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Research on Characteristics of Spacecraft Transport Dynamics Ambient Excitation Based on Conditions of Highway and Railway Transportation

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Abstract. Based on the highway and railway transportation conditions of several spacecraft from Beijing to launch site, the dynamics environment data acquisition scheme is designed. The response values of sensors before vibration reduction of transport packaging box are collected throughout the whole process. The power spectral density is obtained by filtering and Fourier transform, and the peak response frequency of the excitation source of spacecraft transportation environment is analyzed. It can be used as the basis for the design of vibration reduction system for spacecraft transportation, and some suggestions for the optimization design of vibration reduction system are put forward.

1. Introduction

Spacecraft transport is a significant link during the manufacturing process of spacecraft, which mainly contains 3 kinds of conditions, namely deck transport, cabin transport and whole-spacecraft transport, especially under the whole-spacecraft transport condition, which is a quasi-launching condition, vibration environment evoked by transport will have potential influences on the satellite, especially large-scale structural components, so it is a complex condition with high requirements on mechanical environment[1]. After all works of the development stage at the developing area, spacecrafts need to be sent to the launching site for final works before launching, different and complex operating conditions like automobiles and trains, etc. will be experienced during the transportation processes, so it is significant to guarantee a safe mechanical environment during the transportation processes of spacecrafts, as it is directly related to the development of works in the satellite launch site.

With the development of spacecraft development technologies, the transportation states become increasingly complex, and requirements on transportation mechanical environment keep being higher. Generally, vibration transmissibility is reduced by installing an absorber at the pedestal of packaging boxes, which can realize a damping effect. At present, during the designing process of spacecraft transportation packaging boxes, due to insufficiencies in characteristic analysis on external expiation sources, amplification phenomenon may happen to some points of spacecrafts after vibration attenuation through shock mitigation system during the transportation process, which may have certain influences on transportation safety of the spacecrafts, so it is in urgent demands to research the ambient excitation characteristics during spacecraft transport based on operating conditions of highway and railway transportation[2,3].

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2. Research on Necessity of Excittion Characteristic Analysis

Damping effect of spacecraft transportation system is directly reflected by the vibration transmissibility, which is defined as the specific value of response amplitude X_0 and input excitation amplitude X_i, and the standard model of single steel wirerope absorber is composed of a linear spring with rigidity of K and a damper system with damping of C, as shown in Figure 1.

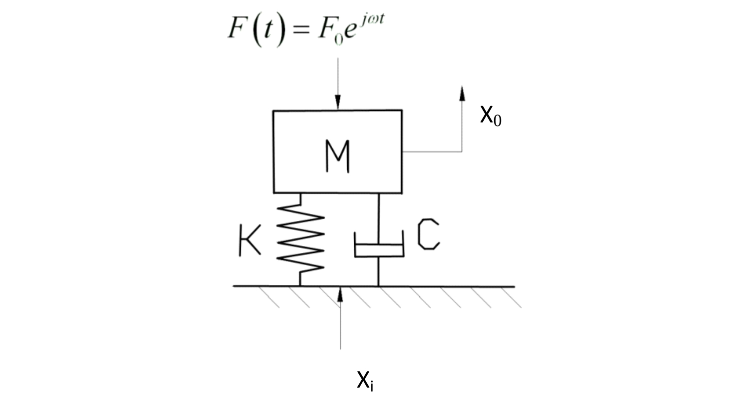

Figure 1. Unidirection model.

Motion equation of vibration isolation system is:

$$M \cdot \ddot{X} + C \cdot \dot{X} + K \cdot X = F_0 \cdot e^{j\omega t} \tag{1}$$

The most common physical quantity to describe and evaluate vibration isolation effect is the vibration transfer coefficient T, and under steady-state sinusoidal excitation, transmissibility T is:

$$T = \frac{X_0}{X_i} = \sqrt{\frac{1+(2\lambda\zeta)^2}{(1-\lambda^2)^2+(2\lambda\zeta)^2}} \tag{2}$$

$\lambda=\omega/\omega_0$, λ is the frequency ratio, ω is the forced vibrational frequency, ω/ω_0 is the inherent frequency of natural vibration, $\zeta=C/C_c$, ζ is the damping ratio of vibration system, and C_c is the critical damping coefficient.

It can be known that vibration transmissibility is influenced by frequency ratio λ, when frequency ratio $\lambda<\sqrt{2}$, T>1, and the vibration is amplified; when frequency ratio $\lambda=1$, T is at its maximum value, and there is resonance; frequency ratio λ continues amplifying, then frequency ratio T will gradually decrease; when frequency ratio $\lambda>\sqrt{2}$, then T<1, and the vibration damper will come into play[4].

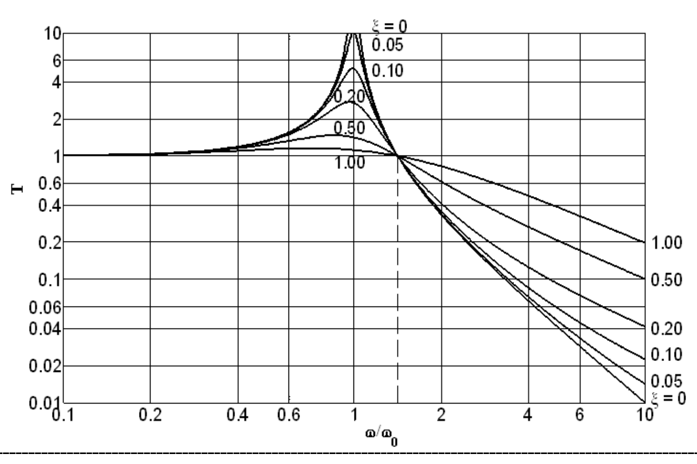

Figure 2. Reelationship between transmissibility, frequency and damping.

Based on Figure 2, when $\lambda=\omega/\omega_0>\sqrt{2}$, the shock mitigation system can be confirmed to keep away from the resonance region and meanwhile has a good vibration damping performance, if the interfering frequency ω of the system is low, the system can hardly fulfill the requirement of $\omega/\omega_0>\sqrt{2}$ when designing, so vibration response of the system must be restrained through increasing the damping of vibration isolation system. It is in urgent demand to know about the ambient excitation frequency during the transportation process of spacecrafts with complex operating conditions, while as spacecrafts are installed in the spacecraft transportation packaging boxes, which are fixed to the automobiles or trains during transportation process, existing road spectrums of highways and railways with different classifications have no referential significance on the shock mitigation system of spacecraft packaging boxes, excitation sources of shock mitigation system should be the response of upper surfaced of automobiles and train carriages, thus it will be of significant meanings on optimization of vibration damping performance of spacecraft packages and improvement of reliability of spacecraft transport to have deep analysis on excitation sources of spacecraft transportation packaging boxes under different road conditions and modes of transportation.

3. Brief Introduction of Spacecraft Transportation System

Spacecraft transportation system mainly contains 3 parts: spacecraft, packaging box and packaging box shock mitigation system, transport vehicle and vehicle shock mitigation system, as shown in Figure 3. The spacecraft is installed in the packaging box through an adapter bracket, a shock mitigation system is arranged between the adapter bracket and baseplate of the packaging box, and the whole packaging box is fixed to the carrier vehicle by a fixing device, during the transportation process, vibrations and impacts caused by road surface on the spacecraft during transportation process will be reduced by the double-layer effect of the shock mitigation system of the vehicle and packaging box.

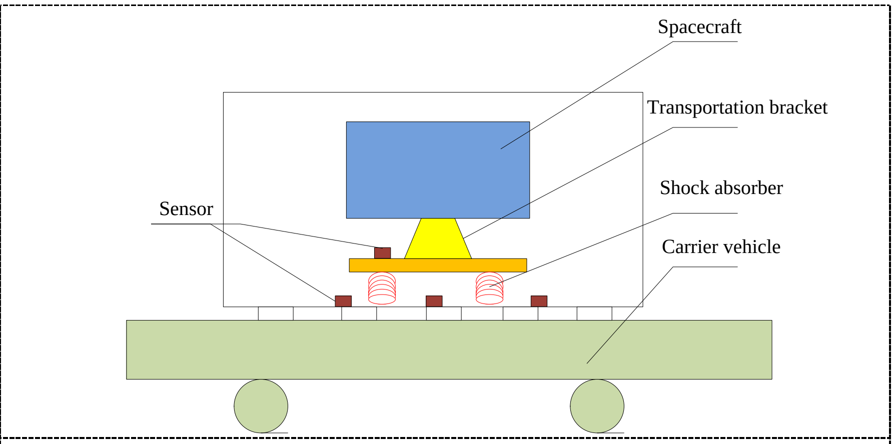

Figure 3. Sketch map of spacecrraft transportation system.

3.1. Road condition

Road conditions during spacecraft transportation process mainly contain those of highways and railways. Highways contain expressways, first-class highways and second-class highways, on which speed of transport vehicles is generally 30~60Km/h[5]; railway classifications contain Class-I or Class-II passenger-freight co-Line railways, on which speed of transport vehicles is generally no higher than 90Km/h[6], and traveling distance of the whole course is 800km.

3.2. Transport vehicles

Transport vehicles contain highway and railway transport vehicles. Highway transport vehicles are large-scale carrier vehicles purposely made by some brand, which come with an air-fuel mixture shock mitigation system that can effectively isolate the vibrations and impacts from road surface, as shown in Figure 4. Railway transport vehicles are railway flatcars, whose main vehicle model is NX17 series, it is with a full-wood floor structure, and there is no special vibration damper inside it[7] , as shown in Figure 5.

Figure 4. Motor transport of packaging box.

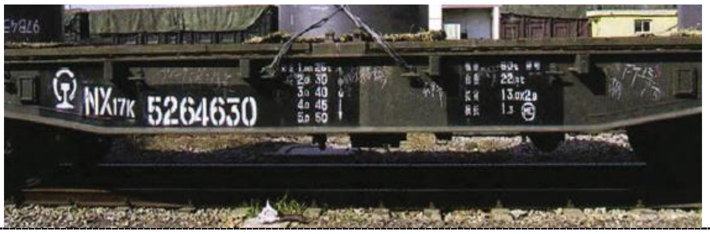

Figure 5. Railway transport flatcar of packaging box.

3.3. Spacecraft transportation packaging box

Spacecraft packaging box is the carrier of spacecraft transport, integrated design is conducted on packaging boxes integrated with demands of satellite development and transport based on universalization and integration theories, which can not only take whole-course highway and railway transportation of spacecraft into consideration, meanwhile it also realizes functions like controllable inside-box temperature and whole-course real-time monitoring of environmental data, etc. for the spacecraft under extreme environmental conditions, thus guaranteeing the environmental safety of spacecraft transport.

Built-in vibration attenuation mode is adopted by the packaging box shock mitigation system, the shock absorber is arranged between the adapter bracket and packaging box of the spacecraft, whose significant characteristics lie in its small volume, simple arrangement and good universality. The spring most widely used by built-in vibration attenuation mode is the steel wirerope spring, which is basically the same as the vibration attenuation mode of spacecraft transportation packaging boxes home and abroad. Figure 6 shows the sketch map of transportation packaging box and shock mitigation system of a foreign spacecraft with a certain model.

Figure 6. Transportation mode of JWST and GOCE satelite of ESA.

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4. Excitation Analytic Data Acquisition

Excitation source of spacecraft transport is the response of upper surface of the vehicle, so the shock mitigation system of transport vehicle is not needed, only shock mitigation system of packaging boxes needs to be considered. In the packaging box shock mitigation system during spacecraft transport, data measured through the vibrating sensor at the bottom of packaging boxes is used as the input source of the shocking mitigation system, computation study is made on the shock excitation spectral characteristics under different operating conditions with data of highway and railway transportation with some model as analytic basis, so as to analyze the characteristics of ambient excitation of spacecraft transport.

4.1. Distribution of measure points of transportation packaging boxes

Totally 3 mechanical sensors are set before vibration attenuation during the transportation process, and responses of the 3 points before vibration attenuation (piont 1, piont 2 and piont 3) are mainly analyzed. Figure 7 shows the measuring points of sensors.

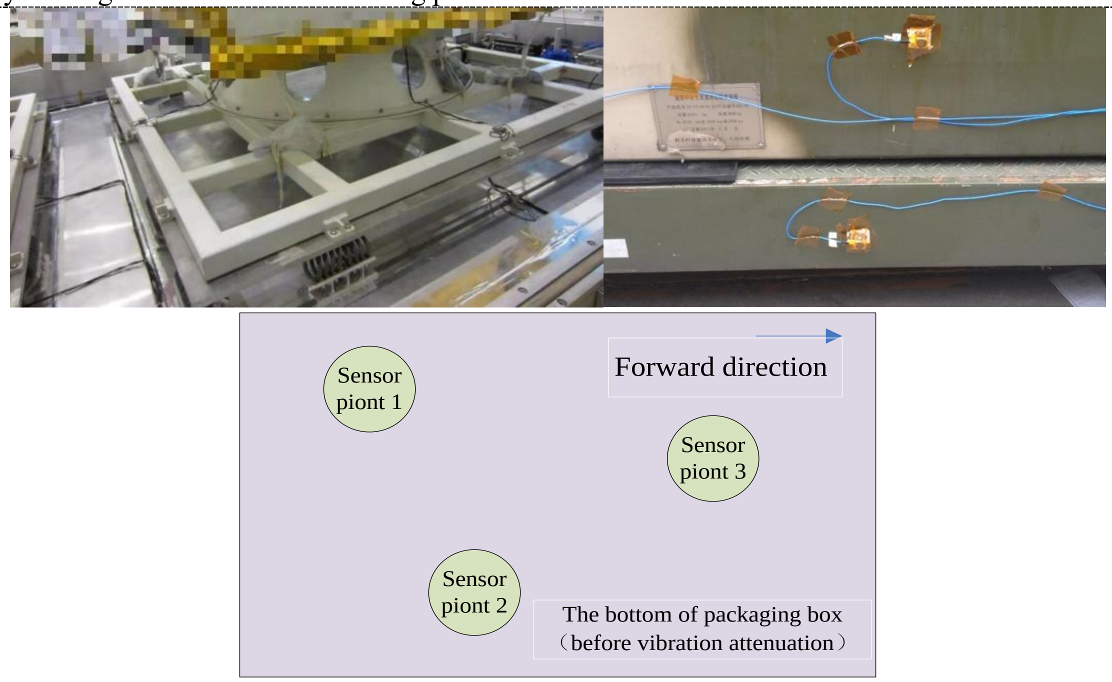

Figure 7. The measuring points of sensors on packaging box.

4.2. Test system conditions

The test system can conduct real-time monitoring on information like vibration, running speed and position, etc. inside the packaging boxes, the piezoelectricity acceleration sensor and signal conditioner of the 3 three-axial direction built-in ICs are connected by low-noise coaxial cables, data of all sensors collected by the main engine is stored in the memory spaces of each channel, meanwhile it is connected with the laptop through the form of Ethernet TCP/IP, which can display the measured real-time data on the computer of the carriage. Monitors conduct curvilinear playback, spectral analysis and power spectral density analysis, etc. on the collected data through data acquisition and analysis software. Figure 8 shows the sketch map of monitoring system composition.

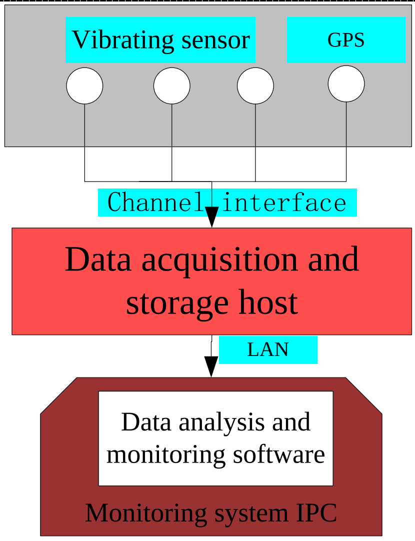

Figure 8. Sketch map of monitoring system composition.

4.3. Data processing

During the test process, packaging box data acquisition system is used to collect the signals during the transportation process, a high-pass filter is adopted to filter the mingled low-frequency noise ingredients in the signals, and FFT is adopted to acquire the PSD curve during transportation process, then analyze the PSD curve and acquire the peak value response frequency, which is the peak value response frequency of ambient excitation source during spacecraft transport. Detailed treatment scheme is shown in Figure 9.

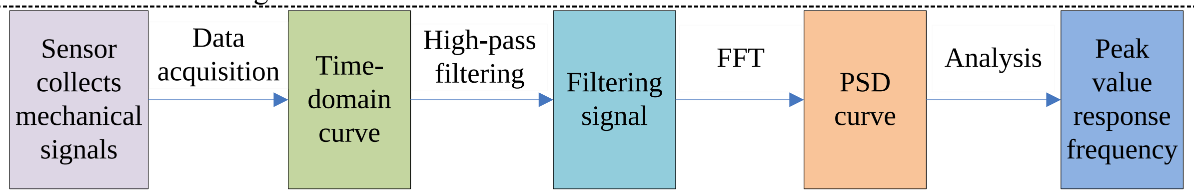

Figure 9. Data processing flow.

4.4. Analysis on applicability of excitation source data towards different spacecraft transportations

Excitation source of packaging box shock mitigation system is the response of upper surface of transport vehicles, when transport vehicles convey spacecrafts with different weights, excitation sources of packaging box shock mitigation system will also change relevantly, to guarantee the universality of the excitation source on different spacecraft transportations, influences of changes in spacecraft weight on changes of excitation need to be researched.

Generally the total weight of a middle-large packaging box of spacecraft is over 10t, and the weight of a spacecraft (remote sensing satellite) is generally 2t~3t, difference among weights of different spacecrafts is about 1t, when transport vehicles are conveying spacecrafts with different models, variation in the weight of carrier is about 7% of the total weight, thus the weight of spacecraft takes a small proportion in the whole transportation system, and it is thought that change in weight of spacecrafts will not affect the ambient excitation of spacecraft transportation.

5. Excitation Analysis of Highway Transportation

Conduct spectral analysis on the time-domain curves of the 3 measure points collected through operating conditions of highway transportation, vibration acceleration spectrum density curves of measure point 1-3 can be seen in Figure 10-12, where vertical acceleration is far higher than that in the forward and lateral direction, and frequency components are concentrated on 2.2Hz, 4.2Hz and 11Hz; difference value of three-way acceleration PSD at measure point 1 and 2, namely the power density spectrum of angular acceleration on baseplate of packaging box is shown in Figure 13, and angular acceleration generated through difference in Z-direction acceleration is far larger than the angular velocity generated through difference in Y-direction angular acceleration.

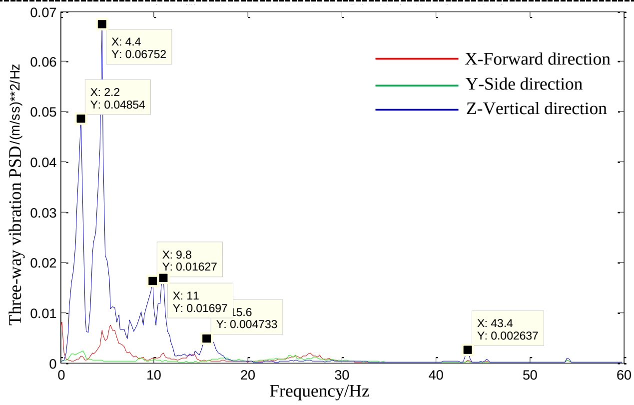

Figure 10. Vibration acceleration PSD spectral line of measure point 1 during highway transportation.

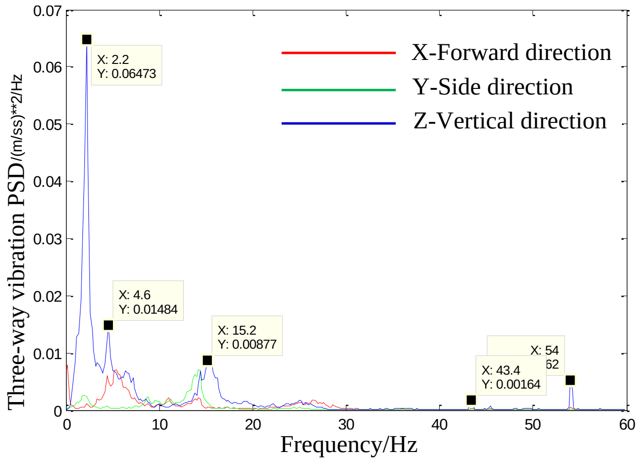

Figure 11. Vibration acceleration PSD spectral line of measure point 2 during highway transportation.

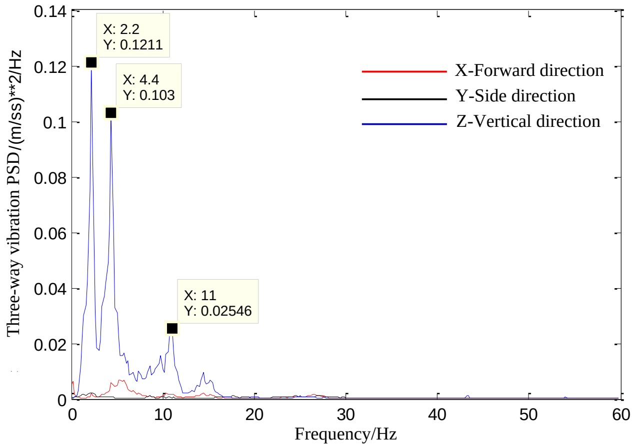

Figure 12. Vibration acceleration PSD spectral line of measure point 3 during highway transportation.

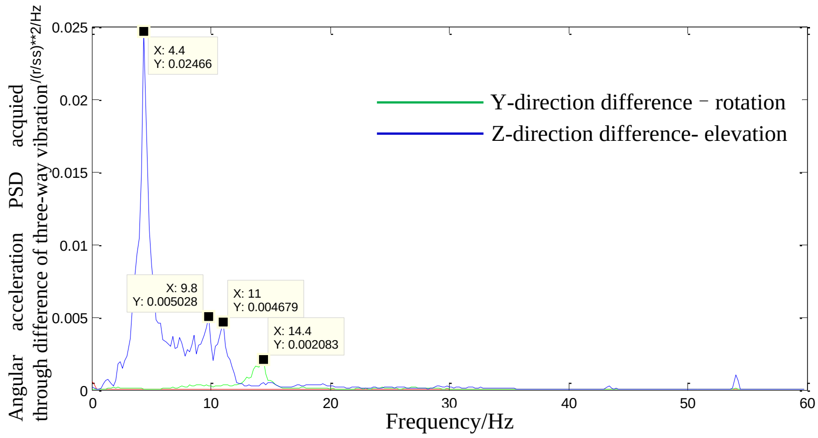

Figure 13. Angular velocity PSD spectral line of packaging box baseplate.

6. Railway transport excitation analysis

The vibration acceleration spectrum density curves at the 3 measure points of operating conditions during railway transport are shown in Figure 14-16, the vertical acceleration is far larger than that of forward and side direction, and the frequency components are concentrated on 1.8Hz and 6.2Hz. Difference value of three-way acceleration PSD of measure point 1 and 2, namely the angular acceleration power density spectrum of packaging box baseplate is shown in Figure 17. Angular acceleration generated through difference in Z-direction acceleration is far larger than that generated through difference in Y-direction angular acceleration, and frequency components are concentrated on 2.2Hz, 6.6Hz, 8.6Hz, 9.8Hz and 11.4Hz.

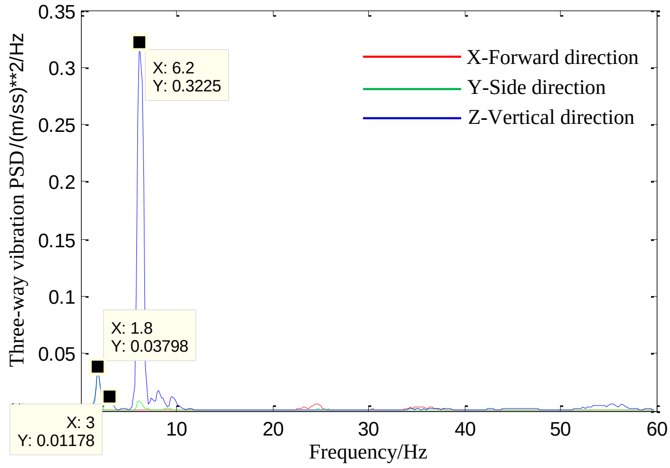

Figure 14. Vibration acceleration PSD spectral line of measure point 1 during railway transportation.

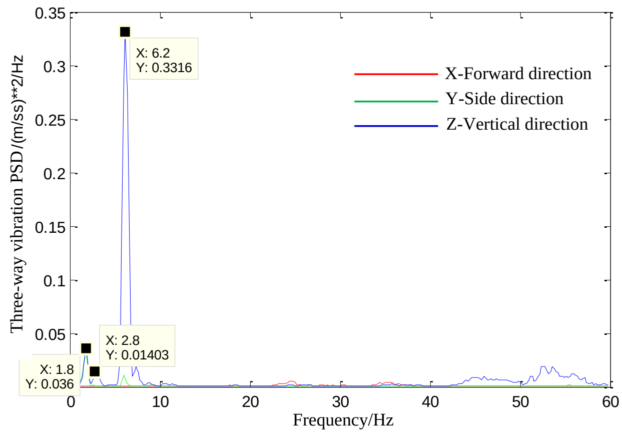

Figure 15. Vibration acceleration PSD spectral line of measure point 1 during railway transportation.

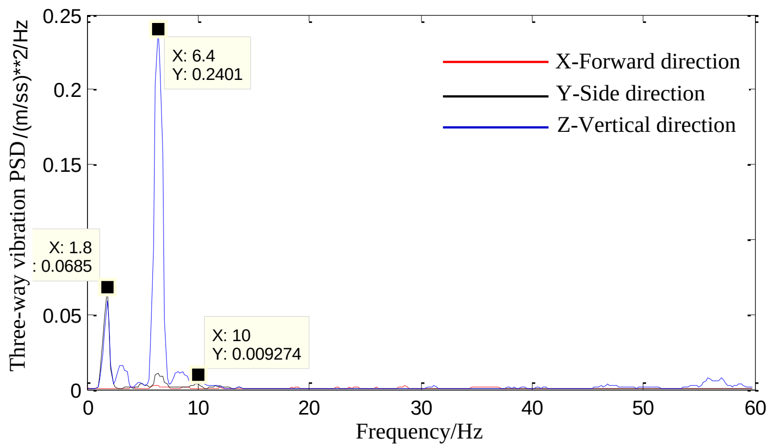

Figure 16. Vibration acceleration PSD spectral line of measure point 1 during railway transportation.

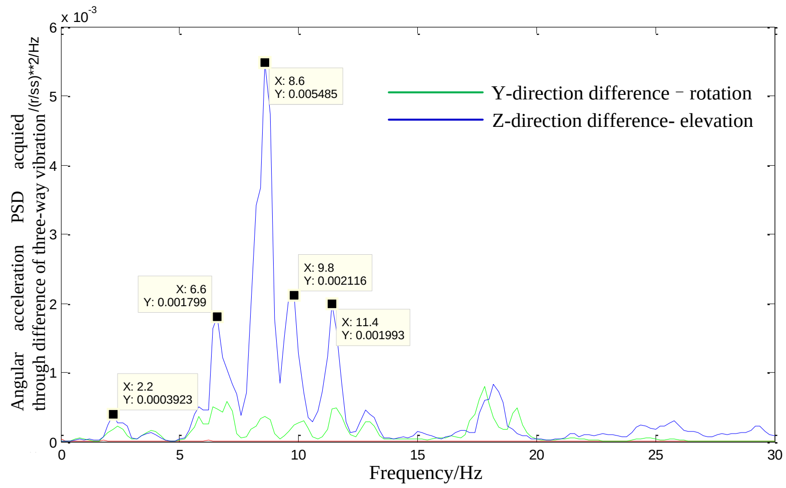

Figure 17. Angular velocity PSD spectral line of packaging box baseplate.

7. Suggestions on Shock Mitigation System for Spacecraft Transport

- Shock excitation of automobile transport is concentrated on: 2.2 Hz, 4.4 Hz and 10- 11Hz, shock excitation of railway transport is concentrated on: around 1.8 and 6.2Hz, and design of inherent frequency of packaging box shock mitigation system should keep away from areas concentrated with energies;
- Maximum energy contribution frequency of excitation is between 2.2Hz and 4.4Hz, to effectively reduce the excitation of this frequency band, the inherent frequency of the system can be reduced to below the maximum contribution frequency, while as the transformation of damper is large, attention should be paid to guaranteeing the stability and system shock resistance capacity, and enough capacitance should be guaranteed for the system under the most rigorous conditions required for the system input environment.
- If the system interfering frequency ω is low, it is difficult to reach the requirement $\omega/\omega_0>\sqrt{2}$,when designing the system, so vibration response of the system must be restrained through increasing the resonance of vibration isolation system, do not simply pursue a best vibration isolation effect without consideration on the influence that large amplitudes will have on spacecraft safety;
- In view of the stiffness characteristics of wire rope dampers and rubber dampers commonly used in spacecraft transportation, the optimum operating conditions of the damper system are fixed when the quality of the transporting products is the same, and the natural frequencies of the damper system can not be adjusted flexibly in the transportation process, which has limitations. The stiffness auto-adjusting vibration absorber system based on air spring has certain advantages, and it is one of the directions for the optimization of the vibration absorber system for spacecraft transportation.

8. Conclusion

Through collecting mechanical data of highway and railway transportation with a certain model, computation and research were made on shock excitation PSD under different transportation conditions to analyze the ambient excitation characteristics during spacecraft transport and to provide basis for the confirmation of inherent frequency of shock mitigation system for packaging box shock mitigation system during spacecraft transportation, and suggestions were put forward for the design of shock mitigation system.

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