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Dynamic analysis and control application of vibration isolation system with magnetic suspension on satellites

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A B S T R A C T

Vibration isolation platform is widely used to isolate the micro vibration that is harmful to the sensitive payloads on satellites. The traditional passive vibration isolation platform has difficulty in isolating vibration with low frequency and designing the stiffness and damping parameters. In this work, a new kind of vibration isolation platform whose actuators are based on the magnetic suspension techniques is presented. The first step studies the force between two coils with currents and gives a simplified model of the force. The model of a single strut of the vibration isolation platform is described and the control currents are designed. Then the dynamic model of the vibration isolation platform is built. Based on this dynamic model, the electromagnetic coupling among struts is discussed, the stability and the parameters sensitivity of the platform are analyzed. Finally, the application of this new vibration isolation platform presented in this paper on satellite is analyzed. The accuracy and efficiency of this study are validated through numerical simulations of an attitude control loop using the vibration isolation platform.

0. Introduction

Nowadays, the remote sensing satellites require high accuracy and high stability [1–3] while working on orbit. Nevertheless, there are lots of micro vibrations with high frequencies [4,5] by attitude control actuators (such as CMGs [6–8] and flying wheels [9,10]) and low frequencies by flexible appendages (such as solar arrays [11] and antennas [12,13]), which will do harm to sensitive payloads on satellites.

Traditional passive vibration isolation system [14,15] can be used to avoid these disturbances. However, the effect of passive vibration suppression is limited. For example, it cannot isolate the vibration with low frequency. Especially when the frequency is near the system natural frequency, the amplitude of the vibration will be amplified due to the resonance effect [16]. What's more, traditional vibration isolation system with mechanical structure is faced with a lot of problems derived from the interaction among mechanical parts, such as friction and collision [17,18].

Active vibration isolation and control methods are widely used to solve those problems. Active vibration isolation system consists of controller, actuator, sensor and digital signal processing. As it is known, PID and classical control methods are the most popular control methods. Kerber et al. [19] designed a kind of PI controller for active vibration isolation. Lin and Liu [20] designed a kind of adaptive fuzzy PID controller of active vibration isolation system. Besides, Positive Position Feedback (PPF) is also a kind of active vibration isolation method, which could realize zero stiffness vibration isolation theoretically. Fenik et al. [21] adapted velocity feedback to design PI controller of PPF to realize vibration isolation. Li [22] adapted PPF control for high-amplitude vibration of a flexible beam to a principal resonance excitation. Hu and Ma [23] presented a new method to vibration isolation of flexible spacecraft during attitude maneuver by the theory of variable structure control to design switching logic for thruster firing and lead zirconate titanate as sensor and actuator for active vibration suppression. What's more, D.F. Wu [24] studied active vibration control of a highly flexible beam using piezoelectric intelligent material. Lei and Samir [25] designed a kind of H_2 controller for vehicle suspensions based on multi-wheel models. Xu et al. [26] studied the modeling and robust H-infinite controller of a novel ultra-quiet spacecraft which employs the non-contact Stewart platform to actively control its support module and payload module. J. Shaw [27] studied active vibration isolation by adaptive control. Chen et al. [28] designed a controller based on neural network to realize active vibration control. Yen et al. [29] used discrete sliding mode active control for a large stroke scanning probe microscope.

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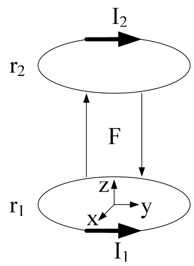

Fig. 1. Force between two coils with currents.

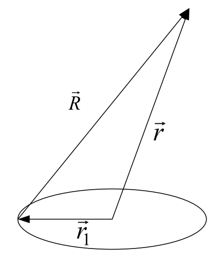

Fig. 2. Position vectors in the model.

Xie et al. [30] used genetic algorithms for vibration reduction of viscoelastic damped structures. Shahruz [31] studied active vibration suppression in multi-degree-of-freedom systems by disturbance observers.

Pedreiro and Nelson [32] firstly put forward the concept of non-contact spacecraft which used non-contact force from electromagnet interaction to connect payloads and satellite bus. This active vibration isolation method can avoid the interaction among mechanical parts. However, there are few studies about the characteristics of actuators, especially the characteristics of the coils as the actuators in the magnetic suspension vibration isolation system.

This paper builds the dynamic model of the vibration isolation platform with magnetic suspension and studies its time- and frequency- domain characteristics. Firstly, the characteristics of forces between the coils are studied. In single degree of freedom, the model of a single vibration isolation strut with magnetic suspension is given. Then, the model of the vibration isolation platform whose struts are based on the magnetic suspension techniques is given by Newton–Euler method and its dynamic characteristics are studied. The control method that divides the control low into two parts is introduced, and with some given parameters, the vibration isolation platform based on magnetic suspension techniques is taken into the control loop of the whole satellite that employs CMGs as actuators. Finally, numerical simulations are used to verify the reliability of the model discussed in this paper.

1. The force between two coils with currents

The vibration isolation platform discussed in this paper relies on electromagnetic force between currents. This section firstly derivates the force between two coils with currents by Biot–Savart law and Ampere force formula. Then a simplified model of the force is given and contrasted with the complete model.

1.1. The detailed model of the force

According to Biot–Savart law and Ampere force formula, the force between the two coils [33] shown in Fig. 1 can be expressed as

$$\begin{aligned}
&\vec{F}_{I_2} = \oint_{r_1} I_2 \vec{B}_{I_1} \times d\vec{r}_2 \\
&\vec{B}_{I_1}(\vec{r}) = \nabla \times \left(\frac{\mu_0}{4\pi} \oint_V \frac{\vec{I}_1}{r} dV \right) = \nabla \times \left(\frac{\mu_0 I_1}{4\pi} \oint_{r_1} \frac{d\vec{r}_1}{r} \right)
\end{aligned} \tag{1.1}$$

In Eq. (1.1), $\vec{B}_{I_1}(\vec{r})$ represents the magnetic field produced by I_1 at the position $\vec{r}$. ∇ is the gradient operator. $\mu_0 = 4\pi \times 10^{-7} N/A^2$, which is the permeability of vacuum. V represents the space where $\vec{I}_1$ exists. I_1 is a constant in the coil r_1, so $\vec{I}_1 dV = I_1 d\vec{r}_1$. $\vec{F}_{I_2}$ represents the electromagnetic force that the coil carrying I_2 surfers. The double integral here is hard to calculate. It is necessary to simplify the calculation of the force.

1.2. The simplified model of the force

This section calculates the force from I_1 to I_2 with a simplified model. When the distance between the two coils is much bigger than the radius of the coil, the vector from each point in coil I_1 to I_2 can be regarded as that from the center of I_1 to I_2. That is to say, in Fig. 2, when $|\vec{r}_1| \ll |\vec{r}|$, $\vec{R}$ can be replaced by $\vec{r}$.

The currents in the coils are constants, so

$$\begin{aligned}
\vec{B}_{I_1}(\vec{r}) &= \nabla \times \left(\frac{\mu_0}{4\pi} \oint_V \frac{\vec{I}_1}{R} dV \right) \\
&= \frac{\mu_0 I_1}{4\pi} \nabla \times \left(\oint_{r_1} \frac{1}{R} d\vec{r}_1 \right)
\end{aligned} \tag{1.2}$$

where

$$\frac{1}{R} = \frac{1}{|\vec{r} - \vec{r}_1|} = \frac{1}{|\vec{r}|} - \vec{r}_1 \cdot \nabla \frac{1}{|\vec{r}|} + \ldots$$

The higher-order terms can be ignored, Eq. (1.2) can be rewritten as follows

$$\vec{B}_{I_1}(\vec{r}) = \frac{\mu_0 I_1}{4\pi} \nabla \times \left[\oint_{r_1} \left(\frac{1}{|\vec{r}|} - \vec{r}_1 \cdot \nabla \frac{1}{|\vec{r}|} \right) d\vec{r}_1 \right] \tag{1.3}$$

Denote $\vec{B}^{(0)}_{I_1}(\vec{r}) = \frac{\mu_0 I_1}{4\pi} \nabla \times (\oint_{r_1} \frac{1}{|\vec{r}|} d\vec{r}_1)$, $\vec{B}^{(1)}_{I_1}(\vec{r}) = -\frac{\mu_0 I_1}{4\pi} \nabla \times (\oint_{r_1} \vec{r}_1 \cdot \nabla \frac{1}{|\vec{r}|} d\vec{r}_1)$. To a certain point, $\vec{r}$ is a constant, so

$$\vec{B}^{(0)}_{I_1}(\vec{r}) = \frac{\mu_0 I_1}{4\pi |\vec{r}|} \nabla \times \left(\oint_{r_1} d\vec{r}_1 \right) = \mathbf{0}_3 \tag{1.4}$$

To the circular coils

$$\begin{aligned}
&\vec{r}_1 = \begin{bmatrix} r_1 \cos\theta & r_1 \sin\theta & 0 \end{bmatrix}^{\mathrm{T}} \quad (0 \le \theta \le 2\pi) \\
&d\vec{r}_1 = \begin{bmatrix} -r_1 \sin\theta & r_1 \cos\theta & 0 \end{bmatrix}^{\mathrm{T}} d\theta
\end{aligned}$$

$$\nabla \frac{1}{|\vec{r}|} = \begin{bmatrix} \frac{\delta \frac{1}{|\vec{r}|}}{\delta x} & \frac{\delta \frac{1}{|\vec{r}|}}{\delta y} & \frac{\delta \frac{1}{|\vec{r}|}}{\delta z} \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} \frac{x}{|\vec{r}|^3} & \frac{y}{|\vec{r}|^3} & \frac{z}{|\vec{r}|^3} \end{bmatrix}^{\mathrm{T}} = \frac{\vec{r}}{|\vec{r}|^3}$$

To calculate $\vec{B}^{(1)}_{I_1}(\vec{r})$

$$\begin{aligned}
\oint_{r_1} \vec{r}_1 \cdot \nabla \frac{1}{|\vec{r}|} d\vec{r} &= \int_0^{2\pi} \begin{bmatrix} r_1 \cos\theta \\ r_1 \sin\theta \\ 0 \end{bmatrix} \cdot \frac{\vec{r}}{|\vec{r}|^3} \begin{bmatrix} -r_1 \sin\theta \\ r_1 \cos\theta \\ 0 \end{bmatrix} d\theta \\
&= \frac{1}{|\vec{r}|^3} \int_0^{2\pi} \begin{bmatrix} -r_x r_1^2 \sin\theta \cos\theta - r_y r_1^2 \sin^2\theta \\ r_x r_1^2 \cos^2\theta + r_y r_1^2 \sin\theta \cos\theta \\ 0 \end{bmatrix} d\theta \\
&= \frac{S_1}{|\vec{r}|^3} \begin{bmatrix} -r_y \\ r_x \\ 0 \end{bmatrix}
\end{aligned} \tag{1.5}$$