Experimental Study on Influences of Modal Parameters of Fiber-reinforced Composite Thin Plate under Different Boundary Conditions

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Abstract: The influences on modal parameters of fiber-reinforced composite thin plate under different boundary conditions are studied in this paper. Firstly, based on the self-designed two-dimensional laser scanner-platform, modal parameter testing system is established. Secondly, the corresponding test methods and procedures of the natural frequencies, modal shapes and damping of composite plate under different boundary conditions are proposed. Finally, TC500 carbon fiber/resin matrix composite plate is taken as study subject, its resulting frequencies, modal shapes and damping of the composite plate under different boundaries, including all-edges clamped, two-opposite-edges clamped, one-edge clamped, are measured with high efficiency and accuracy, and the influence on modal parameters are analyzed. The results show that with the reduction in the number of clamped edges, natural frequencies, damping and the abundance of local modal shapes are declined. Meanwhile, with the increasing of modal orders, the influence of the different boundary conditions on the natural frequencies and local modal shapes are becoming weak.

Key words: fiber-reinforced; composite thin plate; modal parameter; different boundary

1 Introduction

The fiber-reinforced composites are commonly used in the fields of structural engineering and considered as the fundamental structural elements[1-3] in aerospace,

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naval, vehicles, and so on for their orthotropic behaviour. Hence, the wide use of such structures requires investigating the vibration characteristics, especially modal parameters, of orthotropic plates in order to develop accurate and reliable design[4].

The problem of the vibration characteristics of fiber-reinforced composite thin plate has been intensively studied by several researchers from different countries.

Mohan and Kingsbury[5] presented an analytical study of the natural frequencies and modal shapes of anisotropic thin plates. By using of Galerkin method, the change in natural frequencies and modal shapes under different boundaries are investigated. Nair and Durvasula[6] use the Rayleigh–Ritz method for the analysis of the natural frequency and modal shapes of composite thin plate under simple support and clamped boundaries, and an approximate solution of natural frequency was acquired. The natural frequencies and modal shapes of glass/resin and graphite/resin laminated plate under different boundary conditions are solved by Qatu taking the algebraic polynomial method, however without experimental measurement[7]. Natural frequency and damping characteristics of fiber reinforced composite plate under various boundary conditions are analyzed by Rikards through the finite element method (FEM), and the results obtained show great agreement with higher order shear theory and experiment[8]. Further, the problem of approximate evaluation of the frequencies of orthotropic plates is investigated by Biancolini et al[9]. Vibration equation under free boundary condition is deduced by Xing and Liu though method of separation of variables. By introducing the eigenvalues in the vibration equation, frequency equation and natural frequency under different boundary conditions are obtained[10].Damping and stiffiness characteristics of glass fiber-reinforced laminated plate are analyzed by Mishra based on a multiquadric radial basis function method (MQRBF), and the correctness of method is verified though experiment[11]. By the way of putting vibration shapes which set by boundary conditions and natural shapes into strain energy and kinetic energy, the natural frequency of orthogonal anisotropic laminated plate under simply support and clamped boundary conditions are obtained by Sheng Jia and Yang Jia-ming on the base of Ritz method[12]. The natural frequency of graphite/epoxy resin matrix composite plate is calculated and analyzed by Shi Dong-yan etc. though improve Fourier series method (IFSM). The Rayleigh-Ritz Method is used to solve the influence of vibration characteristics of composite thin plate under different boundaries, and finite element simulation is used to improve the effectiveness of the method they proposed.

Though lots of theoretical and experimental researches of the vibration characteristics of fiber-reinforced composite plates have been done, there are relatively few experimental studies on the same composite reinforced plate under different boundary conditions. Furthermore, because fiber-reinforced composite structures have obvious anisotropic characteristics, their natural frequencies, modal shapes and damping under different boundary conditions will change greatly in a practical application, which has not been well solved. Moreover, there are also some improvements in the traditional experimental system in terms of test efficiency and accuracy. Therefore, it is still necessary to develop self-designed vibration test system for researching the vibration characteristics of fiber-reinforced composite structures under different boundary conditions.

The influences on modal parameters of fiber-reinforced composite thin plate under different boundary conditions are studied in this paper. It can also provide technical support for the comprehensive application of composite thin-walled structures in engineering.

2 Experimental system and method of modal parameters of fiber-reinforced composite plate based on two-dimensional laser scanner-platform

In this section, for fiber-reinforced composite thin plates having the characteristics, including thin wall thickness, light quality, rich local vibration mode, and complex section line, etc., the advantages of non-contact laser vibration measurer are utilized during the experimental system of modal parameters of fiber-reinforced composite plate under different boundary conditions established. The corresponding testing methods and processes are proposed as well.

2.1 Modal test system of fiber-reinforced composite plates

Because of the characteristics including thin wall thickness, light quality of the fiber-reinforced composite plates, the use of traditional acceleration sensor will produce large added mass, which affect testing results of natural frequency and damping. Therefore, non-contact laser vibration measurement is chosen to conduct modal parameter testing in this paper. The test system is shown in Fig.1. It consists of four segments including two-dimensional laser scanner-platform, excitation platform, installation platform and acquisition and analysis platform.

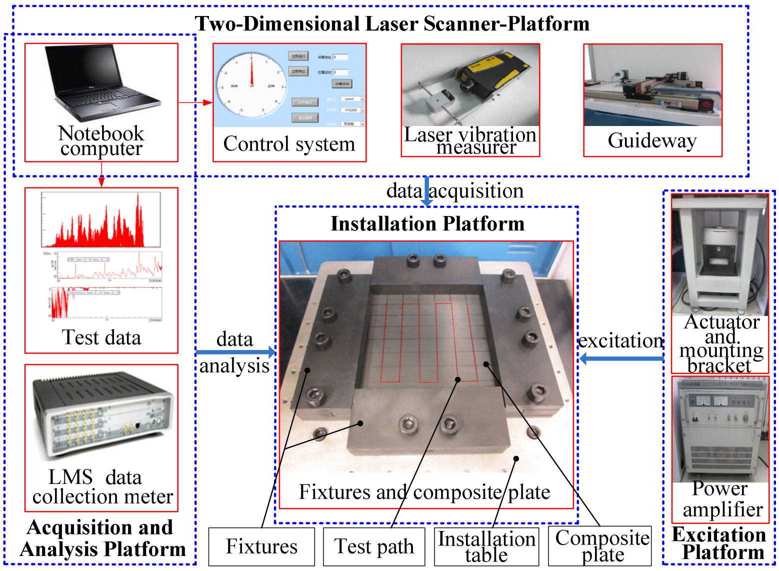

Fig.1. Modal parameter test system of fiber-reinforced plates under different boundary conditions

Among the four segments, two-dimensional laser scanner-platform is composed of guides, laser vibration measurer, computer and control system. During the scanning test, laser vibration measurer is fixed on the guideways, which is controlled by the motor. And the laser light path is adjusted through a 45°reflector first. Then the movement control of the position of the laser point station can be realized by a notebook computer which the development of the corresponding motor control program based on Labview is installed. The self-design two-dimensional laser scanner-platform not only can accurately control test position with single test point and improve the efficiency of the single test point, but also can adjust the rotational speed and the rotation direction of the motor in a continuous scanning test, so as to get vibration response signal of X, Y, or the cross direction.

Excitation platform is made up of Lian-neng JZK-100 actuator, YE5878 power-amplifier and mounting bracket. Thereinto, the maximum excitation force of the exciter and the power amplifier component can reach 1000N. In order to ensure the stiffness of the structure, the mounting bracket is welded by solid square steel. Meanwhile, to ensure the stability in excitation, the vibration reduction is performed at the bottom. The installation platform consists of installation table and installation fixtures. In order to install fixtures and other test instruments, M8 threaded holes are set up on the installation table. The fixtures are divided into two sets of different length, which can be fitted according to the requirement of modal parameters test under different boundary conditions including all-edges clamped, two-opposite-edges clamped, one-edge clamped. Acquisition and analysis platform which can process and analyze the data collected is made up of LMS 16 channel portable data collection meter and notebook computer. The completed fiber reinforced composite thin-plate modal test system is shown in Fig.2.

Fig.2. Picture of the modal parameter testing system of fiber-reinforced composite plate

2.2 The test method of fiber-reinforced composite plate under different boundary conditions

In order to accurately obtain the modal parameter under different boundary conditions, and minimize the influence of the fixture, the test sequence of all-edges clamped to two-opposite-edges clamped to one-edge clamped is adopted. By using this test sequence, it can be sure that every edge of the composite plate to be tightened at one time while the preload will not change as well. Then the consistency of boundary conditions in the test can be ensured. The test process under different boundary conditions is shown in fig. 3, and the detailed procedures are as follows.

(1) Tighten the composite thin plate with all edges clamped

In order to ensure that all edges of the fiber-reinforced composite thin plate are stressed uniformly, the method of the multi-lateral tightening is adopted in the installation. First of all, the composite thin plate is put into the fixtures. Then, according to the test requirements under all edges clamped boundary condition , every bolt is tightened with a torque wrench at the same torque. Doing in this way can ensure that each bolt tightened uniformly and sufficiently, and then ensure that each

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edge is stressed uniformly.

(2) Conduct the prediction test under all edges clamped condition

After the plate is tightened, prediction test is made with exciting-hammer. Then, the natural frequency is acquired according to no less than three times prediction tests. If the differences among the test results are smaller than ±5Hz, then all edges are considered fully fixed. And if the results are larger than ±5Hz, the plate should be reinstalled with larger preload. New prediction test will be continued until the results are satisfied.

(3) Conduct the formal test under all edges clamped condition

After the prediction test finished, the scope of the sweep test can be made sure according to the natural frequency acquired in step 2. The natural frequency test of one order is taken as an example. First, sweep range of frequency is set from 80% to 120% of the natural frequency. Next, the frequency domain response curve which a certain order natural frequency is contained of is obtained through "slow sweep". And the natural frequency can be acquired accurately by identifying the peak of the curve. Meanwhile, damping parameters can be acquired through half-power bandwidth method as well.

And then according to the modal parameter testing system of composite thin plate established in Section 2.1, the plate is aroused in the resonance state at the order with sufficient excitation energy. In the meantime laser scanning vibration response test is completed with laser vibration measurer according to the specified path at a constant speed. At last, the ways of windowing , filtering, and downsizing modal shape are used to handle the modal shape acquired. Then the modal shape in the order can be mapped though loading the date acquired into the laser scanning framework model. Repeat these steps, modal parameters of each order under all edges clamped can be obtained.

(4) Conduct the formal test under two-opposite-edges clamped condition

After finishing the test of modal parameters under all edges clamped condition, the two shorter fixtures are taken down first. And then the boundary condition changes into two-opposite-edges clamped. Next , the sweep range of frequency is set though the range of the natural frequency of each order rapidly obtained by hammering test. And the sweep speed is the same as under all edges clamped condition. In the next moment, according to the method of modal testing under all edges clamped condition, the natural frequency and damping parameters are obtained by the method of frequency sweep. Finally, the modal shape of two-opposite-edges clamped is obtained by means of the test method of modal shape of all edges clamped. Repeat these steps, modal parameters of each order under two-opposite-edges clamped can be obtained.

(5) Conduct the formal test under one-edge clamped condition

After finishing the test of modal parameters under two-opposite-edges clamped condition, one of the longer fixtures is taken down first. And then the boundary condition changes into one-edge clamped. Next , the sweep range of frequency is set though the range of the natural frequency of each order rapidly obtained by hammering test. And the sweep speed is the same as under all edges clamped condition. In the next moment, according to the method of modal testing under all edges clamped condition, the natural frequency and damping parameters are obtained by the method of frequency sweep. Finally, the modal shape of one-edge clamped is obtained by means of the test method of modal shape of all edges clamped. Repeat these steps, each order modal parameters of the plate under one-edge clamped can be obtained.

(6) Analyze and summarize the influences of different boundary conditions on modal parameters

After completing the steps (3) to the steps (5), the data of each order modal parameter in the different boundary conditions will be classified, compared and summarized. Finally, the natural frequency, modal vibration shapes and the change degree of the damping parameters and the purpose of the study are achieved.

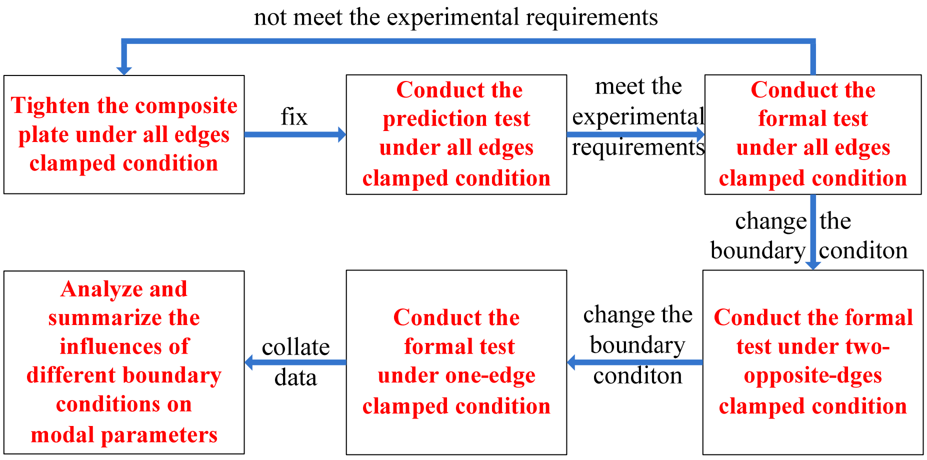

Fig.3. Procedure of modal parameter test under different boundary conditions

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3 The test results and analysis of the modal parameters of the fiber-reinforced composite thin plate

In this section, according to the test system, the test method and the process proposed in section 2, experimental test is carried out respectively. And influences of modal parameters under different boundary conditions are studied.

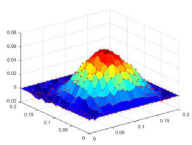
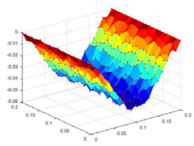
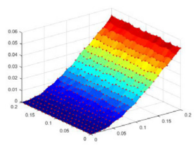
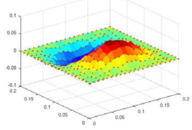
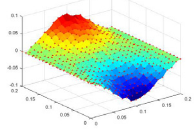
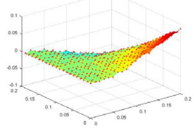
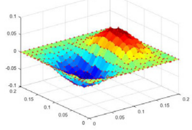
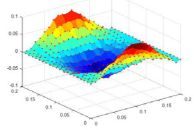
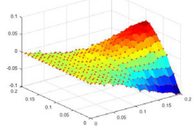
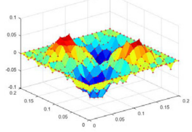
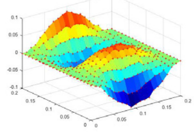
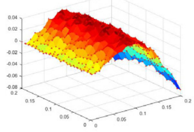
3.1 The test results of the modal parameters of fiber reinforced composite plate under different boundary conditions

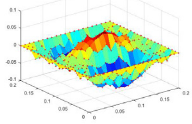
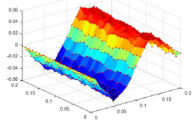
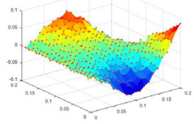
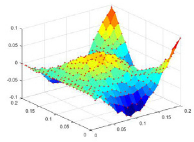
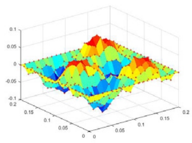
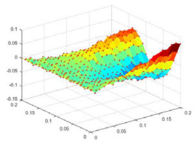
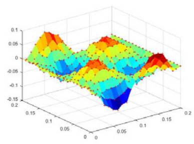
Tab.1. The results and the errors of the frequencies of the fiber-reinforced composite plate under different boundary conditions obtained by experiment and FEM

order	Frequency under all edges clamped condition			Frequency under two-opposite-edges clamped condition			Frequency under one-edge clamped condition		
	Exp. (Hz) A	FEM (Hz) B	Error (%) $\lvert\frac{B-A}{B}\rvert$	Exp. (Hz) A	FEM (Hz) B	Error (%) $\lvert\frac{B-A}{B}\rvert$	Exp. (Hz) A	FEM (Hz) B	Error (%) $\lvert\frac{B-A}{B}\rvert$
1	412.5	470.0	12.2	233.2	262.7	11.2	42.2	44.0	4.2
2	798.8	893.1	10.6	272.7	268.4	1.6	56.3	55.9	0.7
3	1091.0	1033.	5.6	394.9	353.8	11.6	221.5	227.9	2.8
4	1468.3	1305.4	12.5	621.1	649.4	4.4	264.8	275.2	3.8
5	1671.5	1615.6	3.5	664.1	719.7	7.7	307.4	289.8	6.1
6	1881.6	1899.1	0.9	782.8	727.5	7.6	415.2	395.8	4.9
7	1909.4	1932.1	1.2	841.4	781.6	7.7	643.0	596.2	7.8
8	2198.8	2111.5	4.1	1016.0	977.6	3.9	705.1	705.6	0.1

When testing, the plate is installed on the installation platform with torque values of 50 nm first. After the installation is completed, test parameters are set as follows, the test frequency range is 30 ~ 3200Hz, the excitation frequency is 1Hz/s, the excitation amplitude is 2g, the frequency resolution is 0.5 Hz, the sampling frequency is 4096Hz. Meanwhile, in order to ensure the accuracy of the test, the hanning window processing is added to the sweep response signal. Then, through the test system built in section 2.1, experimental test is carried out according to the test methods and procedures proposed in section 2.2. And the natural frequencies, modal shapes and damping ratio are shown in tab.1, tab.2, and tab.3 respectively. For the sake of verifying the test results, a FEM calculation is carried out, and the results of FEM and their errors between experiment and FEM are listed in tab.1 as well. Furthermore, what needs illustration is that due to resonant interference of the self-designed platform, leading to some orders modal shapes are difficult to obtain. For the modal shapes not acquired from the test, "--" is used to express.

Tab.2. The modal shapes of the fiber-reinforced plates under different boundary conditions obtained by experiment

order	all edges clamped	two-opposite-edges clamped	one-edge clamped
1			
2			
3			
4			

5			
6	--	--	
7		--	
8	--		--

Tab.3. The damping ratio of the fiber-reinforced plates under different boundary conditions obtained by experiment

order	all edges clamped (%)	two-opposite-edges clamped (%)	one-edge clamped (%)
1	2.24	1.18	0.66
2	3.37	2.44	1.91
3	3.95	2.94	2.61
4	4.38	3.21	1.95
5	5.39	2.48	1.57
6	2.07	0.54	0.42
7	2.22	0.92	0.30
8	2.11	1.63	0.51

3.2 Influence analysis of modal parameters of fiber-reinforced composite thin plate under different boundary

In this section, based on the obtained test results of the modal parameters, the influence degree and trend of the modal parameters under different boundary conditions are studied in detail.

(1) It can be concluded from the test results of the natural frequency obtained under different boundary conditions that comparing with all edges clamped, the natural frequency of the composite plate with one edge clamped is obviously decreased. However, as the order rising, the effect of the boundary condition on its natural frequency decline gradually. For example, the natural frequency of the fists order of the plate with all edges clamped is 412.5Hz, as with one edge clamped the natural frequency of the first order is only 42.2 Hz. The difference is almost 10 times. However, the natural frequencies of the plate under the two conditions of the eighth order are 2198.8Hz and 705.1Hz respectively. The difference is just nearly 3 times.

(2) It can be informed from the comparison of the natural frequencies obtained by FEM analysis, as the number of constraints decreasing, the errors are gradually shrinking. For instance, the error under all edges clamed condition between FEM and experiment is 0.7% to 12.5%, comparing 1.58%~11.63% under two-opposite-edges clamped condition, and 0.08%~7.84% under one-edge clamped condition.

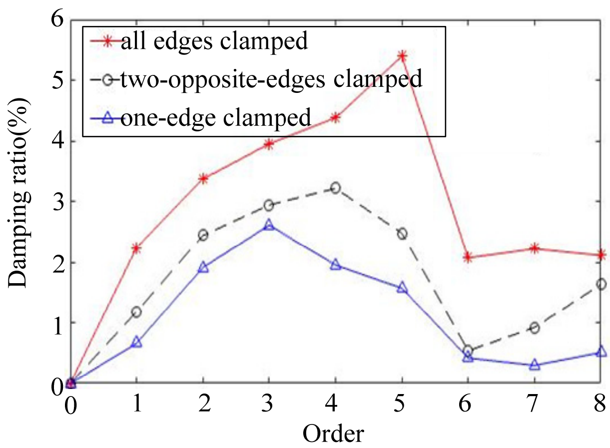


Fig.4. The varying trend of damping of the fiber-reinforced plates under different boundary conditions

(3) It can be seen from analyzing the damping ratio results of different boundary conditions, as the number of constraints decreasing, the damping decreases significantly. The changing trend of the damping ratio of composite plate under different boundary conditions is shown in fig. 4.And in fig.4 we can see that as the modal order increasing, the damping ratio changing trend is up-down-up. Moreover, the changing trend is basically consistent when the plate under different boundary

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conditions. Especially, the difference of the damping ratio is not obvious between one edge clamped and two-opposite-edges clamped, however the difference of the damping ratio is more obvious between all edges clamped and others.

4 Conclusion

By taking TC500 carbon fiber/resin matrix composite thin plate as an object, the influences on the modal parameters of fiber-reinforced composite thin plate under different boundary conditions are studied, and the conclusions are as follows.

(1) With the reduction in the number of constraint boundaries, natural frequencies, damping and the abundance of local modal shapes are declined. Especially, the effect of all edges clamped on modal parameters is the greatest.

(2) With the increasing of modal orders, the influence of the different boundary conditions on the natural frequencies and local modal shapes are becoming weak. However, no obvious varying trend on the effect of the damping ratio is found.

(3) Comparing with the results obtained by FEM, the modal parameters obtained by experiment are good consistency.

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