are under manufacturing at INFPLPR and UPB in Romania, where several national research grant proposals are issued to receive funding.