Dynamic Simulation and Vibration Test of the Active Potential Controller

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Abstract. The Active Potential Controller was used to avoid the risk of damaging the life of astronauts outside spaceships in outer space by controlling the potential of the spaceship. This paper analyzed the structure of the Active Potential Controller by dynamic simulation, including setting up a finite element method (FEM) model, modal character and frequency response. At last, the designing and analysis was proved by the data from a vibration test. In this field, decreasing the weight was a key theme, the goal is cutting the cost. But cancelling or improving the sine vibration test could also save a lot cost, either for the payload or the satellite.

1 Introduction

The solar cell array, with high voltage of 100V, was applied on a cargo spaceship, causing that the cargo ship was keeping at the potential of -100V, comparing with the solar cell array and the surrounding plasma. If an astronaut worked outside the spaceship, he or she would stay at similar potential with nearing plasma in the space environment. When this astronaut got back, the large potential difference would cause terrible discharge and damage to the life of the astronaut. To keep the astronaut safe, NASA set up standards that the potential of the spaceship should be -40V during extravehicular activity.

Based on the technology in the 1970s, Pulsed Plasma Thruster (PPT) and Hollow Cathode Plasma (HCP) were applied on international cargo spaceship for active potential control, producing intensive plasma to supply large current for cargo to control the potential [1].

The cargo ship of China was also equipped with similar units. This paper introduced the active potential controller on the first cargo ship of our country.

Fig. 1 The plasma contactor on space station

Fig. 2 The position of plasma contactor on space station

2 Overview of the controller

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The active potential controller on the first cargo ship of our country was composed of plasma contactor, radio frequency (RF) power source, control unit, potential probe and supply unit, showed in fig 3.

Fig. 3 The composition of active potential controller

The potential probe monitored the potential of a spacecraft. If it exceeds a special safety threshold, the power and control centre sends control signal to the RF source to drive the plasma source start to launch plasma. All information of the parameters of the plasma source was also collected by the power and control centre to calculate and optimize to make the plasma source work at optimal state.

3 Designing of the controller

3.1 Requirements and design criterion

3.1.1 Overall dimension

The device was installed outside the cargo spaceship, as fig 4 in a circle. According to the volume of fairing and other devices, the dimension was constrained at 352mm×300mm×172mm.

Fig. 4 Position outside the spaceship

3.1.2 Stiffness

The fundamental frequency of the active potential controller should be over 100 Hz.

3.1.3 Strength

The structure should not be destroyed in sine and random vibration and the safety margin should be greater than 1. The safety margin was defined as:

$$M.S. = S_a / S_e - 1$$

M.S. -- Safety margin.

S_a -- Permissive load or corresponding stress.

S_e -- Identification load or corresponding stress.

3.1.3 Theoretic analysis

If, without the external force, the structural damping is not taken into consideration, the Equation of undamped free vibration of a system of multiple freedoms is

$$M\ddot{X} + KX = 0 \quad (1)$$

M--mass matrix, $n \times n$;

K--stiffness matrix, $n \times n$;

X--response of the system and displacement vector.

The form of solution is

$$X = A \sin(\omega t + \varphi) \quad (2)$$

Equation (2) was substituted into (1).

$$(K - \omega^2 M)A = 0 \quad (3)$$

The condition of equation (3) with non-zero solutions is

$$\det(K - \omega^2 M) = 0 \quad (4)$$

That is the character equation of the structure. Each natural frequency could be got from it. It can be seen that the natural frequencies, especially the lowest one (100 Hz) above, are related directly with mass matrix M and stiffness matrix K. The natural frequencies could be enhanced by reinforcing stiffness K or decreasing mass M.

3.2 Designing of the active potential controller

The controller was designed as fig 5. At the bottom two PCBs (printed circuit bank) were linked by a mother board, worked as the power and control centre. The plasma source was located at the other side. All parts of supply unit were integrated on a plate on top of the box. The Langmuir probe was placed outside the box, working as the potential probe.

Fig. 5 Designing inside the controller

4 Dynamic simulation and analysis

4.1 Setting up the FEM model

The FEM model was set up as fig 6, including the internal structure. All nodes of fitting holes were constrained and all degree of freedom was limited.

Fig. 6 FEM Model of the active potential controller

4.2 Parameters of Input

Table 1 gave the parameters of input as excitation.

Table 1 Test conditions of sine vibration

Name	Value of parameters
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	Frequency (Hz)			
	4~10	10~17	17~75	75~100
Magnitude(0~peak)	14.7mm	3.6g	9g	5.6g
Scan rate	4 oct/min			
Directions	X,Y,Z			

Table 2 Test conditions of random vibration

Frequency(Hz)	Magnitude (g^2/Hz)
10~95	+6 dB/oct
95~130	1.0 g^2/Hz
130~200	-13 dB/oct
200~600	0.16 g^2/Hz
600~2000	-15 dB/oct
The Total RMS	13.6

The main materials were stated in table 3.

Table 3 The main materials and properties

Name	Elastic Modulus	Density	Poisson Ratio
	E (GPa)	$\rho(\text{g}/\text{cm}^3)$	γ
2A12-H112 (aluminium alloy)	70	2.8	0.30
Nd-Fe-B (magnet)	160	8.0	0.33
Epoxy resin FR-4(PCB)	14	1.75	0.15

4.3 Modal and frequency response analysis

Based on the data above, the fundamental frequency of the active potential controller was calculated by Patran/Nastran. It's 230Hz. The shape of vibration mode was given by fig 7.

Fig. 7 The first mode shape and frequency response

As Fig 7(a), the first mode shape was at the PCB at the bottom. Fig 7(b)(c)(d) were the stress Fig. of frequency response in direction X,Y,Z. The maximum stress of frequency response in direction X was 5MPa, and others were 4.79MPa and 8.46MPa in direction Y and Z separately, including sine and random vibration.

Therefore, the fundamental frequency of the active potential controller was over 100Hz without any doubt. The allowable stress of aluminium alloy was 175MPa and the maximum stress of frequency response in any direction was 8.46Hz. So

$$M.S. = S_a / S_e - 1$$

$$\text{According to 3.1.3, } M.S. = 175/8.46 - 1 \gg 0.$$

5 Vibration Test

Considering the result of dynamic simulation and analysis, including the local area with high stress and design of the active potential controller, 3 accelerometers were pasted outside the active potential controller before the vibration test to measure the acceleration and force real-timely.

Fig. 8 The position of accelerometers for measuring

Fig. 9 Vibration test

6 curves were selected from the results of the vibration test for analysis, representing the maximum response (or, amplification relative to input), in fig 10.

(a) The random response of accelerometer 1 in direction X

(b) The random response of accelerometer 1 in direction Y

(c) The random response of accelerometer 3 in direction Y

(d) The random response of accelerometer 1 in direction Z

(e) The random response of accelerometer 2 in direction Z

(f) The random response of accelerometer 3 in direction Z

Fig. 10 The result of vibration test

From fig 10, curve (f), the random response of accelerometer 3 in direction Z, represented the largest amplification. Nevertheless, there were not any sensitive parts at the position of accelerometer 3 and the structure here nearly bore no load. At the same time, the load of all structure materials at the 3 positions was much less than the allowable stress. It meant enough safety margins[2-5].

So, the designing in section 2 and 3 was proved reasonable by the simulation and test in section 4 and 5.

6 Discussions

According to the results of dynamic simulation and vibration test, it can be seen that the largest response of the active potential controller came from random vibration. In another word, the response in sine vibration was much slighter than random. It's not accidental.

As is known to all, most damage in vibration test resulted from resonance. In section 3.1, one of the requirements was the fundamental frequency should be over 100Hz. In section 4 it could be got from modal analysis, as 230Hz. But the sine vibration condition in table 1 covered only 4~100Hz. It caused an obvious question-no resonance damage happened in sine vibration test, or, sine vibration test could **not** expose defects of a product. It seems that sine vibration test was not necessary.

In fact, the sine vibration test for payload was due to the sine vibration test for satellites, which simulated the transient events in low frequency. Even that, "the use of a swept-sine excitation to simulate a transient excitation can result in the unique situation of causing a simultaneous under-test and over-test of the hardware. The under-test is due to exciting only one hardware resonance at a time during the sweep-sine test, as opposed to the simultaneous excitation of multiple resonances of the hardware, as would be induced by the transient excitation. The potential over-test is due to applying a larger number of stress cycles to the hardware during the swept-sine test than occurs during the transient excitation.Nevertheless, it is recommended that the practice of using swept-sine tests to simulate low frequency transient excitations for

qualification test purposes be phased-out in favour of direct transient tests.”[6]

7 Conclusions

This paper introduced the design of active potential controller in section 2 and 3 and the analysis and test in section 4 and 5. The latter proved that the tolerance of structure for dynamic environment[7-9].

In this field, decreasing the weight was a key theme. The goal is cutting the cost. But cancelling or improving the sine vibration test could also save a lot cost, if the point in section 6 could be proved, either for the payload or the satellite.

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