INFLUENCES OF COUPLE CONTROL POINTS ON MULTIPOINT-RESPONSE-CONTROLLED RANDOM VIBRATION TESTING

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Multipoint response control is a useful and important technique in random vibration testing of large and complex engineering structures, such as aerospace, mechanics and civil engineering and so on. The implementation of a multipoint-response-controlled random vibration testing is influenced by the relationship between multiple control points, in the aftermath of which, pause of the testing or out of control may occur. This paper deals with this situation in which multiple control points in a random vibration testing may affect each other. First, a simulation model is constructed to indicate the influences of couple control points on a multipoint-response-controlled random vibration testing. A six degrees-of-freedom structure is considered, in which the stiffness and the damp of the fifth and sixth degrees-of-freedom sub-structures are coupled with each other. It is found that the first three frequencies of the model are equivalent, but the last three vary largely when the couple exists. The situation will affect the averaged response power spectrum density (PSD) which will be used in the closed loop control in a random vibration test. Secondly, a 10Hz-2000Hz random vibration experiment is conducted. An average control of six points is applied. A sharp peak appears in the control PSD, beyond +3dB reference PSD. Investigation on the relationship of the six control points indicates that the phenomenon may be caused by. Then the six control points are adjusted and adapted in the next testing. In that case, the control PSD matches the reference PSD perfectly. This indicates the key factor should be paid more attention in the similar situation.

Keywords: random vibration, vibration testing, couple, out of control, simulation

1. Introduction

Vibration testing is one of most important environmental tests for engineering structures in many fields, such as aerospace, mechanics and civil engineering and so on. For large and complex structures, multipoint response control in random vibration testing is usually employed, which is to apply a desired load spectrum to the structure through collecting and averaging the response spectrums of multi control points in a closed-loop manner. Therefore, the local responses of control points have important influences on ultimate test results.

Vibration tests are performed to: (1) develop materiel to function in and withstand the vibration exposures of a life cycle including synergistic effects of other environmental factors, materiel duty cycle, and maintenance, (2) verify that materiel will function in and withstand the vibration exposures of a life cycle [1]. Essentially all materiel will experience vibration, whether during manufacture, transportation, maintenance, or operational use. The Sandia National laboratory has developed a software environment integrating analysis and test based models to support optimal modal test design and vibration test design through a Virtual Environment for Test Optimization (VETO). The VETO assists analysis and test engineers in maximizing the value of each modal test or vibration test. It is particularly advantageous for structural dynamics model reconciliation applications [2].

The out-of-control phenomenon of a typical vibration test was reported in [3]. The effects of control points on vibration test were investigated by an out-of-control vibration pre-test and analysis of features of control points. A method to avoid out-of-control for this kind vibration test was presented. Chen [4] studied the influences of some engineering factors on structure response in vibration testing. In addition, some research efforts have been devoted to influence factors of multipoint-response-controlled random vibration testing from various aspects, e.g. the frequency band of control, optimal reference sensor position and dynamic properties of jointed structures [5-7].

Some studies were presented to quantify the effects of control point local responses on random vibration test results by Zhu [8]. A four degrees-of-freedom structure system was considered. The effects of control point local responses were examined by changing the magnitudes of local mass, local stiffness and local damping. In the experimental study, a combined suspension system of missile was considered. A method to avoid out-of-control of vibration testing was given and validated experimentally.

In this paper, the further research is presented to investigate the influences of couple control points on multipoint-response-**c**ontrolled random vibration testing. The paper presents the simulated and experimental studies to quantify the effects of control point local responses on random vibration test results for large and complex structures. In the simulated study, a six degrees-of-freedom model is considered. The effects of control point local responses are examined by changing the magnitudes of both couple stiffness and damping. In the experimental study, an engineering practical product results is applied to show the effects of the couple control points on the vibration testing. A method to avoid over-test or out-of-control of vibration testing is given and validated experimentally. The conclusions are summarized at the end of this paper.

2. Simulated study

2.1 System model

In order to simulate the multipoint-response-**c**ontrolled random vibration testing, a six degrees-of-freedom structure system is considered as shown in Fig. 1. Here, each mass may serves as a random vibration control point.

The control target of a random vibration testing is to keep the measured response power spectrum of system identical to the reference response power spectrum.

From Fig. 1, the mass matrix *M*, the stiffness matrix *K* and the damping matrix *C* of system are written by

$$M=\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 \end{bmatrix},\ K=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 & 0 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 & 0 & 0 \\ 0 & 0 & -k_4 & k_4+k_5+k_6 & -k_5 & -k_6 \\ 0 & 0 & 0 & -k_5 & k_5 & -k_7 \\ 0 & 0 & 0 & -k_6 & -k_7 & k_6 \end{bmatrix},$$

$$C=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 & 0 & 0 \\ -c_2 & c_2+c_3 & -c_3 & 0 & 0 & 0 \\ 0 & -c_3 & c_3+c_4 & -c_4 & 0 & 0 \\ 0 & 0 & -c_4 & c_4+c_5+c_6 & -c_5 & -c_6 \\ 0 & 0 & 0 & -c_5 & c_5 & -c_7 \\ 0 & 0 & 0 & -c_6 & -c_7 & c_6 \end{bmatrix} \quad (1)$$

Where m_i denotes the mass of i-th mass member, k_i denotes the stiffness of i-th spring and c_i denotes the viscous damping coefficient of i-th dashpot.

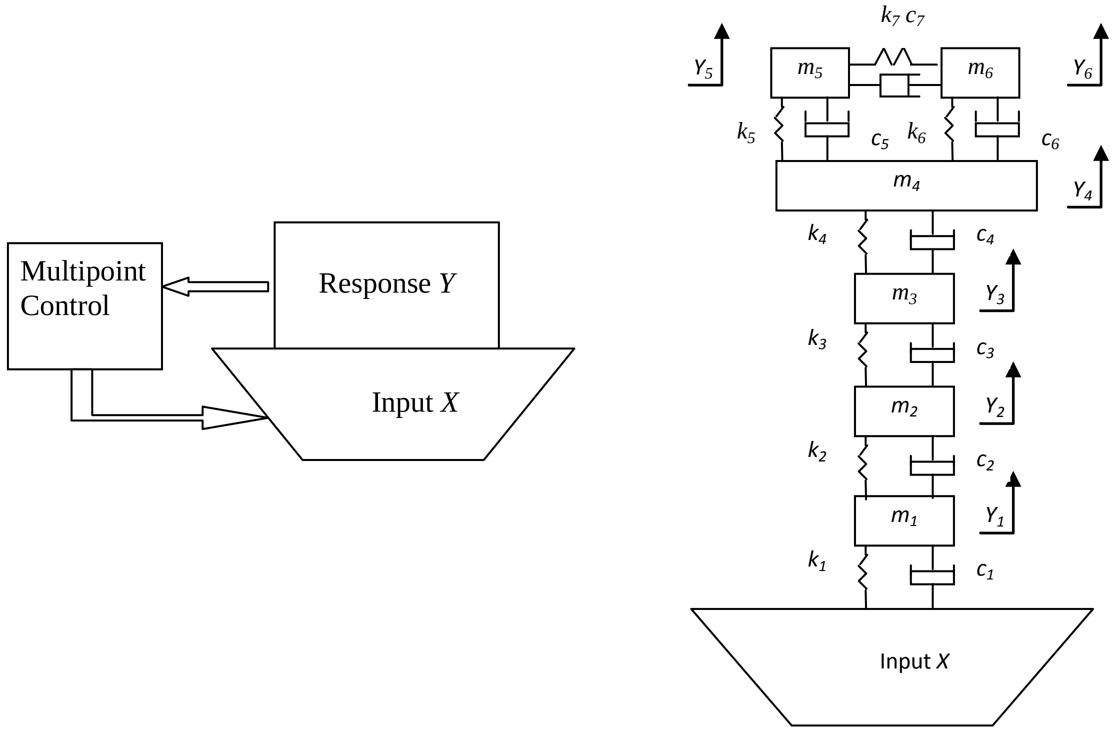

Figure 1: Simulation model for multipoint-response-controlled random vibration testing

According the random vibration theory, the auto-power spectrum response matrix of system can be expressed as

$$S_Y(\omega)=H(\omega)S_X(\omega)H^H(\omega) \quad (2)$$

Where $S_Y(\omega)$ is the auto-power spectrum response matrix of system, $S_X(\omega)$ is the auto-power spectrum input matrix of system, $H(\omega)$ is the transfer function matrix, and the superscript 'H' denotes conjugate transpose.

Assuming the responses of n points in structure are used to control the random vibration testing, then the averaged control power spectrum can be expressed as

$$\overline{S}_Y(\omega)=\frac{1}{n}\sum_{i=1}^{n}S_{Yi}(\omega) \quad (3)$$

Where $S_{Yi}(\omega)$ denotes the response power spectrum of i-th point used to carry out the closed loop control of vibration testing.

2.2 Simulation results

Because the closed loop control of vibration testing is difficulty to simulate in the simulation model, assume the mode is subjected to a base random excitation with input PSD profile shown in Fig. 2.

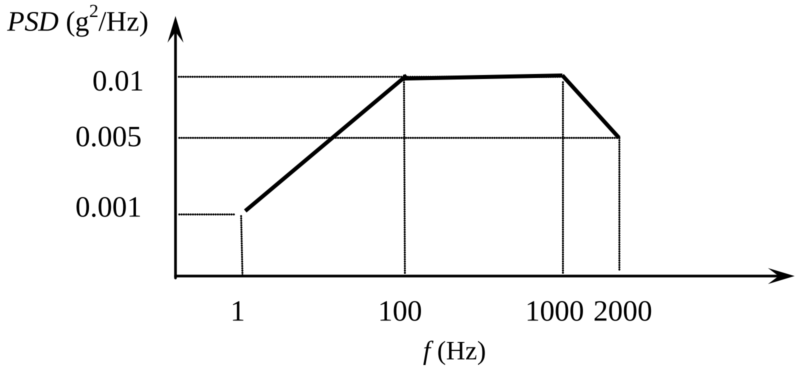

Figure 2: Input power spectrum density of system in simulated study

The original values of mass, stiffness and damping coefficients of system are

$$m_1 = 10Kg, m_2 = 10Kg, m_3 = 10Kg, m_4 = 10Kg, m_5 = 10Kg, m_6 = 10Kg$$
$$k_1 = 100KN/m, k_2 = 100KN/m, k_3 = 100KN/m, k_4 = 100KN/m, k_5 = 8KN/m, k_6 = 12KN/m, k_7 = 6KN/m \quad (4)$$
$$c_1 = 1N/ms^{-1}, c_2 = 1N/ms^{-1}, c_3 = 1N/ms^{-1}, c_4 = 1N/ms^{-1}, c_5 = 1N/ms^{-1}, c_6 = 1N/ms^{-1}, c_7 = 1N/ms^{-1}$$

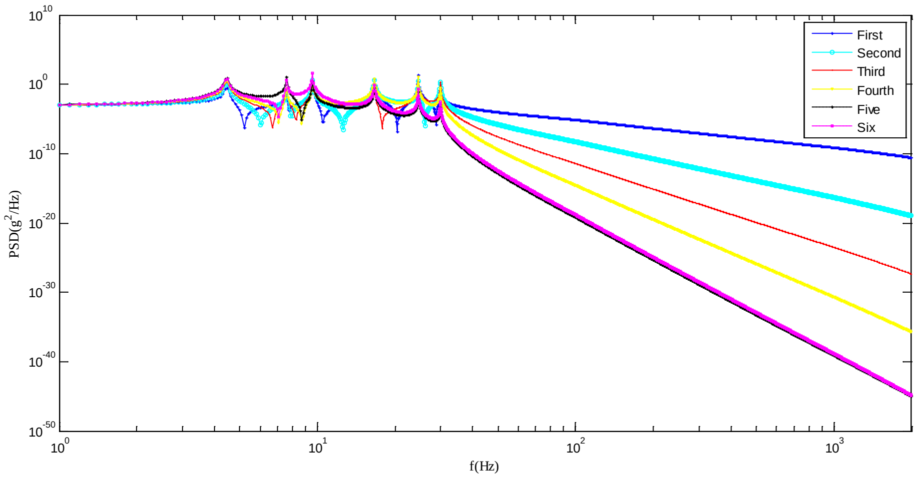

Figure 3: Response PSDs of six points with elements k_7 and c_7 equal 0

The response power spectrums of six masses are simulated and are also used to analysis the affects on the feedback of closed loop control system in random vibration testing. Here, several cases are considered, in each of which only a parameter (mass, stiffness or damping) of specified control point is changed from its original value. Correspondingly, the averaged response power spectrum of system for each case can be used to identify the effects of control point response on vibration testing.

In the simulated model, the major tasks of the results are applied to analysis on the couple elements k_7 and c_7. So the results calculated with elements k_7 and c_7 equal 0 are used to contrast with the results with elements k_7 and c_7 exits.

As an example of the simulated results, figure 3 shows the response PSDs of six control points with elements k_7 and c_7 equal 0. Figure 4 shows response PSDs of six points with couple elements k_7 and c_7. The results show that the difference between Fig. 3 and Fig. 4 can be identified. Six peaks can be identified from Fig. 3 while only five peaks identified from Fig. 4. It is found that the first three frequencies of the model are equivalent, but the last three vary largely when the couple exists. The difference maybe results in the control problem when more control points are applied in one complex random vibration testing.

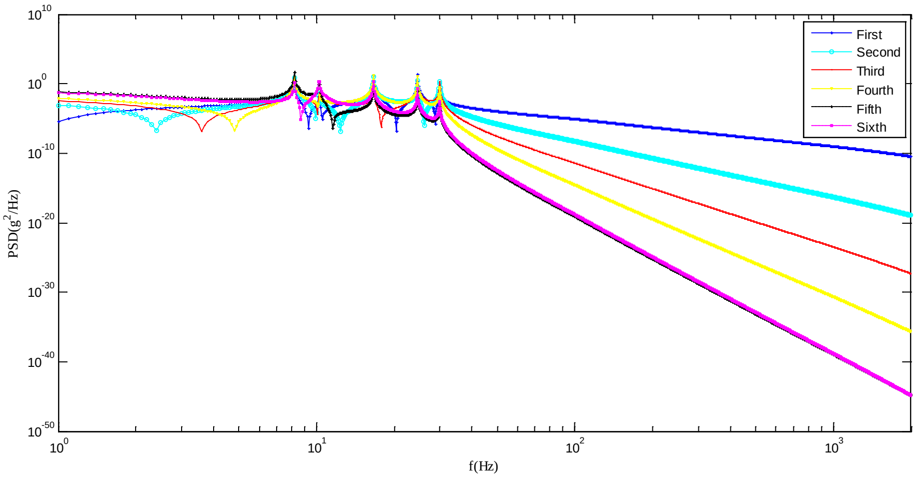

Figure 4: Response PSDs of six points with couple elements k_7 and c_7

It can be seen that the variations of local couple stiffness and damping have pronounced influences on the response power spectrum. The same results can also be observed in some similar situation where the response PSD of multipoint-response-controlled random vibration testing is applied.

3. An experimental study

3.1 The over-test problem with the couple control points

Herein an experimental study is applied to demonstrate the over-test problem with the couple control points. A combined missile is considered in the experimental study.

The random excitation frequency range is 10Hz-2000Hz. A total average PSD of six control points are adapted in the random vibration testing as shown in figure 5. There is a peak which is beyond +3dB reference PSD obviously at the frequency 800 Hz or so. Then this is an over-test situation. Of course, it maybe is not severity situation. In practice +6dB over-test situation test maybe sometimes take place. Here the major objective is used to find the reason for avoiding over-test. Original vibration features of six control points are analyzed to find some better control points.

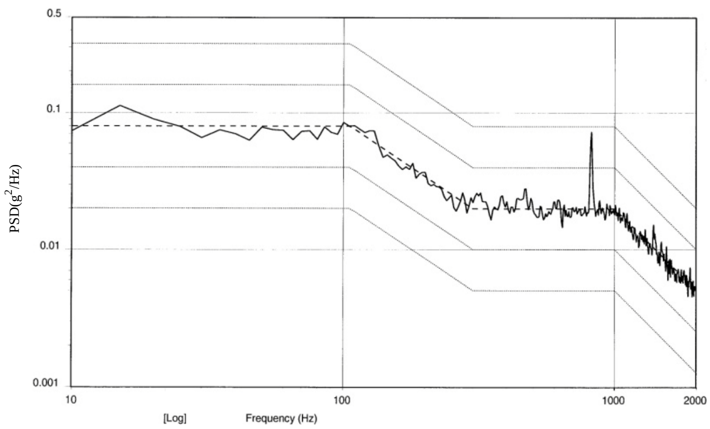

Figure 5: Average control PSD of six points

3.2 Adjusted experiment

In order to identify the effects of random vibration testing on characteristics of structure, a sinusoidal sweep testing with 1 g level is performed. The responses PSDs of six control points are compared. The vibration feature of one of six control points is distinctly different from those of the remained control points, especially at the frequency 800Hz or so. So one of six control points are adjusted to avoided couple with others. Then the six control points are adjusted and adapted in the next testing. Figure 6 shows the average control PSD of six control points adjusted. It is found that the control PSD matches the reference PSD perfectly. As a result, the random vibration testing is fulfilled successfully.

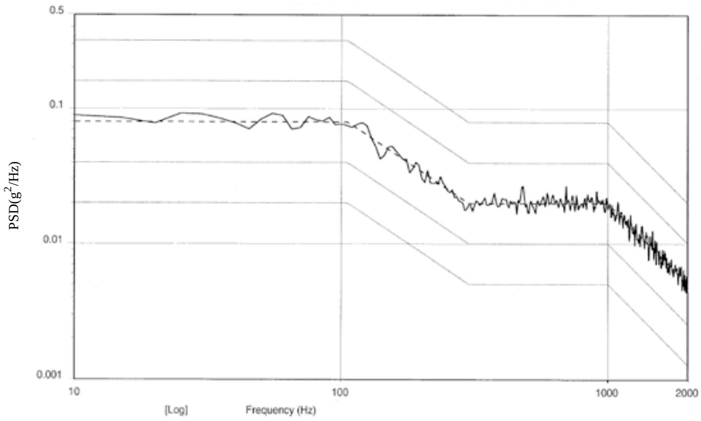

Figure 6: Average control PSD of six points adjusted

4. Conclusions

The influences of couple control points on multipoint-response-controlled random vibration testing have been investigated in the paper. A six degrees-of-freedom model is considered so as to carry out a simulated study. It is found that the variations of local couple stiffness and damping have significant influences on the averaged response power spectrum which will be used in the closed loop control in random vibration testing. The experimental study is conducted on a missile in this study. In the initial testing, it is found that a total average PSD of six control points adapted in the random vibration testing have a sharp peak over +3dB. A sinusoidal sweep testing with 1 g level is performed to find the reason. One of original six control points are adjusted to avoided couple with others. It is found that the control PSD matches the reference PSD well. This indicates that the couple effects of multipoint-response-controlled random vibration testing are the key factor and should be paid more attention.

The couple responses of multipoint-response-controlled random vibration testing result in large over-test or under-test at specific frequencies and locations within a test item. Where the couple responses of multipoint-response-controlled testing occur, the result can be catastrophic, especially when large test items on large complex fixtures are conducted with a testing. Similar problems often occur with small test items, even when the fixture system is well designed because it is very difficult and often impractical to achieve a lowest fixture resonant frequency above 2000 Hz. In cases where the influences of couple control points on multipoint-response-controlled testing cannot be eliminated, consider special vibration control techniques such as acceleration, force limit control or other optional methods. Where the conditions of force control or acceleration limiting control are not easily obtained in many cases, execution of the laboratory test under multipoint-response-controlled random vibration testing based upon the vibration features analysis of control points is an option. Modal surveys of the whole test item can be extremely valuable.

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