ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

RESEARCH ON DUAL-SHAKER SINE VIBRATION CONTROL

Yaoqi FENG[1], Hanping QIU[1]

[1] Dynamic Test Laboratory, BISEE
China Academy of Space Technology (CAST)
yaoqi.feng@yahoo.com

Abstract

This paper analyses and sums up the existing problems which occur in dual-shaker sine vibration testing of large spacecraft structures by using the vibration level controller and the phase controller to control separately the level and phase of two shakers. From this basis, a new method which consists of controlling simultaneously the vibration level and phase of two shakers is proposed for dual-shaker sine vibration control. In the paper, the techniques used to generate the two driving signals, to acquire and process the response data and phase signal, and to control the vibration level and phase of two shakers are described in details. Finally, the paper presents briefly the test results obtained by using the new control method to carry out the sine vibration testing by means of two small shakers, and the test results obtained illustrate that the proposed method can be used for dual-shaker sine vibration testing.

1. INTRODUCTION

The vibration testing of large spacecraft structures has the following characteristics:

- The mass and the size of the structure are big, and the centre of gravity is high.
- The structure is very complex, and the modal density of the structure is very high.
- The test needs to simulate the dynamic interface conditions for the anti-resonance of the launch vehicle from the spacecraft.
- The vibration test system consists of generally two or more than two synchronous excitation shakers.

Therefore, the test condition is very complex, and it makes the dual-shaker vibration test control very difficult [1].

The sine sweep vibration test is one of the important test items of spacecraft environment test. For the time being, the dual-shaker vibration test system, which consists of two 20-ton electric shakers, is used to carry out the large-scale spacecraft's vibration test in CAST. The accurate vibration control is always a difficult issue in dual-shaker sine vibration testing for large spacecraft structures. Therefore, it is very important to do the research on dual-shaker sine vibration control in order to meet the requirement of the spacecraft dynamic test and to improve the test performance.

2. DESCRIPTION OF EXISTING DUAL-SHAKER CONTROL METHOD

2.1 Principle of Dual-Shaker Control

At present, the vibration level controller and phase controller are used to control separately the level and phase of two shakers in the dual-shaker sine vibration testing. The principle of synchronous control consists of two separate control loop as seen in Fig.1.

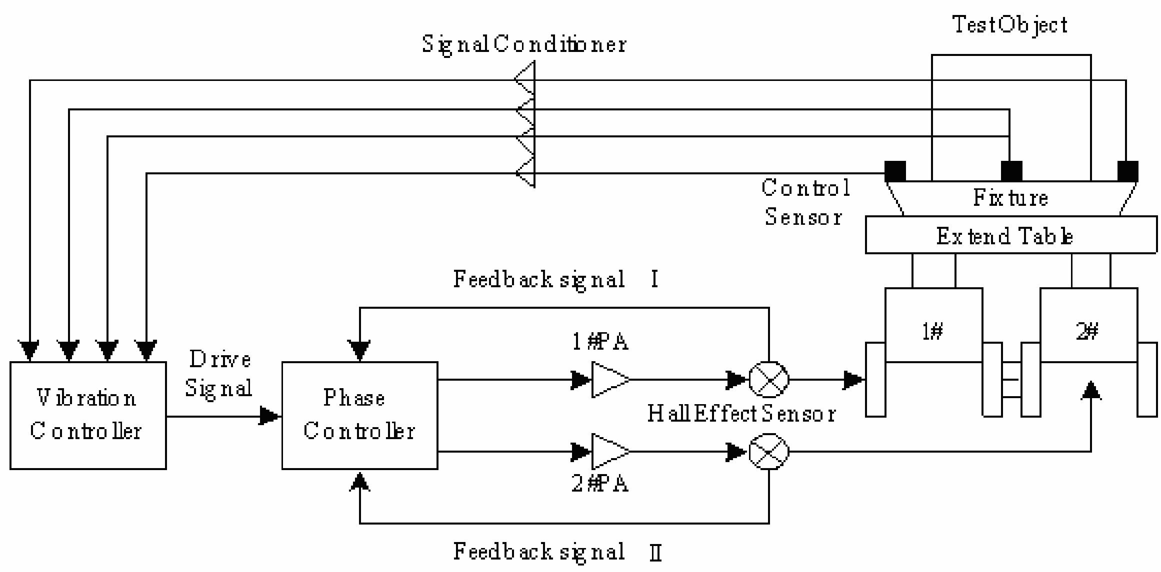

Figure 1. The principle of the dual-shaker's two-closed loop control of amplitude & phase

The outside loop mainly controls the vibration level of two shakers. Normally, the multi-point average control technique is adopted during the test. The vibration level controller calculates the control error in real time according to the difference between the current response spectrum and the test reference spectrum, and it updates continuously the drive spectrum to make the response of the control points correspond to the test reference.

The inside loop mainly controls the vibration phase of two shakers. In order to make the dual shakers vibrate synchronously, the phase controller adjusts the phase of the two driving signals according to the two voltage signals, which are provided by the Hall Effect Sensor and proportional to the driving current of two shakers.

2.2 Problems of Existing Dual-Shaker Control Method

In the existing dual-shaker vibration control system, it is required that the control speed of the vibration controller and the phase controller should be matched. The dependence of the control speed of two controllers results in that it is difficult to update one of them. In consequence, the problem of matching the two controllers should be resolved in the dual-shaker synchronous control.

In addition, there are two control loops during the vibration testing, and in both closed loops, the real time data acquisition and processing of feedback signal should be carried out, which makes the system use more time to finish the task of each control cycle. So, the feedback control speed of system is reduced in some degree, and the control precision of vibration test is affected.

3. NEW IDEA FOR DUAL-SHAKER SYNCHRONOUS CONTROL

Based on the analysis of existing problems described above in two closed loops vibration control system, a new idea for dual-shaker vibration test control is proposed. The principle of new control method is shown in Fig.2.

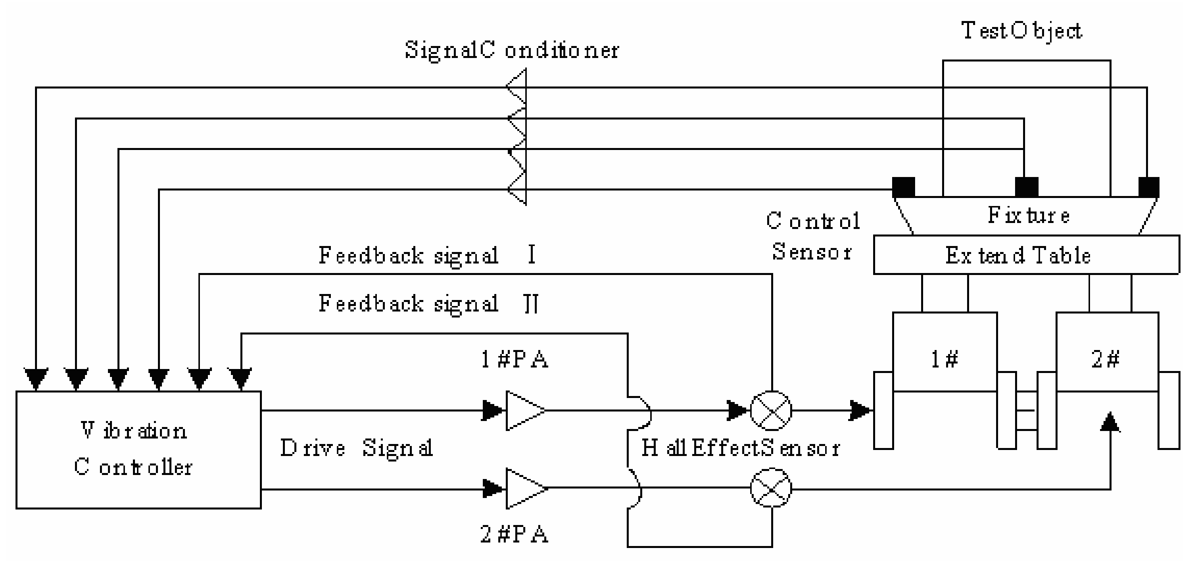

Figure 2. The principle of new synchronous control method for dual-shaker vibration test

Compared with the existing dual-shaker control system, the new method proposes to control simultaneously the vibration level and phase of two shakers in one closed loop. That means the new vibration controller acquires and process not only multi-point response signals, but also two feedback driving signals which pass through the power amplifier. The amplitude and phase of two driving signals are directly controlled by the new controller according to the response level and the phase difference of the two feedback driving signals in order to meet the requirement of synchronous control of dual-shaker sine vibration testing.

4. REALIZATION TECHNIQUES OF NEW CONTROL METHOD

The realization techniques of the new control method for dual shaker sine vibration testing consist of generating the two phased driving signals, acquiring and processing the feedback vibration response signal and driving phase signal, and updating the vibration level and phase of two shakers.

4.1 Generation of Two Phased Driving Signals

The new synchronous control method needs to generate two phased sine driving signals. The generation of the two driving signals is based on the three factors of sine signal: frequency, amplitude, and phase.

Supposing that the frequency and amplitude of the two driving signals are f and $D_{k+1}(f)$, the phase of the two driving signals are φ_1 and φ_2 respectively, and the conversion frequency of digital data to analogue signal is F_s, then the length of sine digital data sequence N_0 for one period can be calculated as following:

$$N_0 = F_s / f \tag{1}$$

Once N_0 is determined, the value of sine sequence $x_1(n)$ and $x_2(n)$ are given by:

$$x_1(n) = D_{k+1}(f)\sin\left(\frac{2\pi n}{N} + \varphi_1\right) \tag{2}$$

$$x_2(n) = D_{k+1}(f)\sin\left(\frac{2\pi n}{N} + \varphi_2\right) \tag{3}$$

Where n=0, 1, 2…N-1 $N = [N_0] + 1$.

The sine digital data sequence obtained by formula (2) and (3) are loaded into DA converter buffer in cyclic order, and then with frequency Fs, the DA converts successively the digital data into analogue signals and generates two continuous sine driving signals which are smoothed by the low-pass filter before outputting to the power amplifier.

4.2 Acquisition & Processing of Response and Phase Signals

For new control method of dual shaker sine vibration testing, the feedback signal acquisition & processing include multiple control point response signals and two driving signals which contain the phase information.

4.2.1 Phase Calculation of Two Feedback Driving Signal

For the sine sweep frequency f_i, the phase of two feedback driving signals can be estimated by tracking filter method. At first, the coherent functions with $\sin(2\pi f_i n\Delta t)$ and $\cos(2\pi f_i n\Delta t)$ of driving signals should be calculated.

$$R_R(0) = \frac{2}{N}\sum_{n=1}^{N} d_n \cos(2\pi f_i n\Delta t) \tag{4}$$

$$R_I(0) = \frac{2}{N}\sum_{n=1}^{N} d_n \sin(2\pi f_i n\Delta t) \tag{5}$$

Where d_n is the nth sample value of driving signal digital sequence.
N is the number of samples in digital sequence of calculation duration.

The amplitude and phase of two driving signals can then be calculated as following:

$$D_i = \left[R_R^2(0) + R_I^2(0)\right]^{1/2} \tag{6}$$

$$\varphi_i = arctg\left[\frac{R_I(0)}{R_R(0)}\right] \tag{7}$$

4.2.2 Amplitude Calculation of Multiple Response Signals

For the amplitude calculation of multiple response signal, besides the tracking filter method described above for the phase calculation of driving signals, three other methods can also be used to obtain the amplitude of the multi-point response signals.

- Peak-value method: $A_p = \max(|a_i|)$ $i = (1,2,......N)$, a_i is the sample value
- Mean value method: $A_{avg} = \frac{\pi}{2} \times \frac{1}{N}\sum_{i=1}^{i=N} |(a_i)|$ $i = (1,2,......N)$
- RMS value method: $A_{RMS} = \sqrt{2} \times \sqrt{\frac{1}{N}\sum_{i=1}^{i=N}(a_i)^2}$ $i = (1,2,......N)$

4.3 Vibration Level and Phase Control

For the new control method, the control process should complete two tasks: one task is the amplitude updating of the driving signals, and the other is the phase correction of the two driving signals.

If the amplitude of the two driving signals is $D_k(f)$ under the exciting frequency f_i, the phase of two driving signals are 0 and φ_2 respectively (the driving signal whose phase is zero is the reference signal). Then the two driving signals can be expressed as follows:

$$x_1(t) = D_k(f)\sin(2\pi f_i t) \tag{8}$$

$$x_2(t) = D_k(f)\sin(2\pi f_i t + \varphi_2) \tag{9}$$

During the test, the phases of the two feedback driving signals are calculated in real time:

$$y_1(t) = D_k(f)\sin(2\pi f_i t + \varphi_1^{'}) \tag{10}$$

$$y_2(t) = D_k(f)\sin(2\pi f_i t + \varphi_2^{'}) \tag{11}$$

Then the phase difference between the two driving signals can be obtained by:

$$\Delta\varphi = \varphi_1^{'} - \varphi_2^{'} \tag{12}$$

The amplitude of two driving signals can be updated according to the system's transfer function $H(f)$ and the multi-point control response error $E_k(f)$. Due to the system's non-linearity and the influence of other errors, the amplitude of driving signal is updated during the test as follows [2]:

$$D_{k+1}(f) = D_k(f) + \alpha \cdot H^{-1}(f) \cdot E_k(f) \qquad (0 \le \alpha \le 1) \tag{13}$$

Where α is the level correction coefficient, it should be carefully chosen because it is directly related to the control precision and the control stability of vibration level.

After the updated amplitude and phase of the two driving signals are obtained, the two driving signals for next sine excitation frequency can be calculated by:

$$x_1^{'}(t) = D_{k+1}(f)\sin(2\pi f_{i+1} t) \tag{14}$$

$$x_2^{'}(t) = D_{k+1}(f)\sin(2\pi f_{i+1} t + \varphi_2 + \gamma \cdot \Delta\varphi) \qquad (0 \le \gamma \le 1) \tag{15}$$

Where γ is the phase correction coefficient, it is directly related to the synchronous control of two shakers.

During the dual-shaker sine vibration testing, by means of the method described above, the amplitude and the phase of two driving signals are corrected and updated in real time. In consequence, the synchronous control of dual-shaker sine vibration testing is realized.

5. VALIDATION TEST OF NEW CONTROL METHOD

5.1 Validation Test System

To validate the new control method, a vibration test system with two small shakers is established. Figure 3 is the schematic diagram of validation test system. The two small shakers and power amplifier used in validation test system are shown in Figure 4.

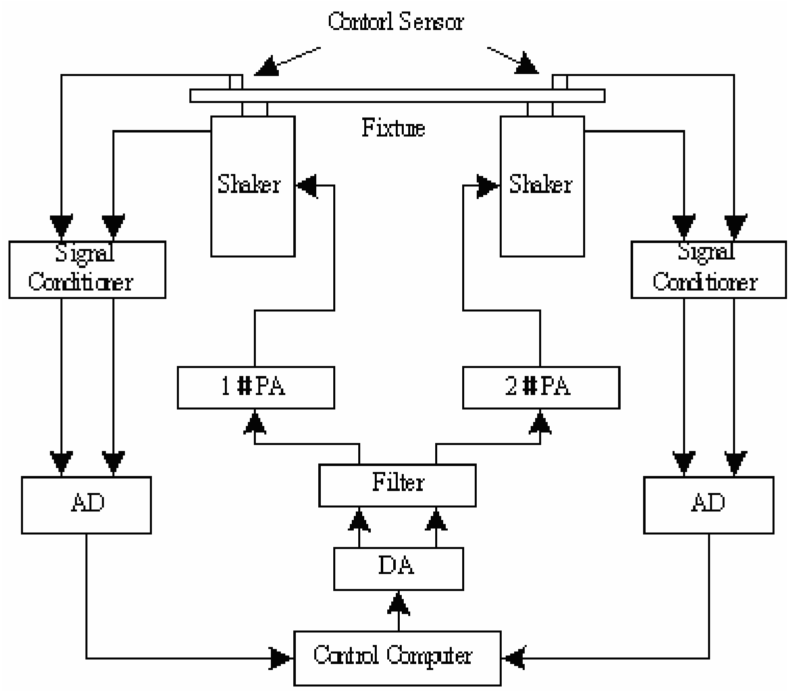

Figure 3. The schematic diagram of validation test system

Figure 4. Two small shakers and power amplifier

5.2 Validation Test

5.2.1 Test Reference

Table 1. Reference spectrum

Frequency (Hz)	Level (g)	Tolerance (dB)
5	0.05	±6
10	0.25	±6
100	0.25	±6
Sweep Rate	2 (oct/min)	

5.2.2 Test Curves

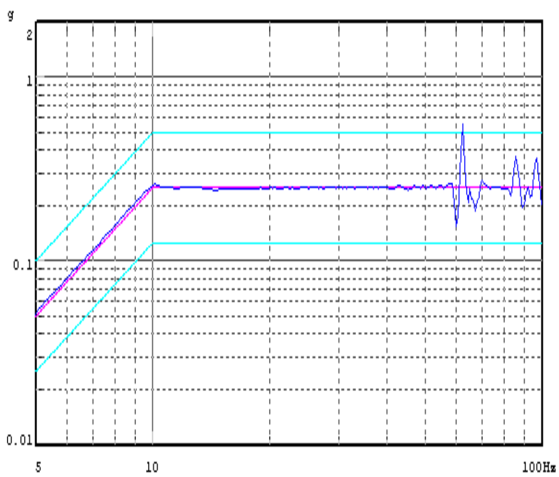

Figure 5. Level control curve (non-phase control)

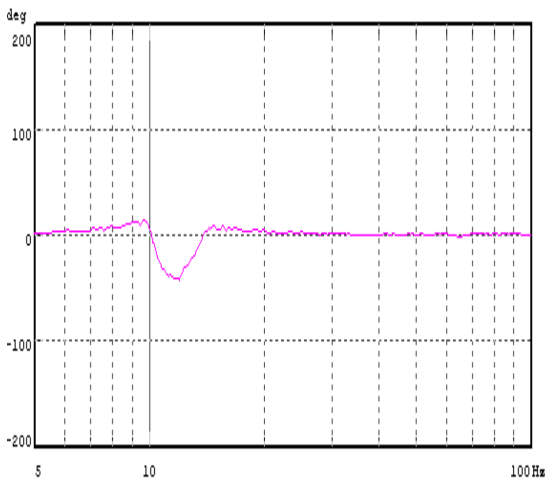

Figure 6. Phase difference (non-phase control)

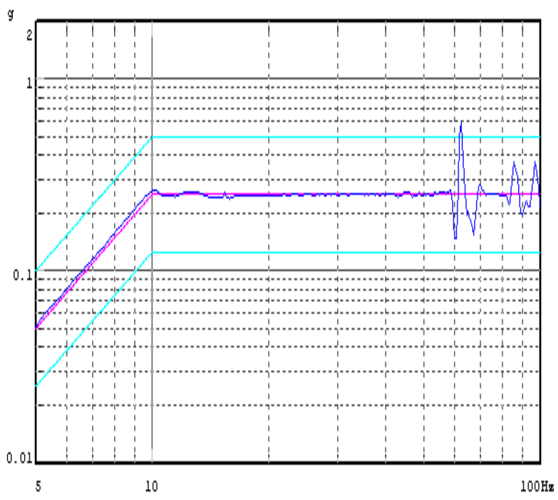

Figure 7. Level control curve (with phase control)

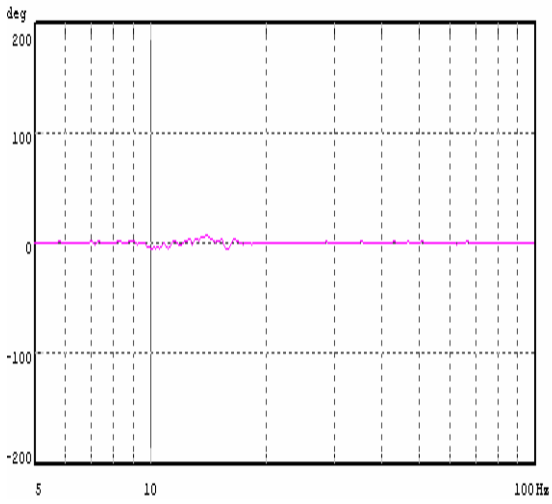

Figure 8. Phase difference (with phase control)

5.2.3 Analysis of the Test Results

Figure 5 and Figure 6 show respectively the vibration level control curve and the vibration phase difference curve of the two shakers obtained in non-phase control test. The maximum vibration phase difference of two shakers during the sine sweep test reaches 42º in this case.

Figure 7 and Figure 8 show respectively the vibration level control curve and the vibration phase difference of the two shakers obtained with the phase control test. In this case, the maximum vibration phase difference of two shakers during the test is reduced to 6.41º.

The validation test results illustrate that the new control method is able not only to control the vibration level, but also to compensate the phase difference of two shakers. So, this control method can meet the requirement of synchronous control of dual-shaker sine vibration testing.

6. CONCLUSION

The control method proposed in this paper can realize synchronous control of dual-shaker sine vibration testing. The application of this method to the vibration environment test of large spacecraft structures can resolve the matching problem of the vibration level controller and the phase controller in dual-shaker sine vibration testing, and can also improve the control precision of dual-shaker sine vibration testing.

REFERENCES

[1] S. Q. Ke, et al., "Satellite environment engineering and simulation test", (Vol.2), Beijing, Space Press, 1996.

[2] T. Keller, M. Underwood. "AN APPLICATION OF MIMO TECHNIQUES TO SATELLITE TESTING" In: Articles of MIMO Vibration Control Techniques Application-Theory and Practice.

[3] G. A. Hamma etc. A Review of Multiaxis/Multiexcitater Vibration Technology. SOUND AND VIBRATION/APRIL 1996.