Study of the dynamic characteristics of the AC dipole-girder system for CSNS/RCS

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Abstract: China Spallation Neutron Source (CSNS) is a high intensity proton accelerator-based facility. Its accelerator complex includes two main parts: an H- linac and a rapid cycling synchrotron (RCS). The RCS accumulates an 80 MeV proton beam and accelerates it to 1.6 GeV, with a repetition rate of 25 Hz. The AC dipole of the CSNS/RCS is operated at a 25 Hz sinusoidal alternating current which causes severe vibration. The vibration will influence the long-term safety and reliable operation of the magnet. The CSNS/RCS AC dipole-girder system takes vibration isolator to decrease the vibratory force and the vibration amplitude of the dipole. For the long-term safety and reliable operation of the dipole, it is very important to study the dynamic characteristics of the dipole-girder system. This paper takes the dipole-girder as a specific model system. A method for studying the dynamic characteristics of the system is put forward by combining theoretical calculation with experimental testing. The modal parameters with and without vibration isolator of the dipole-girder system are obtained through ANSYS simulation and testing. Then, the dynamic response of the system is calculated with modal analysis and vibration testing data. With the simulation and testing method, the dynamic characteristics of the AC dipole-girder are studied.

Key words: AC dipole, girder, vibration, dynamic characteristics, modal analysis, dynamic response

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1 Introduction

The CSNS-Ⅰ accelerators consist of an 80 MeV H-linac and a rapid cycling synchrotron of 1.6 GeV [1, 2]. The RCS ring has a four-folded symmetrical topological structure, which consists of four arc zones and four line segments. There are 24 sets of dipole magnets that are distributed uniformly in the whole RCS ring. The magnets will be operated at a 25 Hz rate sinusoidal alternating current. The magnetic core and coils will generate severe vibration, especially at a frequency of 25 Hz, such as the J-PARC AC dipole magnets. The vibration influences other equipment through the magnet girder system.

The AC dipole-girder system with complex structure and high-precision adjustment is one of the most important pieces of equipment in the CSNS/RCS. Because of the self-excited vibration, the comprehensive technical index of requirement is different from other accelerators, whose vibration is caused by ground vibration. So, it is necessary to study the dynamic characteristics and the dynamic response of the system [3, 4]. The theoretical modal analysis and testing modal analysis are the main research methods that we have used. The theoretical modal analysis is based on the linear vibration theory and finite element method to research the relationship among the excitation, system and response. The testing modal analysis uses the input and response parameters to obtain the modal parameters (frequency, damping ratio and vibration mode) [5]. Although the dynamic characteristics and the dynamic response of the girder are very important, the dynamic response is difficult to measure. Therefore, the AC dipole-girder system is adopted as the research object. The theoretical and testing methods are used to study the dynamic characteristics of the system. Then, the measured data and the ANSYS model are used to simulate the dynamic response of the system.

2 Vibration testing and modal analysis of the AC dipole

The CSNS/RCS AC dipole dipole is operated at a 25 Hz sinusoidal alternating current of 1100 DC with 816 AC, which causes severe vibration. The acceleration sensors will be used to measure the vibration of the dipole. Through testing, the maximum amplitude is shown to be

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4.42 μm in the vertical direction (Y). Although the new dipole vibration amplitude is smaller than the old dipole [6], the vibratory force still exists. So, it is also important to study the dynamic characteristics of the system. At the same time, the vibration isolators are used to improve the dynamic characteristics of the dipole-girder system and reduce the vibration amplitude of the AC dipole.

The theoretical modal analysis and testing modal analysis are the main methods that are used to study the dynamic characteristics of the system. The theoretical modal analysis is based on the linear vibration theory and finite element method to study the relationship among the excitation, system and response. ANSYS software is used to simulate the AC dipole-girder system of CSNS/RCS, both with and without vibration isolators. The finite element structure (FE) consists of AC dipole and girder. The structure physical properties are listed in Table 1.

Table 1. Parameters of the material.

material	Young's modulus/Pa	Poisson's ratio	density/ (kg·m^{-3})
Q345D steel	2.09E11	0.269	7890
silicon steel sheet	1.97E11	0.26	7650
aluminum	6.9E10	0.34	2700
stainless steel	1.93E11	0.31	7750

The FE is constructed with an element of solid-186, and the damping material is constructed with an element of combin-40. During the analysis, the Block Lanczos Method is used to calculate the natural frequency and vibration mode of the system. The top six natural frequencies are obtained as shown in Table 2.

The natural frequency parameters of the system are obtained through the testing modal analysis with the curve fitting analyses of the transfer function of the structure's excitation and response. The frequency response function can be obtained based on the orthogonality condition of the real symmetric matrix [7, 8].

In the testing modal, the transfer function is calculated from the exciting point and responding point parameters. This testing modal analysis takes a force hammer excitation system. The modal parameters identification method of MIMO is also taken. There are 60 measuring points arranged around the whole system, according to the selecting principle, which are used to measure the X, Y and Z direction acceleration of the dipole-girder system. The accelerator sensors arrangement and testing method with vibration isolator are the same as the system that has no vibration isolator. The force hammer and vibration response signals are acquired by the intelligent analyzer of INV3032C. After testing, the system testing modal parameters (natural frequency and damping ratio) are found through the data processing analysis system of DASP [9]. The Eigensystem Realization Algorithm (ERA) fitting method is used in the modal testing data processing of the dipole-girder system [10]. The stabilization chart is used to assessment quality of the testing results, as shown in Fig. 1.

The quality of the modal testing result is found to be quite well from the Fig. 1. So, the testing results are reliable, the testing natural frequencies are shown in Table 3.

The dipole-girder system, both with and without vibration isolator, have the same modal shapes, as shown in Fig. 2. The top six rank modal shapes of the dipole-girder system are overall shaking.

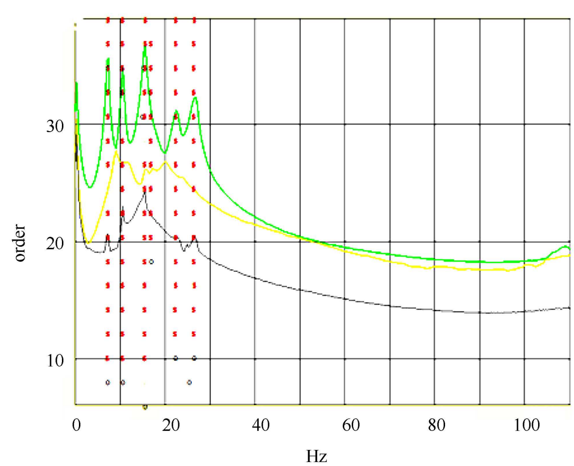

Fig. 1. The stabilization chart of the testing.

Table 2. The modal analysis simulation results of the dipole-girder system.

modal order	1	2	3	4	5	6
ANSYS natural frequency without isolator f/Hz	6.658	11.23	14.59	23.77	28.45	36.33
ANSYS natural frequency with isolator f/Hz	5.984	10.289	14.113	18.789	22.741	26.165

Table 3. The testing modal analysis results of the dipole-girder system.

modal order	1	2	3	4	5	6
testing natural frequency without isolator f/Hz	8.66	11.09	15.33	23.21	28.44	36.22
testing damping ratio without isolator (%)	1.772	2.602	2.647	5.519	2.786	3.922
testing natural frequency with isolator f/Hz	7.25	10.47	15.48	16.81	22.34	26.38
testing damping ratio with isolator (%)	1.727	2.101	2.196	9.293	3.264	2.845

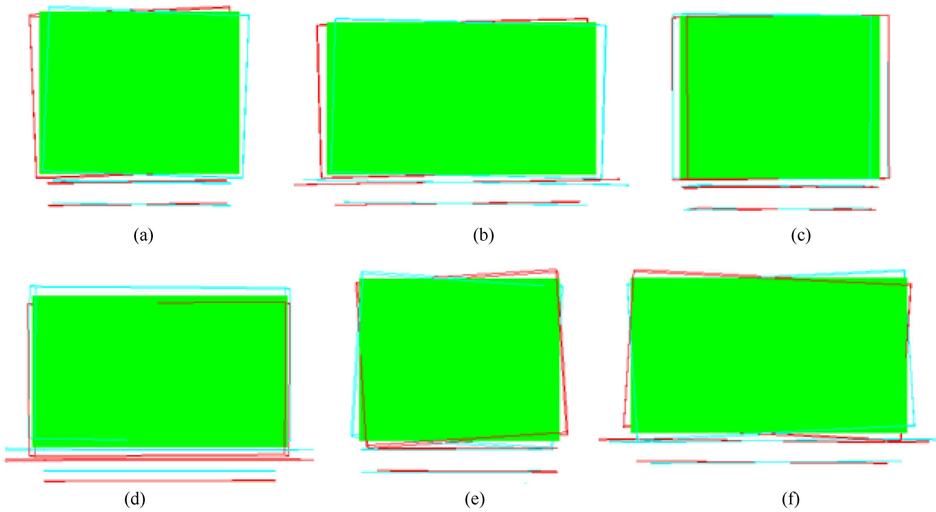

Fig. 2. (a), (b), (c), (d), (e) and (f) are respectively the top 6 rank modal shapes of the dipole-girder system.

Figure 3 shows that the natural frequencies contrast between simulations and testing. The two conditions, simulation and testing, almost have the same modal shapes and two of the fourth modal shapes have a vertical movement in the X-Z plane (Y direction). When using the vibration isolator, the high order natural frequencies are decreased. It is shown that the fourth natural frequency of the system is reduced to 16.81 Hz when compared with the two conditions. The damping ratio is increased to 9.293%, which is close to the design objective 10%. The modal analysis results indicate the dipole-girder would not take resonance phenomenon. The simulation results are almost identical with the testing results. So, the modal analysis of the system and the FE is reasonable.

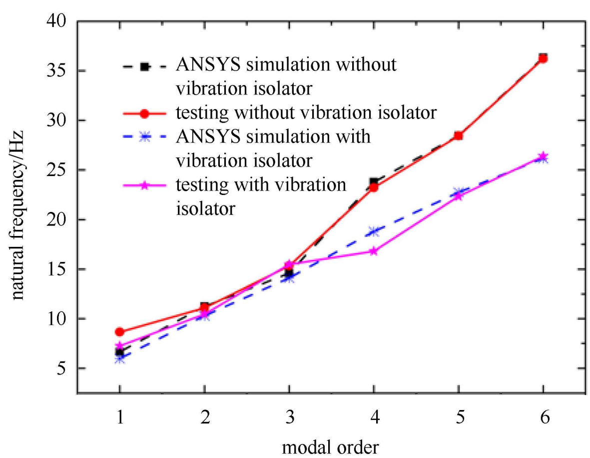

Fig. 3. The natural frequencies contrast.

3 Dynamic response analysis of the dipole-girder system

The traditional structural strength analysis is static analysis. The maximum stress of static analysis is usually less than the material yield limit. The maximum static strain and maximum static stress of the system are 0.042 mm and 33.4 MPa, which are shown in Fig. 4. The maximum stress is less than the permissible stress 345 MPa of material. It is a safe system if the dipole does not vibrate. However, because of the safe-excited vibration, it is necessary to study the dynamic characteristics response of the system.

The dynamic response of the system is simulated through ANSYS. The vibration testing data will be used as the excitation signal of the simulation. The dynamic characteristics response is calculated with modal analysis and vibration testing data, the computational procedure is shown in Fig. 5.

In this paper, a new absorber is designed for the CSNS/RCS AC dipole with metal rubber. Then, the acceleration sensor will be used to measure the vibration of the dipole. The three direction acceleration magnitudes of the dipole are shown in Fig. 6 and Fig. 7.

The average acceleration magnitude of the dipole is the excitation source of the vibratory force. The main frequency of the force is set as 25 Hz. The dynamic response of the dipole-girder system is calculated with the harmonic response simulation method. The dynamic strain and dynamic stress are obtained as shown in Fig. 8, Fig. 9 and Table 4.

Table 4. The dynamic strain and stress of the dipole-girder system.

simulation situation	without vibration isolator	with vibration isolator
dynamic strain/mm	0.064	0.026
dynamic tress/MPa	41.4	22.9

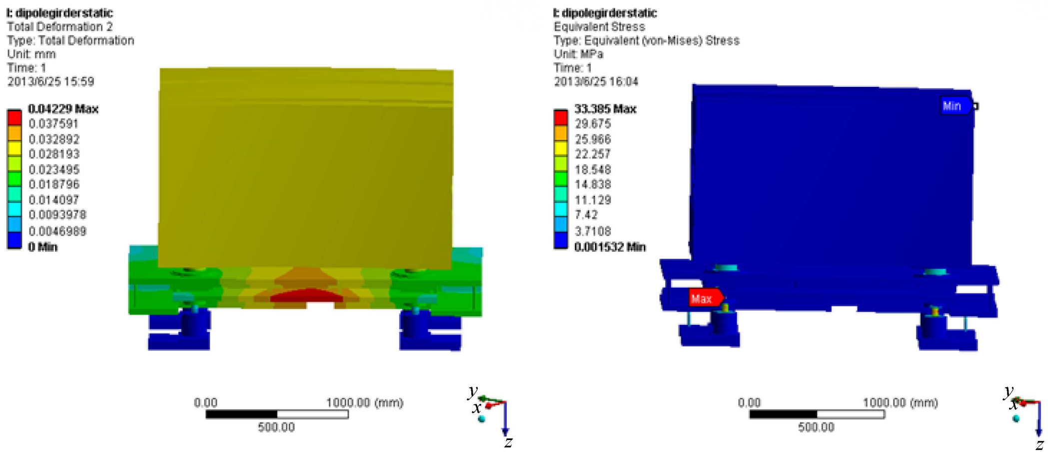

Fig. 4. The static analysis of the dipole-girder system.

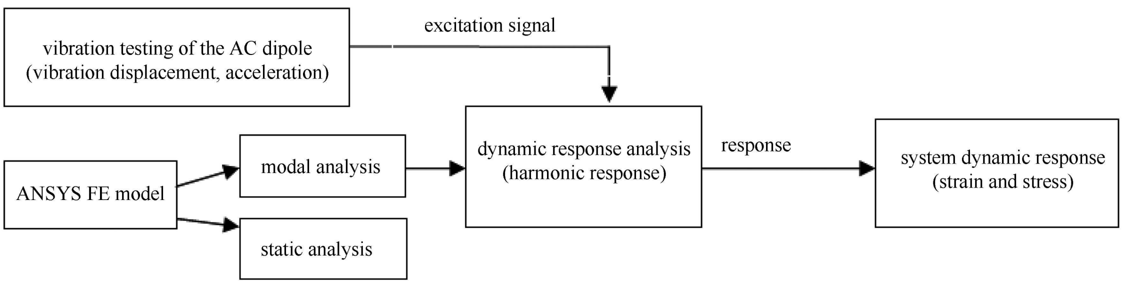

Fig. 5. The computational procedure of the dynamic analysis.

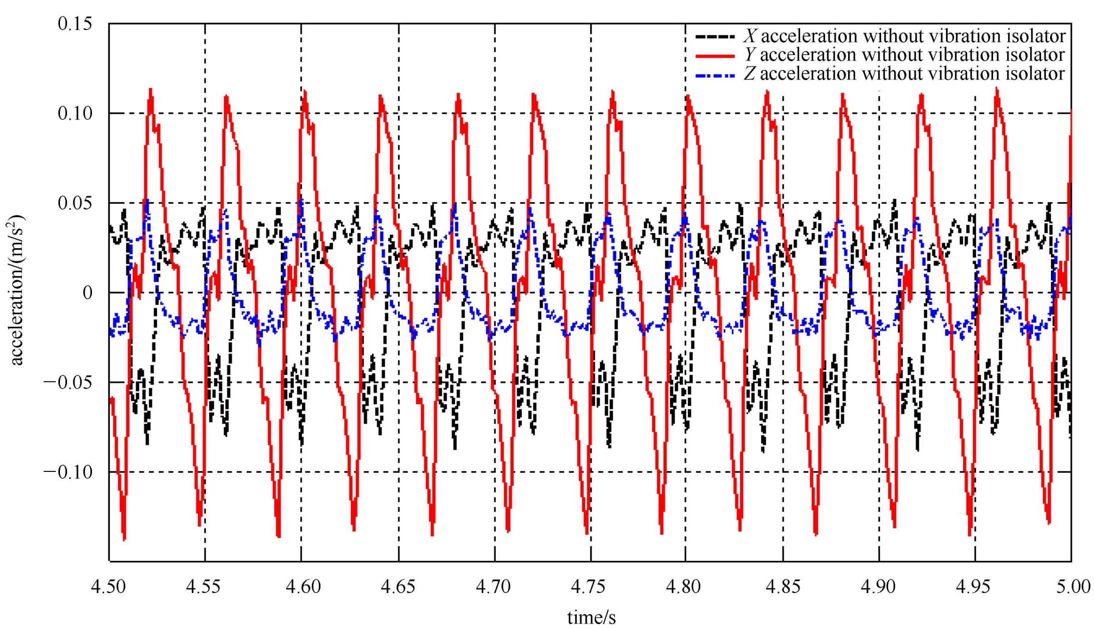

Fig. 6. The acceleration magnitude of the dipole without vibration isolator.

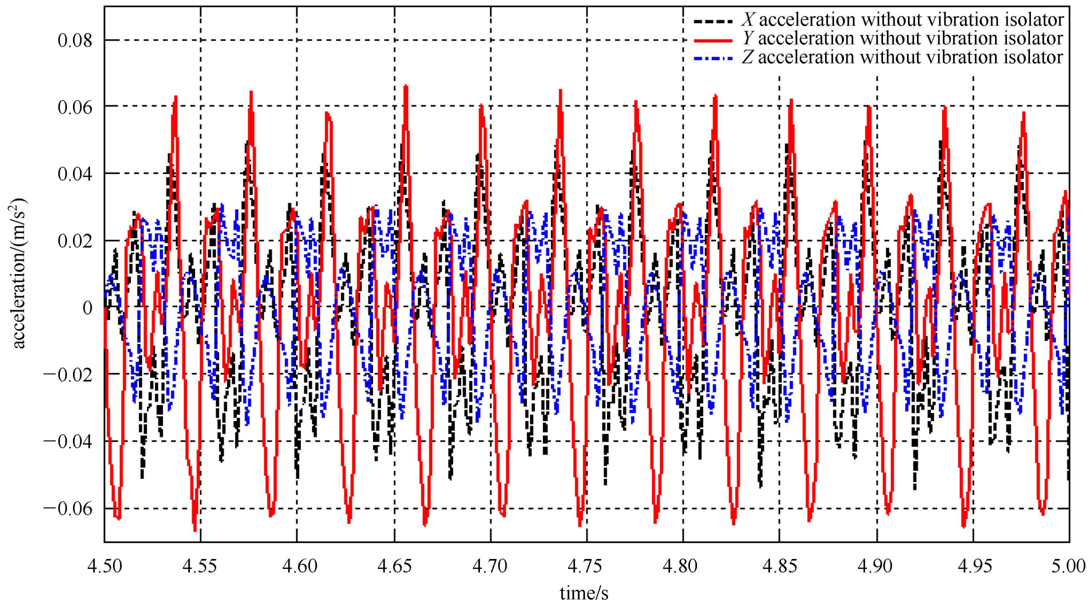

Fig. 7. The acceleration magnitude of the dipole with vibration isolator.

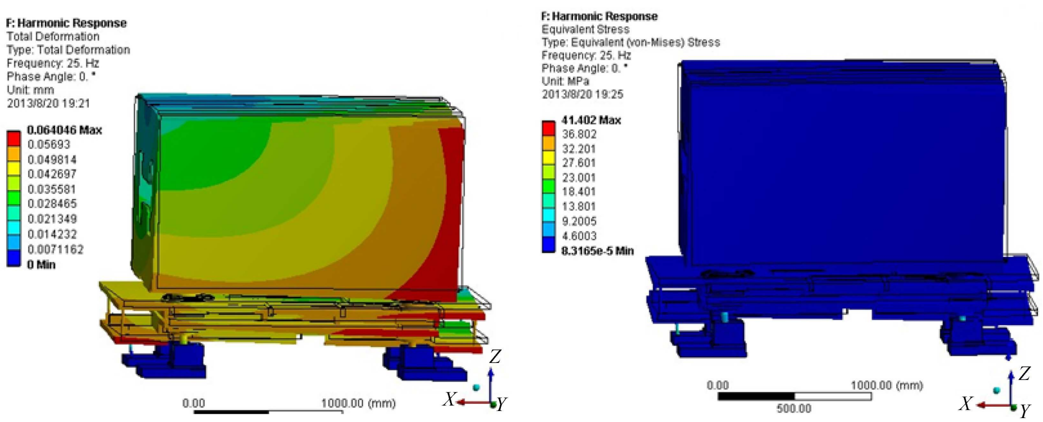

Fig. 8. The dynamic strain and stress analysis without vibration isolator.

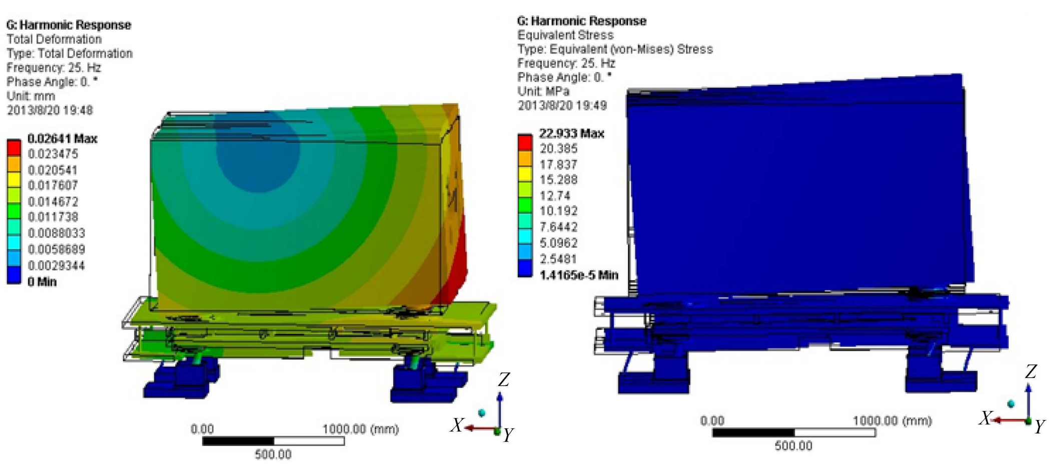

Fig. 9. The dynamic strain and stress analysis with vibration isolator.

The simulation results show that the dynamic response analysis is quite different from the traditional static analysis. The maximum dynamic strain is more than the static strain without a vibration isolator. Hence, it is very important for the designer to check their structure design. The dynamic strain may cause strain fatigue in long-term operation. With the vibration isolators, the dynamic strain and stress are less than the values of the system without vibration isolators. The vibration isolator also changes the dynamic stress's position. The maximum dynamic stress is located at the vertical adjustment system without vibration isolators but the maximum dynamic stress is located at the spring with vibration isolators. The vibration isolators improve the dynamic characteristics of the system. The dynamic strain and stress are reduced by half with the vibration isolators, and it will decrease the strain and stress fatigue odds of the weld reinforcing steel plate.

4 Conclusions

The AC dipole and girder system plays a very important role in the CSNS/RCS accelerator, so it is necessary to study the dynamic characteristics of the system. This paper establishes the suitable finite element structure of the dipole-girder system. A method for analysing and studying the dynamic characteristics of the system is put forward by combining theoretical calculation (ANSYS simulation) with experimental testing. The dynamic characteristics response is calculated with modal analysis and vibration testing data. The dynamic response characteristics are studied, which are difficult to measure in actual working conditions. The dynamic response results also provide a reasonable way to design the structure and make the material choice, which will decrease the strain and stress fatigue odds of the equipment.

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References

1 WEI Jie, FU Shi-Nian, FANG Shou-Xian. Proceedings of EPAC. 2006
2 WEI Jie, CHEN He-Sheng, CHEN Yan-Wei et al. Nuclear Instruments and Methods in Physics Research Section A, 2009, **600**: 10–13
3 Doose C, Sharma S. MEDSI02, APS, Chicago 2002. 133–139
4 ZHANG Lin, Lesourd M, Lewis T. PAC2001, 2001. 1465–1467
5 Hermans L, Vender Auweraer H. Mechanical Systems and Signal Processing, 1999, **13**(2): 193–216
6 LIU Ren-Hong, ZHANG Jun-Song, QU Hua-Min, WANG Hai-Jing. Nuclear Science and Techniques, 2012, **23**: 328–331
7 Ward H, Stefan L, Paul S. Modal Analysis Theory and Testing. Beijing: Beijing Institute of Technology Press, 2001.1–70
8 Ibrahim S. AIAA Journals of Spacecraft and Rockets 15/5. 1978. 313–316
9 SHEN Song. Journal of Vibration Engineering, 2000, **13**(3): 492–495
10 Juang J N, Pappa R S. Control and Dynamics, 1985, **8**(5): 620–627