Structural Design and Static Performance Verification of Semi-active Vibration Isolation Device for PAF

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Abstract: The vibration environment during satellite launch is very harsh, and the vibration excitation spectrum from all directions is extremely wide. The satellite is easily damaged, leading to the failure of launch mission. The whole-spacecraft vibration isolation is achieved by modifying the structure of the payload attach fitting (PAF), or placing a vibration isolation device between the original adapter and the star-arrow connection surface. This paper improves the traditional PAF, and a semi-active vibration isolation system based on electromagnetic mechanics is designed. Maxwell software is used to simulate the static performance of the active vibration isolation module, and an experimental system is built to verify the simulation results. It is preliminarily confirmed that the designed device can meet the vibration isolation requirements.

Key words: active vibration isolation; Ansoft Maxwell; static performance

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0 Introduction

The orbital satellites are not restricted by regional boundaries. For having wide information coverage and long-time stable operation[1], they are gradually becoming an indispensable part in people's lives. Therefore, how to send satellites safely into orbit has also become the focus of research[2].

NASA's research on the causes of satellite launch failures shows that 41% of satellite launch failures can be attributed to excessive vibration and noise excitation during the launch process. And another 25% of satellite damage events may also be caused by vibration loads during the launch phase[3]. It can be seen that the vibration environment in the satellite launch phase is very severe, and the vibration load is the main cause of satellite damage[4]. Therefore, improving the dynamic environment of satellites is an urgent problem to be solved in the application of satellite engineering.

In the process of satellite launch, the satellite and the rocket are connected through the payload attach fitting(PAF)[5]. In order to ensure the strength of the structure, the traditional PAF is designed to have a large stiffness[6]. But such a design can only play the role of connecting the satellite and the launch vehicle, and cannot isolate the mechanical vibration transmitted by the launch vehicle to the satellite, resulting in these vibration loads to act almost directly on the very flexible satellite, which is very easy to cause the structural failure of the satellite[7].

By modifying the existing star-rocket adapter or designing a set of vibration isolation devices to replace it, the vibration excitation from the launch vehicle can be effectively isolated, and the mechanical environment of the satellite during the launch process is greatly improved[8-9]. This is the concept of whole-spacecraft vibration isolation. Therefore, it is of great significance to develop a new type of whole-spacecraft vibration isolation system for improving

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the effective mass ratio of satellites in orbit, and improving the safety of the satellite launch process[10-11].

This paper incrementally designs the existing whole-spacecraft adapter, and installs a semi-active vibration isolation system on it. The static performance simulation of the active vibration isolation module is carried out by using Ansoft Maxwell software, and the principle verification experiment is designed to verify the static performance of the active vibration isolation module.

1 Design of Payload Attach Fitting

The vibration isolation part of the semi-active vibration isolation device for the PAF designed in this paper is mainly composed of the high stiffness spring unit and the electromagnetic active vibration isolation unit. The overall simplified structure of the PAF is shown in Fig.1.

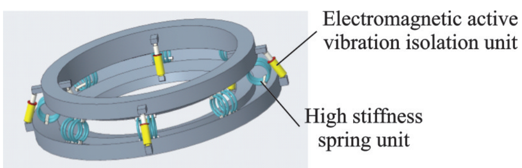

Fig.1 Design scheme of payload attach fitting

2 Theoretical Model Analysis of Vibration Isolation

In order to find out the output law of the electromagnetic vibration isolator in the PAF, the vibration mechanics model of the satellite installed inside the rocket fairing during the rocket launch is now carried out. The specific model is shown in Fig.2, where M represents the rocket body and m the satellite body. k and c represent the wire rope spring and the electromagnetic vibration isolator in the PAF, respectively.

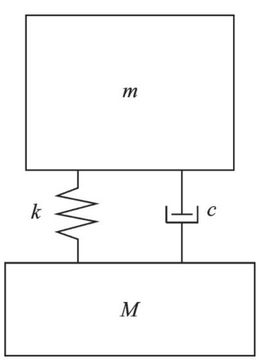

Fig.2 Problem description model

In Fig.2, c (the force output by the electromagnetic vibration isolator) is the required force, and the rest of the initial conditions are shown in

$$\begin{cases} m = 100 \text{ kg} \\ k = 2.5 \times 10^3 \text{ N/m} \end{cases} \tag{1}$$

Assuming that M is known, that is, the vibration law of the rocket is shown in Eq.(2), where D is the amplitude and ω the vibration period.

$$x_f(t) = D\sin(\omega t) \tag{2}$$

We use M, that is, the rocket body as the reference coordinate system, to establish the model, as shown in Fig.3.

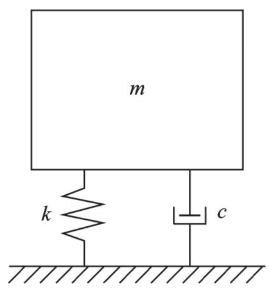

Fig.3 Simplified model

Based on the simplified model shown in Fig.3, we conduct vibration force analysis on m (the satellite body) and the results are shown in Fig.4, where F_k is the force provided by the spring compared with the initial compression state and F_c the force output by the electromagnetic vibration isolator. F_G is the relative inertial force, which is the inertial force generated by vibration, and F_m represents the inertial force, elastic force and damping force of the satellite.

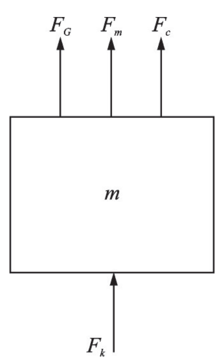

Fig.4 Vibration force analysis results

Eq.(3) can be obtained by expressing the force analysis result as a differential equation of vibration mechanics, where x_1 is the displacement of m relative to M and x_m the absolute displacement of the vibration component of the center of mass of m.

$$m\left(\ddot{x}_1(t)+\ddot{x}_f(t)+\ddot{x}_m(t)\right)-F_c(t)+kx_1(t)+kx_m(t)+c_m\dot{x}_m(t)=0 \tag{3}$$

Since the absolute displacement of the centroid of m is always 0 in an ideal state, x_m and its derivatives are all 0. After eliminating the relevant terms, Eq.(2) is brought into Eq.(3), and the differential equation shown in Eq.(4) can be obtained after sorting.

$$m\ddot{x}_1(t)+kx_1(t)=mD\omega^2\sin(\omega t)+F_c(t) \tag{4}$$

Since the control objective is to make the satellite displacement relative to the ground without vibration components, x_1 in Eq.(4) is a known quantity, and its expression is shown in

$$x_1(t)=-x_f(t)=-D\sin(\omega t) \tag{5}$$

From the above formulas, we have established the model. Substitute Eq.(5) into Eq.(4), and after sorting, we can obtain F_c, as shown in

$$F_c=-k\cdot x_f(t)=-k\cdot D\sin(\omega t) \tag{6}$$

In summary, we have obtained the expression of the output force of the electromagnetic vibration isolator in the vertical direction, which is a force curve with an amplitude of kD and a frequency of ω.

3 Static Performance Simulation and Experimental Verification

3.1 Electromagnetic vibration isolator design

In order to achieve the output force of the electromagnetic vibration isolator in the vertical direction in Section 3, the specific design of the electromagnetic active vibration isolation unit is given as shown in Fig.5. It is mainly composed of an inner cylinder, an outer cylinder, two excitation coils, an induction coil and a balance position adjusting device. And the relative position of the excitation coil and the induction coil, can be adjusted by the balance position adjustment device to adapt to the time-varying overload of the rocket launch stage.

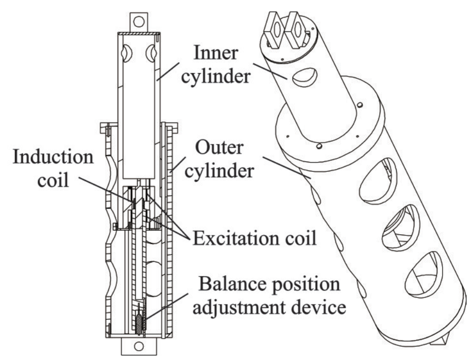

Fig.5 Electromagnetic active vibration isolation unit structure

3.2 Simulation and experimental setup

In order to verify the correctness of the principle of the designed electromagnetic vibration isolator, the static performance simulation and experimental verification of the core component, namely the coil part, are to be carried out. The design and construction of the overall test and verification settings are shown in Fig.6.

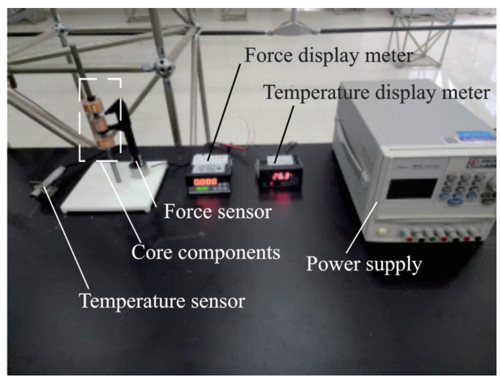

Fig.6 Experiment settings

The specific composition and state of the core components after wiring are shown in Fig.7, and the parameters of the experiment components are shown in Tables 1, 2. Beside, the material of magnetic conductor is iron(DT4C).

Among them, the temperature sensor is only used to ensure that the coil works at a suitable temperature during the test, and not used to record the data. According to the installation position of the core components shown in Fig.7 and the coil parameters shown in Table 1, the core component model of the electromagnetic active vibration isolation unit shown in Fig.8 is established in Maxwell software, in which the two excitation coils are wound in opposite ways.

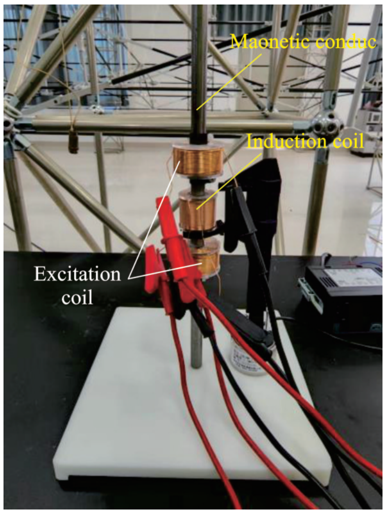

Fig.7 Experimental core components

Table 1 Coil parameters

Test module	Wire diameter/mm	Turn numbers
Excitation coil	0.6	448.5
Induction coil	0.4	782.5

Table 2 Sensor parameters

Sensor	Range	Instrument error
Force sensor	0—2 kg	±0.002 kg
Temperature sensor	0—200 ℃	±0.1 ℃

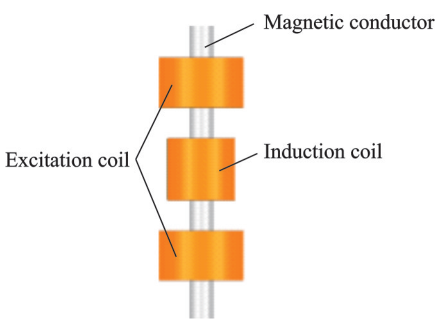

Fig.8 Maxwell model for core components

Referring to the maximum current that can be passed through different wire diameters, it is determined that a current of 0.5—1.4 A is passed into the excitation coil, and a current of 0.5—1.0 A is passed into the induction coil, and the different power-on conditions are combined in pairs to form a total of 60 kinds of test/ simulation conditions.

4 Comparison of Simulation and Experimental Results

Taking the simulation method described in the previous section, the simulation results are shown in Table 3, where I_1 represents the current in the excitation coil and I_2 the current in the induction coil.

Table 3 Simulation results mN

I_2/A	I_1/A					
	0.5	0.6	0.7	0.8	0.9	1.0
0.5	193.2	232.1	271.1	310.3	349.3	388.3
0.6	231.5	278.5	325.4	372.3	419.1	465.3
0.7	269.9	324.6	379.4	434.5	488.8	543.0
0.8	308.4	370.7	433.4	495.9	558.5	620.9
0.9	346.9	416.9	487.5	554.8	628.0	697.3
1.0	385.6	463.3	539.2	616.1	697.9	773.0
1.1	424.2	509.7	594.7	681.4	767.1	850.1
1.2	463.1	554.0	649.5	742.6	835.1	927.7
1.3	500.8	600.5	703.5	804.7	903.7	1 004.3
1.4	538.7	646.1	758.0	865.6	972.6	1 079.8

Three measurements are made for each working condition, and the results are summarized as shown in Figs.9—14. The simulation result range in the figures is obtained by adding the simulation result to the instrument error of the force sensor, which matches the display accuracy of the sensor. The experimental results are accurate to the level of 10 mN.

It can be seen from the figures that all the test measurement results fall within the range of the simulation results, that is, the measurement error re-

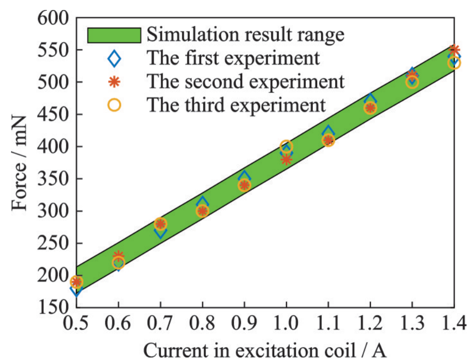

Fig.9 Induction coil current of 0.5 A

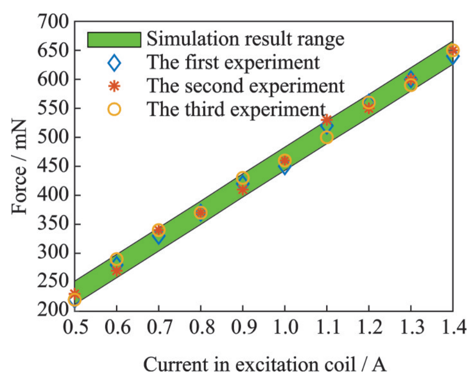

Fig.10 Induction coil current of 0.6 A

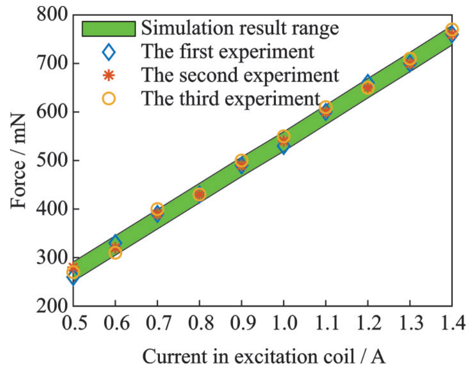

Fig.11 Induction coil current of 0.7 A

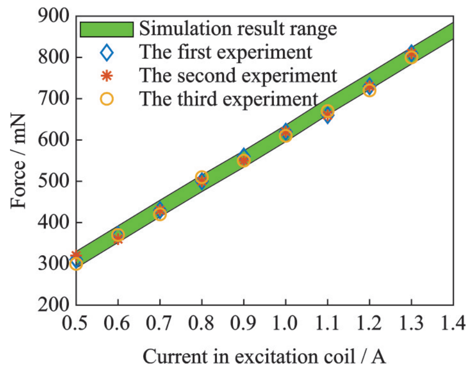

Fig.12 Induction coil current of 0.8 A

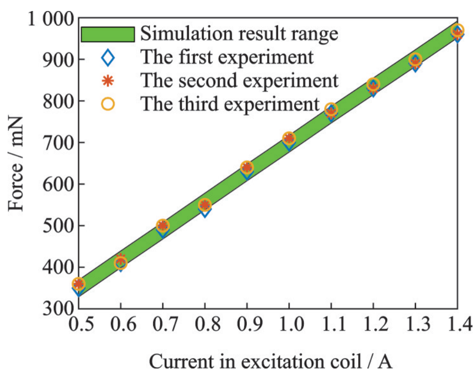

Fig.13 Induction coil current of 0.9 A

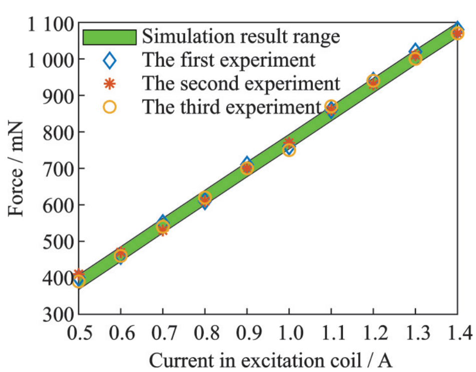

Fig.14 Induction coil current of 1.0 A

quirements are met, which confirms the correctness of the simulation results.

5 Conclusions

Based on the background of improving the vibration environment during satellite launch, a semi-active vibration isolation system is designed on the PAF, and its feasibility is confirmed by theoretical calculation. At the same time, the core components of the active vibration isolation system in the vibration isolation system are simulated and verified by experiments. The test results show that: under the existing settings, the test output force is between 180—1 080 mN, and the maximum error with the simulation results is greater than 20 mN of the instrument, which does not exceed the built-in error of the instrument, meeting the measurement error requirements. And the static characteristics of the core components of the electromagnetic vibration isolator meet the requirements of active vibration isolation.

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Author contributions Mr. **GAO Xiangyu** conducted modeling, simulation design, experiments, data processing and analysis, and wrote the original manuscript. Dr. **JIA Shan** contributed to concept proposal, modeling methods, and experimental guidance, and wrote the review and edited the manuscript. Prof. **CHEN Jinbao** contributed to investigation, formal analysis, and project management, and wrote the review and edited the manuscript. Mr. **LIU Chang** helped with the experiment and made contributions to formal analysis and data processing. All authors commented on the manuscript draft and approved the submitted manuscript.

Competing interests The authors declare no competing interests.

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基于星箭适配器的半主动隔振装置结构设计与静态性能验证

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摘要：卫星发射过程中的振动环境非常恶劣，来自各个方向的振动激励频谱极宽，卫星极易遭到破坏而导致发射任务失败。而星箭隔振通过修改星箭适配器的结构，或是将隔振装置放入原适配器与星箭连接面之间以实现减振隔振。本文对传统PAF(Payload attach fitting, PAF)进行改进，设计了一种基于电磁力学的半主动隔振系统，应用Maxwell软件对其中的主动隔振模块进行静态性能仿真，并搭建了试验系统对仿真结果进行了验证。初步确认了所设计的装置可以满足隔振要求。

关键词：主动隔振；Ansoft Maxwell；静态性能