Research on non-propellant electromagnetic control based on Eddy Current Brake under non-uniform magnetic field

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Abstract. High-speed space debris threatens the safety of satellites in orbit, and efficient removal of space debris has become an inevitable trend. However, the spacecraft is still dependent on the active consumption of propellant to maintain the relative distance in the eddy current brake process. By discussing the high-speed rotating target of non-contact de-spun method and drawing technology, electromagnetic de-spun and drawing technology based on a non-uniform magnetic field is proposed to use alternating current form to control rotate-target magnetic field force during electromagnetic interaction process. Through the simplified model and condition, put forward electromagnetic satellite of one coil control method. The feasibility of the technique is verified by numerical simulation. The simulation results show that the relative distance between the electromagnetic satellite and the target can be effectively affected the output current of the electromagnetic coil controlled through distance feedback under nonuniform magnetic, so as to realize the long-term mission without propellant.

1. Introduction

In the face of the urgent needs of in-orbit services, in-orbit control technology characterized by spacecraft docking, capture, de-orbit, and cluster control has become a research hotspot in the aerospace field. Low-earth orbit space is limited by the space debris have been increasing, actively remove space debris is to delay the feasible methods of Kessler phenomenon[1], and space debris removal process need to through the de-spun processing to capture and remove operation, and de-spun processing is the key link, it can be divided into contact de-spun technology and non-contact de-spun technology according to whether the target is contacted or not. Because of its outstanding comprehensive performance, electromagnetic de-spun technology has become a research hotspot.

Electromagnetic de-spun is a technology that generates induced eddy currents by rotating and cutting magnetic field lines in the electromagnetic field through the target. The induced eddy currents always hinder the cause of induced eddy currents, which is manifested as the de-spun torque so as to attenuate the angular velocity of the target. Prasad K. Kadaba et al.[2]. first proposed a method to eliminate satellite rotation by inducing vortices on the surface and verified the feasibility of method. But the research of superconductivity technology was not mature at that time, and the research of electromagnetic de-spun had been stagnant. With the progress of the second generation of high temperature superconductivity technology, the problem of small torque in the electromagnetic de-spun technology has been solved, and the need to remove space debris has become more and more urgent, so the electromagnetic de-spun technology has once again become a research hotspot. The research team led by Professor Scott J.I. Walker of the University of Southampton[3; 4; 5]. had carried out a comprehensive study on the method of eddy current de-spun by using HTS coils to generate super...
magnetic fields. The research team has studied the mechanism of eddy current braking, the electromagnetic and eddy current interaction force/torque model, and carried out simulation example analysis. A ground experimental platform was specially designed to verify the mathematical model. Yongkang Shi et al.[6]. analyzed the technical feasibility of superconduct eddy current brake by qualitative analysis. According to actual de-spun mission requirements such as the typical high-speed rotation, low-speed rotation, and the composite rotation of the target de-spun dynamics simulation and the study show-superconduct eddy current brake have strong enough braking ability, and an effectively eliminate the target's high-speed rotation or compound rotation motion. Yunfeng Yu et al.[7]. analyzed the electromagnetic interaction of the target satellite system, established the relative translational dynamics of the target-satellite system and the attitude dynamics of the target, and proposed to carry out the detumbling through the establishment of double satellite formation. The simulation results showed that the non-contact space debris detumbling method using double satellite electromagnetic formation was feasible.

Most of the existing electromagnetic de-spun technology studied did not regard the electromagnetic satellite and rotating object as electromagnetic de-spun formation system. It still relys on external forces such as thrust device serving of satellite to maintain relative distance for a long time. In addition, in the research process, the problem of magnetic additional field force, which will affect the relative position of electromagnetic satellite and target caused by rotating target under non-uniform magnetic field, is not considered. The above problems greatly limit the application process of electromagnetic de-spun technology. This article explores through the satellite of single electromagnetic coil to simulate the condition of nonuniform magnetic field, which controls alternating current of the coil to control the impact force to effect relative distance, alternating type electromagnetic de-spun method is proposed, establish the concept of electro-magnetic de-spun formation. The relationship between current, magnetic field, force and relative position in the process of de-spun is established and verified by numerical experiments.

2. Electromagnetic de-spun formation model

2.1. Electromagnetic field model

The electromagnetic satellite is regraded as a single electromagnetic coil, the size and direction of the magnetic field generated by controlling the current of the coil. According to the literature[6], the magnetic field generated by the coil under the action of current i can be accurately calculated as follows:

\[
B = B_x \cdot d + B_y \cdot r
\]

\[
B_x = B \frac{1}{\pi \sqrt{Q}} \left[ E(k) \frac{1}{Q-4\alpha} + K(k) \right]
\]

\[
B_y = B \frac{\gamma}{\pi \sqrt{Q}} \left[ E(k) \frac{1}{Q-4\alpha} - K(k) \right]
\]

where, \(B_x\) is the component along the central axis of the coil, \(B_y\) is the component along the radial direction of the coil, respectively is the unit vector along the central axis of the coil and its perpendicular direction. The other symbols are:

\[
\alpha = r / R \quad \beta = d / R \quad \gamma = d / r \quad Q = (1 + \alpha^2 + \beta^2) \quad k = \sqrt{4\alpha / Q}
\]

K(k) is a complete elliptic integral of the first class, E(k) is a complete elliptic integral of the second class, k is module, r is the distance from the measured point to the central axis of the coil; d is the distance from the measured point to the central point of the coil; \(B=\mu_0 Ni/2R\) is the magnetic induction intensity at the central point of the coil; \(\mu_0\) is the vacuum permeability.

2.2. Force and moment models

The rotating target is assumed an aluminum thin-walled spherical shell model, an approximate eddy
The current torque model of the target is derived based on the magnetic field intensity by using magnetic tensor theory. The effect of other structures of debris on detumbling is ignored and only detumbling on debris surface is calculated. The radius is $r$, the center of mass coincides with the center of the sphere, and the spherical coordinate system XYZ is established with the center of mass as the origin. The surface thickness of the sphere is $e$, the conductivity of the material of the sphere is $\sigma$. The relation of electromagnetic satellite and rotating target model are shown in the figure 1.

![Figure 1 Electromagnetic satellite and rotating target model](image)

Under the non-uniform magnetic field, the eddy current force model of the target is:

$$F_d = \mu_{eff} M \Lambda (\omega \times B)$$

where, $B$ is the magnetic induction intensity at the center of gravity of the debris, $\Lambda$ is the Jacobian matrix of the magnetic field, $\omega$ is the angular velocity of rotation of the object and $M$ is the electromagnetic tensor of the thin-walled spherical shell target, the matrix equation is shown as follows:

$$M = \frac{2\pi \sigma R^4_e}{3} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where, $\sigma$ is conductivity of material, $R$ is the radius of the spherical shell, and $e$ is the thickness of the spherical shell. $\mu_{eff}$ is correction factor for non-uniformity of magnetic field. Eddy current torque error caused by uneven magnetic field.

$$\Lambda = \frac{3\mu_0}{4\pi d^4} (mc) \begin{pmatrix} -2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + mc_L \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where, $\mu_0$ is the vacuum permeability, $d$ is the relative distance between the coil and the target, $mc$ is the magnetic moment of the coil. the eddy current torque model of the target is:

$$T_d = (M(\omega \times B)) \times B$$

According to the literature[8], it is considered that the interaction between the rotating target and the source magnetic field in the induced eddy field will produce magnetic additional field forces affecting the relative position, mainly including the lateral force $F_c$ caused by the first-order eddy current and the repulsive force $F_r$ caused by the second-order eddy current.

$$F_c = \sigma \omega r^3 B_r B_d \pi^2 / 4$$

$$F_r = \beta B_r B_d (\pi^2 + 5\pi)$$

$$B_d = \mu_0 \sigma r B_d / 3 = \beta B_d$$

In this paper, it is considered that the current is controllable and the magnetic field is controllable, so the electromagnetic interaction is controllable, and the size and direction of eddy current force, lateral force and repulsive force are controlled, so they are regarded as control forces. Then the control force of the electromagnetic de-tumbling formation can be written as:

$$F = F_d + F_c + F_r$$
Because magnetic fields are related to electric currents, the ratio can be denoted as a coefficient $c$:

$$B = c \cdot i$$  \hspace{1cm} (11)

Substitute Equation (2.11) into Equation (2.10), which can be written as:

$$F = \mu_0 M A (\omega \times c \cdot i) + \sigma \omega r^3 c^2 \cdot i \cdot i, \cdot i, \cdot \pi^2 / 4 + \beta c^2 \cdot i \cdot i, \cdot \pi^2 (\pi^2 + 5\pi)$$  \hspace{1cm} (12)

### 2.3. Relative distance control scheme

The electromagnetic satellite and rotating target are regarded as service star and target star respectively. According to the dynamical equation of relative motion in close range under the assumption of near-circular orbit, namely Hill equation, the Hill equation about service star and target star can be established by ignoring the interference term:

$$\begin{cases}
\ddot{x} - 2n\dot{y} - 3n^2 x = F_x / m \\
\ddot{y} + 2n\dot{x} = F_y / m \\
\ddot{z} + n^2 z = F_z / m
\end{cases}$$  \hspace{1cm} (13)

where, $F$ is the control force, $n$ is the orbital angular velocity, and the distance between the two stars in the electromagnetic racemic formation is 10 meters. Since the electromagnetic interaction between the two stars is mutual, the force $F_1$ acting on the service star and the force $F_2$ acting on the target star are equal in size and opposite in direction, and the masses of the service star and the target star are 2$m$ and $m$ respectively, then the Hill equation of the electromagnetic racemization formation can be written as:

$$\begin{cases}
\ddot{x} - 2n\dot{y} - 3n^2 x = 3 F_x / 2m \\
\ddot{y} + 2n\dot{x} = 3 F_y / 2m \\
\ddot{z} + n^2 z = 3 F_z / 2m
\end{cases}$$  \hspace{1cm} (14)

When there is a relative distance tracking instruction using PID controller according to the relative distance of two stars to feedback calculation of excitation current of the output time, size and orientation of the excitation current of the output time is electromagnetic interaction time, the direction of the field current is to control the direction of the traction, the size of the exciting current is to control the size of the traction and the function of the electro-magnetic braking effect, Allowing to maintain relative distance while continuing to de-spin target’s angular velocity. Then the current control is:

$$i = K_p (b \cdot d^* - d) + K_i \cdot T \cdot \frac{1}{s-1} (d^* - d)$$  \hspace{1cm} (15)

### 3. Numerical study

According to the above calculation formula, the initial parameters are set as follows: the superconducting coil radius is 1m, the coil turns is 500, and the current is 100A. The target debris is mainly aluminum alloy, a common aviation material, with a conductivity of 35335690s/m. The central axis of the electromagnetic coil passes through the center of gravity of the target star, the spin axis of the target star is perpendicular to the central axis of the coil, and the distance $d$ from the center of the coil to the center of gravity of the target COG is 10m. The calculation of the effective factor of magnetic field at 10m is 0.994547. The angular velocity of target is $[0,10,10]$. Combined with the typical de-spun tasks, the mathematical model and simulation model was used to study in transformation forms of non-uniform magnetic field in carrying out the long-term advantage in the de-spun task without propellant. Simplification of the research is as follows: When the relative position of 5 meters, the entire electro-magnetic racemic formation system failed. Firstly, the influence of additional magnetic field force on the de-spun process is studied. Secondly, the influencing factors of braking ability and maintaining relative distance of the non-uniform magnetic field in the form of alternating cur-rent are studied. Finally, the simulation of distance control by adjusting the output current through displacement feedback shows the advantages of using alternating current in long-term de-spun
tasks and improving the overall de-spun effect.

Adding the magnetic field additional force in the process of electromagnetic interaction to the whole electromagnetic de-spun system model will make the relative distance of the two satellites change more violently, but it has no de-spun effect on the target. According to equation (2.5), it is easy to know that the change of distance under long term effect can cause the change of magnetic field intensity of rotating targets, which will indirectly affect the electromagnetic de-spun effect of electromagnetic satellites on targets. However, when alternating current is applied to the electromagnetic coil, the magnitude and direction of the additional force of the magnetic field in the electromagnetic interaction are controlled, which can be regarded as the control force. Taking the AC electromagnetic field in the form of sine wave and square wave as an example compared with the constant electromagnetic field, checks in maintaining the relative distance and de-spun rate of the two stars.

Alternative electromagnetic field on the maintain long-term de-spun mission power has obvious advantages, but when the distance of 10 meters, in terms of de-spun rate, coincidence of braking effect curve shows that spinning target in the square wave form of alternating electromagnetic field braking effect is equal to rotate in constant electromagnetic field. But electromagnetic satellites continue to close to, the magnetic field on the rotating target increases and the de-spun effect increases. It is not difficult to see that the electromagnetic field and relative distance with fixed variation does not meet the needs of real task. And the electromagnetic interaction of the electromagnetic de-spun formation system will be weakened due to the de-crease of the target's rotation speed, but maintain through reducing relative distance until lower than 5 meters of the whole system finally fails. In order to avoid or reduce the use of propellant, the distance feedback control is adopted to ensure the relative distance between the
electromagnetic satellite and the target. The size, direction and action time of alternating electromagnetic field are controlled by distance feed-back, and a one-day de-spun task simulation is carried out to compare, in which the harmonic harm of non-sinusoidal alternating electromagnetic field in engineering application is ignored.

Figure 6 Effect of sine wave feedback controlled magnetic fields on relative distance

But this result of angular velocity compare with the result form the literature[6], it’s easy to see the decline of angular velocity is too slowly for the following reasons:(1) The coil is not always facing the rotating target, so the target is not in the maximum magnetic field. (2) When the relative distance between the satellite and the target increases, the electromagnetic interaction between the two is weakened. (3) When the angular velocity of the target decreases, its electromagnetic interaction with the satellite is weakened. (4) The satellite is subjected to a torque of reaction, which produces rotation. (5) The nutation Angle of the rotating target weakens the electromagnetic interaction. Fig. 7 and Fig. 9 are schematic diagrams of changes in sinusoidal current and square wave current respectively.

Figure 8 Effect of square wave feedback controlled magnetic fields on relative distance

Figure 9 Square wave feedback controlled current
4. Conclusion
This paper mainly studies the possibility of electromagnetic de-spun formation between electromagnetic satellite and uncontrolled target, establishes the mathematical model of alternating electromagnetic field and the relative motion equation of formation system, and uses alternating electromagnetic field to convert the electromagnetic force affecting relative distance into active traction force. The following conclusions can be drawn from the simulation results:(1) the electromagnetic satellite can realize the long-term non-propellant task by using the Electromagnetic interactions of rotating target and alternating electromagnetic field, but the electromagnetic satellite itself needs to actively maintain the relative attitude to achieve the best de-spun effect; (2) The designed controller can convert the relative distance error signal into the current input signal, and maintain the relative distance while de-spun. However, with the decrease of angular velocity, the stability of the control system will decline, but it can still be accepted; (3) By comparing the effects of different input current forms, it can be found that the sinusoidal current form can better maintain the relative distance between the service star and the target star, while the square wave input current form has better performance in de-spun.

This paper creatively uses the additional magnetic force under non-uniform magnetic field to maintain the distance between electromagnetic satellite and uncontrolled target, so as to completely eliminate or reduce the use of propellant. Compared with traditional methods, this technology can not only be used for de-spun, but also completely rely on electricity to maintain the relative distance. Therefore, it can also be used in the field of passive traction of space targets.

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