The Test and Verification Methods for the Transportation Vibration Absorption System of Spacecraft

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Abstract. The complicated road conditions for the transportation of spacecraft give rise to the need for plenty of running tests so as to validate the performance of the vibration absorption System. According to the principles of subscale test, a research is conducted on the approaches to testing the vibration absorption System for the transportation vibration absorption system of spacecraft. Besides, the subscale model and verification system are designed for the vibration absorption System, and the reliability of the vibration absorption system in transit is validated, which provides a means to conduct effective evaluation of the system for energy efficiency and an approach to the optimization design of it.

1. Introduction

As the aerospace undertakings are undergoing a fast-paced development in China, the number of space missions is on the increase exponentially. Due to the fact that the manufacturing bases of satellites and their launch sites are distributed across different regions, the transportation of aircraft has become a crucial link of type development. Whether the aircraft is transported on highway or by rail, the package used to pack those sophisticated aerospace products would be subjected to various vibrations, which has a potential to affect the sophisticated aerospace products for their performance.

In general, the vehicles used to transport aircraft are complete with a multi-tiered vibration absorption System. For example, tyres, suspension system, as well as the first-tier vibration absorption System and second-tier spring system of rail carriages. Apart from that, the package in itself comes with an independent vibration absorption System. Before transport, the configuration of the vibration absorption System has to be performed based on the characteristics of what is to be transported and the conditions of transport. Nevertheless, the variations of practical driving conditions makes it easy for the vibration data to exceed the specified range when the aircraft is in transit.

The complex conditions of transport lead to an increasingly high requirement on the reliability of aerospace products, as a result of which the development of a testing and verification system as the critical facility to test reliability is increasingly significant. Therefore, it is considered as a critical issue facing the transport of sophisticated aerospace products to construct a subscale model for the package of aerospace products before transport and the vibration absorption System and validate the in-transit reliability of the vibration absorption System.

2. Introduction of the commonly-used methods of testing

Whether at home or abroad, there are two major ways to perform vibration test on transport packaging. One is to load the package onto the vehicle for running test to be conducted in line with the
specifications on road conditions, vehicle type, vehicle state, driving speed and mileage. The other one
is to perform an in-lab simulation experiment to the standard drawn up according to the specific
conditions of transport [1,2].

- On-board test
  The item under tested is loaded onto a vehicle, which is required to drive a certain distance based
on the specified load, speed, as well as road and meteorological conditions. Then, the item is unpacked
to check whether it is intact. The merits include simplicity in operation and intuitiveness of test results.
On the flip side, the drawbacks include expensiveness, long duration, as well as the difficulties in
conducting quantitative analysis and exercising control over the testing conditions.

- Indoor simulation test
  This is premised on a thorough study conducted of the vibration data on the practical conditions of
transport. It shows such merits as low cost of experimentation, quickness, typical experimental
conditions, and easy control. Moreover, it exhibits an excellent reproducibility, which is beneficial to
reduce the time and monetary costs of experimentation. On the flip side, it shows the drawbacks like
high initial cost of investment and demanding requirements technically.

In vibration test, the test piece needs to be excited based on the actual environment of vibration.
According to the nature of the applied load, the test is classed into three different types. The first one
is sinusoidal vibration test, where the test piece is subject to sinusoidal vibration, including sine FM
and swept-sine vibration tests. The second one is randomized vibration test, where the test piece is
subject to random vibration. Based on the size of bandwidth, it can be further classified into broad-
band random vibration test and narrow-band random vibration test. The third one is mixed vibration
test, where the test piece is subject to both sinusoidal vibration and random vibration simultaneously
[3,4]. In transit, the occurrence of vibration is a randomized process. Due to various factors like the
unevenness of road surface, vehicle type, loading, driving speed and so on, the vehicle is subject to
randomized excitation in transit. Therefore, the randomized vibration test is usually performed for
indoor simulation.

3. The design of subscale model
The subscale model is chosen to perform test because some of the aerospace products are
characterized by heavy weight and large volume, which means that it would be costly to use the
original items for testing. Subscale test is known as a commonly-used approach to verification in
engineering. The key to its success lies in the design of a specific subscale model. In principle, the
main experimental data obtained from the model and the prototype system must be close. Therefore,
the verification test shall start with the determination of subscale model based on the geometric
similarity principle and the physical similarity principle, the key to which is to ensure the consistency
of dynamic behavior in between the two [5,6]. Geometric similarity refers to that the subscale model
has a similar aspect ratio and a similar way of connection to the shock absorber to the prototype test
piece, while physical similarity is to ensure that the subscale model shows similar characteristics of
vibration to the original one, with consideration primarily given to the similar natural frequency of
subscale model to the original one.

For the vibration absorption System of aircraft transport, the mathematical model could be
simplified into a SDOF spring-quality system with damping. The packaging used for aircraft transport
is installed in the rear of the vibration table, which is connected to a model of it that is constructed
based on the model of a single packaging box. As the the vibration table is purposed to simulate the
vibration output of the bottom plate in the carriage, the mathematical model of the vibration absorption
System for the packing box can be simplified into a SDOF spring-quality system with damping and
classified as foundation vibration, as shown in Figure 1.
The subscale model has a similar kinetic equation to the actual system, as a result of which the performance of the vibration absorption System obtained from the random test is sufficient to indicate that of the real system. Thus, a reasonable design of the parameters for the subscale model is essential, including mass denoted as m, rigidity denoted as k and damping denoted as c

- Simulation of the packaging box (m indicating mass)

As the packaging box is considered as rigid, consideration is primarily given to the mass and rigidity of the packaging box for the subscale model. With dimensions concerned, the connection to the vibration absorber needs to be considered in the first place, followed by the shape of the packaging box. Therefore, to achieve the purpose of simulation, a similar container to the packaging box can be used to be stuffed with what is easily changeable in mass.

- Selection of the shock absorber (k indicating rigidity and c indicating damping)

When the working characteristics of the vibration absorption System are identical to the real system, m and k can be obtained from the identical first-step natural frequency of the system, with the damping ratio unchanged. Otherwise, the interval with insignificant variation shall be taken wherever practical to perform test. The variation in response between the subscale model and the real model is calculated and rectified after experimentation.

4. Design of the testing and verification system for vibration isolation of aircraft transport

4.1. The overall plan

The testing and verification system is designed to validate the effectiveness of vibration isolation under the specified shock spectrum for the packaging box used for aircraft transport, and to provide guidance on how to optimize the vibration absorption System. Placed on the table of the verification system is a subscale model of the packaging box with a vibration absorption System. In the test, the bottom plate of carriage is subject to random vibration and then the output response is measured on the table. In doing so, the performance of the vibration absorption System is validated.

The rationale behind the verification system is shown in Figure 2. The signal generator is responsible for sending off the signal required by the verification system. The power amplifier is to amplify the current and voltage provided by the signal generator for the exciter, which provides the exciting force for the vibration table according to the input of the signal generator. The vibration table is the source of vibration for the system, that is to say, vibration stems from the table before the excitation spectrum is specified. The measurement and control system is purposed to measure the vibration value and exercise control of the exciter, so as to achieve the expected output of vibration load.
4.2. The schematic diagram of the system

Figure 3 shows the schematic diagram of the verification system. In the subscale vibration absorption System, the air spring shock absorber with in-built dampers is taken as the component of vibration isolation. In order to improve the state of loading, the dampers are deployed at an angle in pairs, as shown in Figure 4.

4.3. Design of the excitation system

4.3.1. Excitation system. The excitation system represents the core equipment of the vibration test. In order for the occurrence of expected and controllable vibration that the test piece would be subject to, the excitation system is required to be capable of providing the alternating force with excellent waveform and sufficient amplitude and a certain steady force within the specified range of frequency. The former gives rise to acceleration speed for the test piece and the latter offsets the self-weight of it. In terms of power source, the excitation system can be either electrical, mechanical or hydraulic. The electrical excitation system is characterized by high frequency, excellent waveform, easy control and
low capacity of single loading, which makes it suitable for the applications where the dynamic analysis and testing of components are required, such as aerospace, electrical instruments, auto parts and the likes. The hydraulic excitation system is characterized by ultra-low frequency, high excitation force and strong loading capacity, which makes it suitable for the applications where the reliability test has to be conducted on the heavy-weight and massive components or host equipment, such as shipbuilding, locomotive manufacture and car making. The mechanical excitation system is characterized by low frequency, high capacity, poor waveform and cheap affordability, which makes it suitable for the applications where the vibration resistance test is required, such as home appliance and instruments. Based on the above analysis, the electrical excitation system is chosen for the purpose of verification.

4.3.2. The main parameters of the vibration testing system. For an excitation system, the major parameters include the maximum thrust, the range of working frequency, the maximum load and the maximum acceleration speed. The selection and use of an excitation system require a full consideration given to these parameters as referred to above. The relationship between thrust and acceleration speed is expressed as follows.

\[ F = (m_1 + m_2) a \]  

(1)

\( F \) represents the thrust generated by the vibration table, with the unit of N or kgf
\( m_1 \) indicates the mass of moving components, with the unit of kg
\( m_2 \) indicates the mass of the test piece and the fixture, with the unit of kg
\( a \) indicates the acceleration speed, with the unit of \( \text{m/s}^2 \) or \( \text{g} \)

The maximum acceleration speed of the excitation is based on no load. When load is applied, the maximum acceleration speed that can be achieved by the vibration table is less than when no load is applied. Besides, the extent of reduction relates to the load. Figure 5 shows the relationship between the thrust, load and acceleration speed.

\[ T = \begin{cases} \text{The zone of useful thrust} \\
\text{The line of the maximum thrust} \end{cases} \]

![Figure 5. The relationship between the thrust, load and acceleration speed](image)

In the case of sinusoidal vibration, the relationship between displacement, speed, as well as the amplitude value and frequency of acceleration speed is as follows.

\[ V = \omega A = \frac{2\pi Af}{10^3} (\text{m/s}) \]  

(2)

\[ a = \omega^2 A = \frac{A(2\pi f)^2}{10^3} = 2\pi fV (\text{m/s}^2) \]  

(3)

\( a \) means the amplitude of acceleration speed in \( \text{m/s}^2 \)
\( A \) indicates the amplitude of displacement in mm
\( f \) denotes frequency in Hz

It is a common practice that the multiple of gravity acceleration speed is taken to denote the acceleration speed. Therefore, equation 3 can be rewritten as:
\[ a = \frac{A(2\pi f)^2}{9.8 \times 10^3} \times 0.004Af^2 \text{ (g)} \]  

(4)

A set of parameters of DY-300 that are designed specifically for the low-frequency transport test are shown in Table 1.

| Element                        | Style             |
|--------------------------------|-------------------|
| Range of vibration frequency   | 2-2000 HZ         |
| Rated sinusoidal thrust        | 2.94 KN           |
| Rated random thrust            | 2.058rms          |
| Maximum acceleration speed     | 367 m/s²          |
| Maximum speed                  | 1.50 m/s          |
| Maximum displacement           | 40mm              |
| Maximum load                   | 130 kg            |
| Mass of moving component       | 8 kg              |

Table 1. The parameter of the DY-300 electrical vibration table article.

Based on the parameters shown in Table 1, an analysis can be conducted of the basic performance of this excitation system. Further with this, it can be judged whether or not the requirements on package vibration test can be met. Meanwhile, equation 2 is used to calculate the maximum displacement and the crossover frequency at the maximum speed.

\[ f_{AV} = \frac{V \times 10^3}{2\pi A} = \frac{1.5 \times 10^3}{2\pi \times 20} = 11.9 \text{ (Hz)} \]  

(5)

Equation 3 is used to calculate the maximum speed and the crossover frequency at the maximum speed.

\[ f_{V_{av}} = \frac{a}{2\pi V} = 38.9 \text{ (Hz)} \]  

(6)

The DY-300 electrical vibration table can reach the maximum displacement at 11.9 HZ, the maximum speed at the range between 11.9 HZ and 38.9 HZ, and the maximum acceleration speed only at a frequency that is above 38.9 HZ.

An analysis is conducted of the impact of load on the output maximum acceleration speed of the vibration table. When the weight of the sample reaches the maximum load of 130kg, according to equation 3,

\[ a_{\text{max}} = \frac{F_{\text{max}}}{m_1 + m_2} = \frac{2.94 \times 10^3}{8 + 130} = 21.3 \text{ (m/s}^2) \]  

At this time, the maximum acceleration speed of the vibration table declines from 36.7 m/s² when there is no load to 21.3 m/s².

According to the applicable national standard, for tests conducted on cushion materials and packaging pieces, the vibration table is required to provide either fixed-frequency or swept-frequency vibration, with a fix acceleration of 0.5g and frequency ranging from 3 HZ to 100 HZ. The DY-300 electrical vibration table is capable to meet these requirements.

4.4. Design of the subscale vibration absorption System

4.4.1. Technical route. The technical route is shown in Figure 6.
4.4.2. The subscale model of the packaging box. The subscale model of the box is substituted with a rigid container, which can be filled with discrete object to adjust the overall mass.

4.4.3. Design of the subscale vibration absorption System. As the rigidity of the air spring is adjustable and significantly variable, a set of air springs can be applied to simulate the springs used in the vibration absorption System for packaging box in most cases. The air spring vibration absorption System consists of air springs, damper and rigidity-adjusting device. The air-adjusting device is controlled via a touch screen and is capable of making automatic adjustment of gas pressure based on the target value. Figure 7 shows the layout of the control panel.

Figure 6. Technical route

Figure 7. The layout of the control panel for the rigidity-adjusting device

4.4.4. Design of the data collection system and analysis system. A wireless data collection system is used to ensure convenience and reliability of testing on the relevant data. The JM5842 wireless testing device for acceleration speed is capable to meet the relevant requirements on testing.
5. The expected effect of the testing and verification system
Prior to transport, the quality of products to be transported and the conditions of transport are evaluated as input for testing and verification. The testing and verification system is applied to perform simulation of the vibration absorption System and identify the most appropriate layout of shock absorber deployment, which is beneficial to avoid the repeated running test that has to be conducted each time prior to transport, thus reducing labor and monetary costs.

6. Conclusion
By conducting a research into the approach to testing and verifying the vibration absorption System for the packaging of aerospace products, the simulation test table of vibration absorption System is designed and the vertical excitation that is similar to the bottom plate of carriage box is generated on the table. An environmental vibration test is conducted on the vibration absorption System, which provides a means to conduct effective evaluation of the system for energy efficiency and an approach to the optimization design of it.

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