A propellant-free superconducting solenoid thruster driven by geomagnetic field

Heng-Wei Kuo\textsuperscript{a}, Kuo-Long Pan\textsuperscript{a,*}, Wei-Li Lee\textsuperscript{b}

\textsuperscript{a}Department of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC
\textsuperscript{b}Institute of Physics, Academia Sinica, Taipei, Taiwan, ROC

\textbf{Abstract}

Introduction: Space travel nowadays relies on physical ejection of propellants, which is challenged by reachable distance of a vehicle in desirable time. In contrast, electromagnetic propulsion was proposed to be a potential solution without need of carrying bulky mass of propellants, by using force interaction of local magnetic dipoles with the external natural magnetic field. Further development of this technique, however, has been daunted by extremely small magnetic induction that can be obtained.

Objectives: To generate a significant thrust by a system with a reasonable scale, we propose an alternative concept of design, based on the variation of local magnetic dipole moments that has not been considered.

Methods: A magnetic dipole is created by wrapping a solenoid around an iron core. It is varied spatially by changing the cross-sectional area of the solenoid, hence giving a gradient of magnetic dipole moment. The interaction force is measured by an in-house force sensor based on a cantilever, which has a high sensitivity of one micro-Newton. In addition, numerical simulation is used to calculate the magnetic field and created force via the Maxwell stress tensor.

Results: As shown by experimental measurements and numerical simulations, a substantially larger magnitude of force is obtained on the solenoid with varying cross-sectional area, indicating a much stronger interaction with the geomagnetic field. Furthermore, to enhance electric current with negligible dissipation, a superconducting solenoid can be adopted at low temperature in space. With readily attainable conditions of operation, we demonstrate generation of a thrust comparable to that of present electric propulsion thrusters which are deemed as the most promising techniques for long-term space travel.

Conclusions: By incorporating supplementary means, we provide a breakthrough solution for constructing an efficient thruster with minimal energy consumption and nearly null propellant load for near-Earth transportation and deep-space exploration.

\textsuperscript{C211}2020 THE AUTHORS. Published by Elsevier BV on behalf of Cairo University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Introduction

Motivation

The modern technologies on space travel have relied on physical ejection of propellants, which imposes a limit on the reachable distance of a vehicle in reasonable time [1]. In contrast, electromagnetic propulsion (EMP) was proposed [1–3] to apply the force interaction between the local magnetic field of the vehicle and the external natural magnetic field specifically the geomagnetic field. This removes the need of carrying bulky materials such as chemical propellants and electric power facilities [4] for creation of physical reaction forces and largely enhances possibility of long-term flight in space. However, the practicability has not been truly envisioned since the thrust that can be generated by the nonuniform geomagnetic field is extremely small. Here we propose an alternative concept of design, based on the variation of local magnetic dipole moment that has not been considered in the literature, and demonstrate its feasibility. We computed the force exerted on a solenoid in an applied magnetic field, and compared it with the experimental results to verify the effect of magnetic moment gradient on the resulted force. The force was further enlarged when an iron core was inserted. To test, we placed the solenoid in the geomagnetic field and measured the forces corresponding to different gradients due to variation of the cross-sectional area and electric current magnitude. The results indicate a proportionality between the force and these factors, as predicted by the theory. Furthermore, to enhance the electric current with negligible dissipation, we plan to employ a superconducting solenoid that can take advantage of low temperature in space. With accessible conditions of operation, our results demonstrate feasibility of creating a thrust that is comparable, and even superior, to that of present electric thrusters which are deemed as the most promising techniques for near-future space travel [5].

Prior work

Electromagnetic propulsion [1,3], or magnetic propulsion [2,6], is a conceptual means of accelerating an object via the interaction of external magnetic field and a local magnetic field generated by an electric current. The external natural magnetic fields such as the geomagnetic field, extend largely around the Earth and could be used effectively via the force interaction. In contrast to modern-day propulsion techniques based on propelling of certain matter from the object so as to generate a reaction force, EMP relies on the repelling force, specifically the Lorenz force, created via the interaction of a self-generated field with the applied magnetic field. By means of well-controlled local electric current without any ejection of carried mass, the force can be maintained constant and yield steady propulsion conditions. Furthermore, by using superconducting wires to transport electric current, which may take advantage of the low-temperature environment in space, very little or almost no energy would be dissipated. As a consequence, the energy input can be kept very low. The minimum demands of propellants and energy sources thus render a remarkable prospect of far-field travel for interplanetary flights, but not only for near-earth missions such as orbital maneuvers of satellites and the international space station (ISS) including spacewalk of an astronaut and onboard conveyance.

In spite of the greatly favorable features for space exploration, however, further development of the proposition has remained dormant due to the weakness of available geomagnetic field that has very low induction magnitude and nonuniformity. While the works in [1–3] have raised possibility conceptually for development of such techniques, their proposed systems are extraordinarily huge, thus frustrating further demonstration along this line. In this work, we propose a simple way to fulfill this goal based on elements that are readily obtainable. By using a miniature or even micro-scale system, the essential principle of force generation can be demonstrated by experiment readily. With a straight scale-up, a thrust that is capable of propelling an object in space is foreseen. With advancement of modern technologies, more solutions can be integrated to raise the feasibility and prospect.

Preliminary analysis

The interaction force of a solenoid and the geomagnetic field can be evaluated by \( \mathbf{F} = \nabla(\mathbf{M} \cdot \mathbf{B}) \) [7]. Here the magnetic dipole moment created at the solenoid is \( \mathbf{M} = N\mathbf{A} \), where \( N \) is the number of coil turns per unit length, \( l \) the electric current, and \( A \) the area of the coil \( A = \pi r^2 \). The cross-sectional area of the solenoid had been assumed to be invariant in previous studies [1–3] and therefore \( \mathbf{F} = M_s(\mathbf{r} \cdot \nabla \mathbf{B}) \) was considered. Since the geomagnetic field is nearly uniform, the gradient of \( \mathbf{B} \) and consequently the magnitude of this force are extremely small. To make use of the interaction force, the product of the size \( A \) and \( Nl \) has to be relatively huge. To be specific, consider a reaction force generated by \( M_s \) and the geomagnetic dipole moment, \( M_g \). As analyzed in [2] and rephrased in [3], the dipole-dipole interaction will yield a force in two components:

\[
F_r = -3\mu M_g M_s (3\cos^2 \theta + 1)^{3/2} \left( 4\pi R^4 \right)
\]

\[
F_\theta = -3\mu M_g M_s \sin \theta \left( 3\cos^2 \theta + 1 \right)^{3/2} \left( 8\pi R^4 \right)
\]

Here \( F_r \) and \( F_\theta \) are the thrust forces in the radial and tangential directions, respectively. \( \theta \) is the latitude angle and \( R \) is the distance from the center of Earth. \( \mu_0 \) is the permeability of free space whose value is \( 4\pi \times 10^{-7} \text{ N} \cdot \text{m} / \text{A}^2 \). The permeability of a substance is the product of the relative permeability \( \mu_r \) of the substance and \( \mu_0 \), i.e., \( \mu = \mu_r \mu_0 \). By inserting an iron core [3], being a ferromagnetic material with \( \mu_r = 5000 \), the magnitude of the magnetic field flux density can be significantly increased. To estimate the largest force that can be created by using such a solenoid, considering the geomagnetic dipole moment about \( 8.2 \times 10^{22} \text{ Am}^2 \) [2], and the distance \( R \) which is the radius of Earth, 6378.245 km at the equator, plus the altitude of the vehicle, taken to be 200 km, which is equal to 6578.245 km. To have a force reaching a scale on the order of one Newton, we need \( NI = 10^5 \) given by, e.g., \( N = 10^5 \) and \( I = 1 \) A, or \( N = 10^4 \) and \( I = 100 \) A, when we set \( r_s = 1 \) m. The requirement of a large \( N \) or \( I \) would exclude immediate employment of the technique, particularly when superconducting wires are used to eliminate heat dissipation and prevent related issues on the mechanical considerations and energy input. It is further restricted by the allowable magnitude of \( NI \) owing to a constraint on the critical values of current density and magnetic field. Although the barrier could be mitigated by provision of a much larger coil size, the substantial increase of the whole system covering the superconducting solenoid tends to diminish the practicality and ease of implementation.

If we consider the spatial variation of a magnetic dipole moment and orient the axis of the solenoid toward the z-axis in the spherical coordinates, the force is

\[
F_z = M_s \frac{\partial B_z}{\partial z} + B_z \frac{\partial M_s}{\partial z}
\]

By locating it at the North Pole, for instance, the gradient of the geomagnetic field is about \( 10^{-7} \text{ T/m} \), and the geomagnetic field \( B_z \) is about 0.03 T. Consequently, if we can keep the gradient of the magnetic dipole moment \( \partial M_s / \partial z \), e.g., by simply changing the cross-
sectional area of the solenoid, it is likely to enlarge the interaction force significantly. In this work, we have conducted both experimental and numerical simulation to test the viability. By using a homemade force meter that can measure a miniature force down to the micro-Newton level, it is demonstrated that with adequate design of the solenoid configuration, the coupling between the local magnetic field and the ambient geomagnetic field can be increased by 1000 times and even larger. This yields high possibility of applying the electromagnetic propulsion readily for near-earth transportation and also for long-distance travel with further modification that incorporates superconducting materials.

**Material and methods**

To test the effect and controllability of the second term in Eq. (3), \( B \cdot (\nabla \mathbf{M}_s) \) or \( B \cdot \frac{d}{dr} \mathbf{M}_s \), we have constructed an experimental setup including a brass solenoid with varying area of the coils, wrapping up an iron core. By using a Hall sensor, the magnetic field around a magnet is measured, providing a distribution of \( B \) for calculation of the two terms. To measure the interaction force, we have developed a force sensor in terms of a cantilever connected to a capacitor. When a magnetic force exerts a bending on the cantilever that is made of a thin metal plate, the capacitance is changed and can be measured with a high precision to determine the magnitude of applied force, giving a sensitivity of one micro-Newton. This high sensitivity for measuring a tiny force enables us to identify the geomagnetic field via the interaction. To realize the interaction of dipole moments based on the fundamental electromagnetism, we have employed the software COMSOL-Multiphysics to simulate the three-dimensional (3-D) magnetic field and calculate the force exerted on a solenoid. This is performed by computing the Maxwell stress tensor via the surface integration throughout the volume surrounding the solenoid. The accuracy of simulation has been verified by a convergence test and a comparison with the experiment data, as seen later in the validations. Furthermore, a Sensitive Quantum Interference Device (SQUID) magnetometer is adopted to measure the magnetic permeability and \( \mu_r \) of the iron core, which provides an input for solving the Maxwell equations. By comparing the results of experimental measurements with that of numerical simulations, we can comprehend the interactions and resulting forces upon variations of the parametric conditions. It shows that inclusion of the magnetic moment gradient can greatly enhance the force exerted on a solenoid in a magnetic field. By using this concept of design, a superconducting solenoid thruster driven by the geomagnetic field is proposed, which will have advantages of low energy consumption and propellant-free propulsion in space. More details are given in the following.

**Experimental instrumentation**

To measure the thrust that can be generated by the present method of propulsion, an instrument has been established to measure forces down to the micro Newton level. The technique has been a critical component of development in the progress of such studies [8]. In contrast to the measuring device developed in [8], where a pendulum is used, the proposed idea of magnetic propulsion using superconductors can be tested at a smaller scale via a compact microelectromechanical systems (MEMS) device, which comprises a flexible cantilever. The detection of a small deflection in the cantilever enables the measurement of a weak force (or torque) with a sensitivity as high as one micro-Newton. Fig. 1 is an illustration of the flexible cantilever, where a small displacement of the cantilever can be detected with a high precision via the capacitance measurements. Specifically, when a small weight is loaded on the arm, the capacitance is increased, which is inversely proportional to the separation distance from the metal plate at the bottom, thus enabling measurement of the loading force.

Another advantage of such a MEMS device is the easy integration to existing environments of low temperature and magnetic field due to its compact size of less than 1 cm \( \times \) 1 cm. There are several different methods that have been developed to detect a smaller deflection in the cantilever. Optical interference [9] is one important approach to achieve the detection of a very small displacement of the cantilever down to a few nanometers. However, considering the requirement for the integration to limited space with extreme conditions, capacitance measurements for the cantilever displacement would give much less heat load to the device and also achieve a high sensitivity by using a capacitance bridge. Another important goal is to fabricate proper flexible cantilevers using different materials in order to achieve the highest sensitivity for measuring force.

The magnetic force on the superconducting coils due to the geomagnetic field from Earth can then be precisely measured by a cantilever that was made of a thin metal plate. The force sensitivity of the cantilever was calibrated in advance by using a motorized
stage as shown in Fig. 2, where a cantilever sits on the cover glass in the middle of the container. Fig. 3 shows the nearly linear relation between the force and measured capacitance, indicating a slope that is about 0.01287 N/pF. Since the precision of the capacitance measurement (Ultra Precision Capacitance Bridge 2500A) is $10^{-4}$ pF, the sensitivity for measuring the force is $10^{-6}$ N.

**Numerical methodology**

The simulation is performed by the software COMSOL-Multiphysics, based on the construction of free tetrahedral elements for unstructured meshes in the computational domain, as shown in Fig. 4(a). The Maxwell equations are solved with adequate boundary conditions. The force acting on the solenoid is calculated by the Maxwell stress tensor ($\mathbf{F} = \int \mathbf{n} \cdot \mathbf{T} \, dS$), with a surface ($S$) integration for the control volume (Fig. 4b), where $\mathbf{n}$ is the normal vector on the surface. It is seen in Fig. 5 that, with sufficient mesh resolution, the calculated force is insensitive to the increase of element number, and thus numerical convergence is attained for the simulation.

**Validation**

To verify the accuracy of the numerical simulation and identify the effect of varying magnetic moment via the spatial gradient, we first implement a solenoid in a nonuniform magnetic field provided by a magnet. The 3-D simulation clearly produces the distribution of magnetic flux density, as shown in Fig. 6(a). The force calculated via the Maxwell stress tensor is compared with the experimentally measured value. As shown in Fig. 6(b), by varying the magnitude and direction of the electric current, the quantities and variations obtained by the two approaches indicate a remarkable agreement. The unanimity is observed even when different configurations of solenoids are tested. It is observed that, as compared to the case with a constant coil area, the inclusion of a spatially varying magnetic moment, $B_z \frac{\partial M_z}{\partial z}$, indeed renders an increase
of interaction force in accordance with the corresponding increment of the solenoid slope that gives the gradient.

Results and discussion

Interaction force versus the slope of a conical solenoid

The solenoid is then placed in the geomagnetic field that has a much smaller magnitude of magnetic flux intensity, as shown in Fig. 7(a). It is also seen that the geomagnetic field is nearly uniform. With negligible contribution of $M_s \frac{\partial B_z}{\partial z}$, the interaction force can be approximated by

$$F_z = B_z \frac{\partial M_s}{\partial z} = B_z NI \frac{\partial (r^2 \pi)}{\partial z} = 2 \pi B_z NI \frac{\partial r}{\partial z}$$

(4)

By changing the slope of the solenoid according to the parameters shown in Fig. 7(b), Eq. (4) becomes

$$F_z = 2 \pi B_z NI \frac{\partial r}{\partial z} = \pi B_z NI (r_1 + r_2) \frac{\partial r}{\partial z}$$

(5)

where $r_m$ is the mean radius of the cross-section of coils whose radius is $r_1$ at the bottom and $r_2$ at the top. Fig. 8 demonstrates a linear relation between the force and the slope of the solenoid, and versus the electric current as well. The comparison of the results obtained by the experiments and numerical simulations again demonstrates high fidelity of the latter. As numerated in Table 1, however, there is a slight offset that is likely due to the measurements of geomagnetic field intensity and relative permeability as well as deflection of the cantilever on account of the gravitational effect.

In addition to this range of test, we further calculate the force given by a conical solenoid with $r_1 = 0$, $r_2 = 5$ mm, $I = 0.1$ A, $L = 6$ mm, and $N = 120$. The numerical simulation predicts $F = 1.25 \times 10^{-3}$ N, which is much larger than that covered in Fig. 8. By extrapolating the curve of $I = 0.01$ A as delineated in Fig. 8 to the newly targeted value of $r_m$, with a magnitude 20 times larger due to the increasing $NI$, the force is estimated to be $1.3 \times 10^{-3}$ N. Furthermore, the experimentally measured value of interaction force is $F = 1.215 \times 10^{-3}$ N. These three quantities are very close to each other, with a deviation of only 3–4% from the computational prediction. It thus verifies the linear relation between $F$ and $r_m \frac{\partial r}{\partial z}$, given by a slope proportional to $BNI$, which yields a weighting of the magnetic moment gradient on the interaction force. Therefore, by
simply using this relation, one can evaluate the magnitude of force that is drastically increased by raising the dominating factors.

Performance compared with up-to-date technologies

Following this methodology, we can estimate the attainable force in terms of practicable conditions. Table 2 shows the thrust magnitude that can be generated by a high-power Hall thruster [10] available presently, which is considered as one scheme having the most potential for future space travel. By using a similar size, e.g., \( r_2 = 100 \text{ mm} \), for the present system \((I = 0.1 \text{ A}, L = 6 \text{ mm}, \text{ and } N = 120)\), we can create a thrust that increases by 400 times, i.e., \( F = 0.5 \text{ N} \). If not to have a largely increased slope of the solenoid cone, we may simply elongate the solenoid, e.g., to \( L = 60 \text{ mm} \). As a consequence, the force magnitude is compromised by having a moderate slope, which would facilitate fabrication for readily application. The compromise could be made up by increasing the number of turns, \( N \), which can be easily doubled by wrapping two layers of wires. Alternatively, one may simply use \( I = 1 \text{ A} \), which then yields an identical force \( F = 0.5 \text{ N} \). As compared with the state-of-the-art technology of a Hall thruster, this design can reach the same magnitude of thrust as that of SPT-200 and NASA T-220. With a doubled size as that of NASA-400M, the force can be increased to 2 N. It is hence expectable to generate a thrust of 20 N simply by raising the current to 10 A. The magnitude can be further raised by using delicate techniques of manufacturing for wrapping the coils to form more turns, and even by changing the spatial distribution of the turns to yield a nonzero \( \frac{\partial N}{\partial z} \), e.g., by wrapping a varying number of coil layers. Therefore, it is very likely to produce a thrust on the order of 100 N simply by using the techniques that are readily available, leading to testable results for a prototype.

Strategies of operation

Based on the same framework, superconducting wires can be used to fabricate the coils so as to operate at a persistent mode with zero resistance of electric current. This method will yield zero dissipation and energy consumption, thus giving a high prospect of space propulsion for long-distance travel which needs a long life cycle and minimum loads. Inasmuch as a low temperature is required to maintain the superconductivity, the space environment shall provide a supporting reservoir for natural cooling, as long as an appropriate shield is built for protection of human inside the spacecraft. The material we have used is NbTi alloy which has a superconducting transition temperature \( (T_c) \) of about 9.7 K. Another low-temperature superconductor of popular use we have tested is made of Nb3Sn, which has a higher \( T_c \) as 18 K. It is supposed that proper superconducting materials to use would be those with \( T_c \) well above the cosmic microwave background temperature \((\approx 2.725 \text{ K})\), and most of the materials used for making a superconducting magnet nowadays (working at liquid helium temperature of 4.2 K) would be applicable.

Considering also the dependence of superconductivity on the critical magnetic field and critical current [3], one may use magnesium diboride (MgB2), which is a simple ionic binary compound. In addition to high critical values of current densities and fields as well as \( T_c \) (39 K), it has a simple crystal structure and large coherence lengths, associated with transparency of grain boundaries to current [11]. These advantages may highlight its potential use in large-scale applications and electronic devices. Further advancement would be achieved if high-temperature superconductors can be implemented, e.g., by using some cuprate-perovskite.

Table 1

| \( r_2 \) (mm) | Capacitance (pF) \((I = 0)\) | Capacitance (pF) \((I = 0.01 \text{ A})\) | \( F \), experimental (N) | \( F \), computational (N) | Error |
|---------------|-----------------|-------------------------------|---------------------|----------------------|-------|
| 2.5           | 4.4701          | 4.4717                        | 2.20E–05            | 2.40E–05             | 8%    |
| 3             | 4.4729          | 4.4749                        | 2.60E–05            | 2.90E–05             | 10%   |
| 4             | 4.4761          | 4.4796                        | 4.20E–05            | 4.40E–05             | 5%    |
| 5             | 4.4801          | 4.4846                        | 5.80E–05            | 6.10E–05             | 5%    |

Table 2

| Thruster type | Thrust (N) | Outer diameter (mm) |
|---------------|------------|---------------------|
| SPT-200       | 0.15–0.552 | 200                 |
| SPT-250       | Up to 1.5  | 120                 |
| NASA T-220    | 0.318–0.524| 220                 |
| NASA-300M     | Up to 1.13 | 300                 |
| NASA-400M     | 0.27–2.1   | 400                 |
| NASA-457M     | 0.37–2.9   | 457                 |
| PPS-20k ML    | Up to 1.05 | 320                 |

Fig. 9. Schematics of (a) a thruster moving along and across the geomagnetic field lines and (b) a three-axis solenoid modulator used for changing the direction of movement.
ceramic materials which have a critical temperature above 90 K. In this way, liquid nitrogen (boiling at 77 K) would be carried onboard to create superconduction for present spacecraft use. It will also facilitate many experiments and applications that are less practical at lower temperatures. Moreover, the modern technologies of fabricating a superconducting solenoid would make possible a large number of turns per unit length, e.g., \( N = 10^6 \text{m}^{-1} \) [12] and even higher. In addition, as discussed in [3], using alternate means such as rotating superconductors [13,14] and optimization of superconducting solenoid coils [15] could further enhance the magnetic field and generate greater propulsive forces.

By taking advantage of the low-temperature space environment or carrying liquid helium onboard, the device could also be applied for near-Earth missions such as satellite operations and sustain-ent. Considering the period operating at a condition of higher temperature that prevents attainment of a persistent mode, the energy dissipation could be made up by other means of supplementary energy provision such as solar cells.

The demonstration thus provides a perspective to build a magnetic propulsion device that has competing and even superior features of thrust generation. To control the direction of a thrust, however, supplementary devices would be needed. That is, since the interacting force is directed mainly along the magnetic field \( B \), where the maximum gradient of magnetic moment \( \frac{dM_s}{dT} \) is to be constructed, the thrust allows the object ultimately to slide along the magnetic field lines, as illustrated in Fig. 9(a). To increase the flexibility of movement specifically regarding the orientation, the object may carry additional one or two solenoids, as typified by a three-axis modulator in Fig. 9(b), either with constant or variant cross-sectional area. The modulator would harness the nonuniform geomagnetic field, i.e., via \( F = M_s (\nabla B) \) or \( M_s \frac{d}{dt} \). While the magnitude is relatively small, it could still yield a force that changes the direction of interaction and consequently the location across the magnetic field lines. Another solution is to utilize a secondary propulsion system, e.g., by a thruster based on chemical or electric propulsion which may carry only a small amount of propellant. Therefore, without compromising essentially the advantages of the EMP system, the object has sufficient maneuverability.

Concluding remarks

In summary, by simply changing the cross-sectional area of a solenoid, with readily accessible conditions of the system such as electric current and coil turns, in contrast to much larger demands as required by previous studies, we have demonstrated viability of using the geomagnetic field as an effective propulsion source. By adequately scaling up this EMP system, approaching the size of an electric propulsion system that is most promising nowadays for deep-space travel, the magnitude of produced thrust is comparable to and can even surpass that of the electric thrusters with slight modifications. While the maneuverability is somehow limited by the distribution of the naturally applied magnetic field, the EMP thruster can be used as a main or secondary device that draws the object efficiently along the magnetic field lines. To enhance the flexibility of movement, the operation would be adjustably assisted by additional thrusters. By adopting superconducting wires for the coils, the system has advantages of very low consumption of energy and nearly propellant-free loading, exhibiting a revolutionary potential for far-field space exploration. Moreover, the local magnetic field may provide a shield preventing outside radiation [3], which would reduce the requirement of bulky equipment onboard. This methodology thus provides an immediate solution for satellite movement and space travel toward long-distance targets such as Mars and other interplanetary journeys.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Declaration of Competing Interest

The authors have declared no conflict of interest.

Acknowledgments

The study was supported by National Taiwan University and Academia Sinica Innovative Joint Program, Taiwan, under the Project Number: NTU-AS-108L104307.

References

[1] Engelberger JF. Space propulsion system. US patent 3,504,868. US Cl. 244-1; 1970.
[2] Pulatov V. Magnetic propulsion systems. Prog Aero Sci 2001;37:245–61.
[3] Dadich A. Electromagnetic propulsion system for spacecrafts using geomagnetic fields and superconductors. 54th AIAA aerospace sciences meeting (AIAA SciTech 2016), paper number: 2016-0481, 2016.
[4] Sutton GP, Biblarz O. Rocket propulsion elements. 7th ed. Wiley; 2001.
[5] Choueiri EY. New dawn of electric rocket. Sci Am 2009;300:58–65.
[6] Pulatov V. Physics of magnetic propulsion systems. Prog Aero Sci 2005;41:64–91.
[7] Jackson JD. Classical electrodynamics. 3rd ed. New York: John Wiley & Sons; 1999.
[8] Brady DA, White HG, March PJ, Lawrence TF, Davies J. Anomalous thrust production from an RF test device measured on a low-thrust torsion pendulum. 50th AIAA/ASME/SAE/ASEE joint propulsion conference (propulsion and energy forum), paper number: 2014-4029; 2014.
[9] Erlandsson R, McClelland GM, Mate CM, Chiang S. Atomic force microscopy using optical interferometry. J Vac Sci Technol A 1988;6(2):266–70.
[10] Piragino A, Leporini A, Giannetti V, Pedrini D, Rossodivita A, Andreussi T, et al. Characterization of a 20 kW-class Hall effect thruster. The 35th international electric propulsion conference, 2017.
[11] Buzea C, Yamashita T. Review of the superconducting properties of MgB2. Supercon Sci Technol 2001;14:R115–46.
[12] Kunzler JE, Buehler E, Hsu FSL, Matthias BT, Wahl C. Production of magnetic fields exceeding 15 kilogauss by a superconducting solenoid. J Appl Phys 1961;32:325–6.
[13] Hildebrandt AF. Magnetic field of a rotating superconductor. Phys Rev Lett 1964;12:190–1.
[14] Tajmar M, de Matos CJ. Gravitomagnetic field of a rotating superconductor and of a rotating superfluid. Physica C 2003;385:551–4.
[15] Feng ZX. Optimization of superconducting solenoid coil. IEEE Trans Magn 1988;24:926–9.