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Experimental Study on Modal Testing Methods for Typical Composite Honeycomb Sandwich Structures

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Abstract: *The high-lift devices of civil aircraft wings and the acoustic linings of engines are subjected to noise loads and high temperatures. To understand the typical vibration characteristics of local composite panel honeycomb sandwich structures under these conditions, a study on modal testing methods in high-temperature environments is necessary. To address this issue, various independent modal tests were conducted using impact hammer excitation, transient excitation, pulse sequence excitation, and random noise excitation methods. The results obtained from these methods were compared with those from the impact hammer excitation method to verify the advantages and disadvantages of each method and to identify the optimal modal testing method for high-temperature environments. The results show that all four methods—impact hammer excitation, transient excitation, pulse sequence excitation, and random noise excitation—can yield reasonable and effective modal measurement results.*

Keywords: *High-temperature modal testing; Composite honeycomb sandwich; Transient excitation; Pulse sequence excitation*

1. Introduction

The wing high-lift devices and engine acoustic linings of civil aircraft often utilize honeycomb sandwich structures. These components are located near the engines, within the engine jet stream, and are subjected to noise loads and high temperatures. High temperatures not only reduce the fatigue performance of materials but also generate localized thermal stresses that alter the vibration characteristics of the structures. Therefore, conducting modal testing in high-temperature environments to understand the changes in structural vibration characteristics is a crucial part of structural strength evaluation. At normal temperatures, modal testing can be performed using impact hammer excitation, with accelerometers picking up vibrations at various points, and modal parameters can be obtained by analyzing the acceleration frequency response functions. However, when the temperature of the test piece is high, using a manual impact hammer can pose a danger to the experimenter, and the presence of heating systems and insulation devices often results in a cramped space around the test piece, making it difficult to operate. Additionally, when the temperature near the test piece is high, conventional accelerometers may not be usable, and measuring vibration responses in high-temperature conditions also becomes a challenge. Therefore, it is necessary to find a modal measurement method suitable for high-temperature environments to solve the problem of modal measurement for honeycomb sandwich structures in such conditions.

In the research on modal testing methods for composite honeycomb sandwich structures, Fuhao Peng, Rui Zhao, et al. [1] established a full-field thermal vibration testing system. They applied discontinuous excitation using an exciter, captured displacement with a high-speed camera, and obtained the visualized modal frequencies and mode shapes of the honeycomb sandwich structure at 900°C using the Variational Mode Decomposition (VMD) framework. At Beihang University, Dafang Wu et al. [2][3] used a high-temperature alloy excitation rod to excite the wing and rudder structures of hypersonic vehicles at 1200°C and conducted modal tests by picking up vibration responses with a laser vibrometer. Lianjing Ma and others from Beijing Institute of Mechanical Engineering [4] compared the differences in excitation methods for missile rudder thermal modal tests under high-temperature conditions using a shaker and a speaker, verifying the feasibility of using environmental testing equipment such as shakers and speakers to excite structures for modal tests in high-temperature environments. Huachang Su et al. from Beijing Institute of Strength and Environment [5] used a shaker's short-time burst sweep to excite an air rudder, testing the first-order bending and torsional modes of the structure under high-temperature conditions. In their experiments on the dynamic response of metal plates under noise excitation, Zhenqiang Wu et al. [6] used a traveling wave tube as a sound source and applied noise excitation to metal plates. By analyzing the structural response data, they obtained the natural frequencies of the structure and their variation with temperature. Geng et al. from Xi'an Jiaotong University [7] conducted modal tests on clamped aluminum alloy plates using acoustic excitation and compared the test results of acoustic excitation with those of an exciter. Overall, the excitation loads generated by shakers and speakers generally do not meet the testing requirements for the "force-response" point-to-point frequency response function in classical modal tests, making it impossible to obtain structural frequency response information. Therefore, it is necessary to extract the modal characteristics of the tested structure through methods that use only response data [8] or through parameter identification methods based on structural acceleration transmissibility [9][10]. Scanning laser Doppler vibrometers (LDV) can perform multi-point measurements in a single test [11-14], but the sequential measurement of each point introduces different time delays in the data, requiring the tested structure to maintain steady vibration during scanning. This limitation prevents its use in structures with significant time-varying characteristics. The above research work generally covers the principles and technical approaches of conducting modal measurements using different excitation methods and vibration pickup techniques, yielding many valuable test results. However, there has not been a systematic evaluation of the effectiveness of various excitation methods and vibration pickup techniques in conducting modal measurements[15-16].

In this paper, typical composite honeycomb sandwich panels are used as test objects. Automatic impact hammers and exciters are employed to replace manual impact hammers for excitation, and non-contact vibration response measurements are used at the testing end to solve the problem of response measurement in high-temperature environments[17-18]. In this study, independent modal tests were conducted sequentially using impact hammer excitation, transient excitation, pulse sequence excitation, and random noise excitation methods on the same test piece. The measurement results obtained from these methods were compared with those of the impact hammer excitation method to verify the advantages and disadvantages of various modal testing methods and to explore the optimal modal testing method for high-temperature environments[19-21].

2. Test Study

2.1 Research Approach

Modal measurement methods mainly differ based on the excitation method used, including impact hammer modal measurement, transient excitation operational modal measurement, exciter excitation operational modal measurement, and random noise excitation operational modal measurement. A typical flat honeycomb sandwich structure test piece was designed and manufactured. Various excitation methods were employed, and the structure's vibrations were sequentially measured and analyzed using a laser vibrometer. By comparing the experimental results, the effects of different excitation methods on the modal measurement results were analyzed, leading to the formation of research conclusions.

2.2 Test Piece Design

The design of the test piece was primarily based on the actual structural form and dimensions of the composite honeycomb sandwich structure used in civil aircraft flaps. For ease of installation, it was designed as a flat panel composite honeycomb sandwich structure. The dimensions are shown in Figure 1, and a photograph is provided in Figure 2. The raised side of the test piece is the upper panel, which is uniformly distributed with numerous small holes, each with a diameter of 0.2 mm. The flat side is the lower panel, which has no holes. The upper and lower panels of the test piece are made of C/C composite materials, with a paper honeycomb core in between. The material and ply information for the panels are detailed in Table 1.

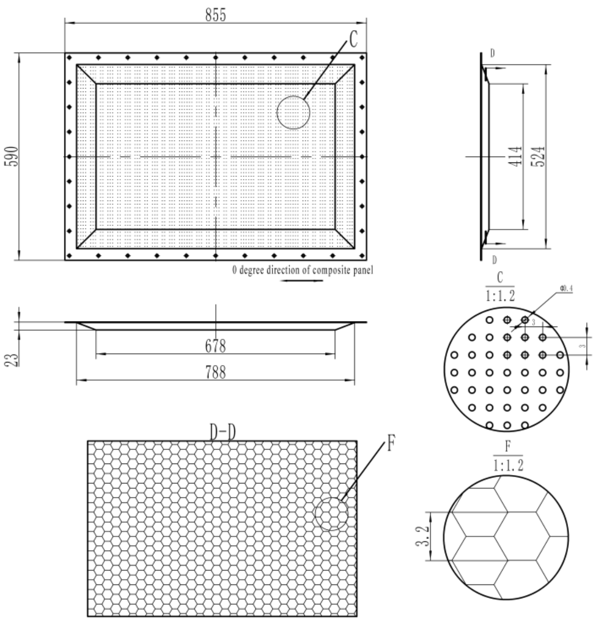


Figure 1 Schematic Diagram of the Main Dimensions of the Test Piece (Unit: mm)

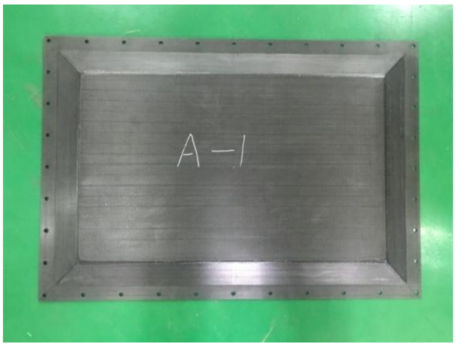


Figure 2 Photograph of the Test Piece

Table 1 Material and Ply Information of the Test Piece Panels

	Number of layers	Paving material	Thickness of paving layer (mm)	Direction of paving layer
Upper panel	1	BA3202W	0.2	0°/90°
	2	BA3202W	0.2	±45°
Lower panel	1	BA3202W	0.2	±45°
	2	BA3202	0.131	0°
	3	BA3202	0.131	0°
	4	BA3202W	0.2	0°/90°
	5	BA3202W	0.2	0°/90°
	6	BA3202	0.131	0°
	7	BA3202	0.131	0°
	8	BA3202W	0.2	±45°

The honeycomb core material is aramid paper, with a height of 20 mm. The honeycomb core has hexagonal cells with a side length of 3.2 mm and a density of 48 kg/m³. The arrangement direction of the honeycomb core is aligned with the length of the test piece, defined as the W direction. The adhesive film used is J-402, and the curing method is adhesive bonding.

2.3 Test System

The test system consists of a traveling wave tube, fixtures, test piece, exciter, laser vibrometer, and dynamic signal analyzer. The test piece is secured to the fixture using a metal frame. The combined test piece and fixture are rigidly mounted on the side wall of the traveling wave tube, with the flat surface of the test piece facing outward from the tube. A photograph of the test system is shown in Figure 3.

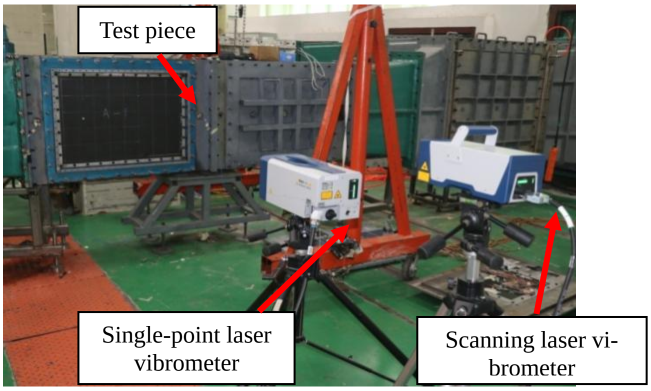


Figure 3 Photograph of the test system

2.4 Test Items

There are four test items, including one modal test and three operational modal tests. These tests incorporate four different measurement methods: impact hammer excitation, transient excitation, pulse sequence excitation, and random noise excitation. For details, see Table 2.

Table 2 Modal/working modal test items

No.	Type	Environmental conditions	Measurement method
1	Modal test	Normal	Force hammer method
2	Operating Modal Test	Normal	Temperature Transient Excitation Method
3		Normal	Single point shaker excitation, velocity response multi-point time division measurement method
4		Normal	Random Noise Excitation, Velocity Response Multi-point Time-Lapse Method

2.5 Test Methods

2.5.1 Impact Hammer Modal Measurement

A 6×9 grid was drawn on the surface of the test piece, with the corner points of each grid cell serving as the impact points for the hammer. The impact hammer was used to strike each intersection point of the grid lines, and an accelerometer was employed to capture the vibrations at each impact point. By analyzing the frequency response functions (FRF) obtained from the accelerometer data, the modal frequencies, mode shapes, and modal damping of the main modes below 1000Hz of the airworthiness verification test piece in the installed state were measured.

2.5.2 Transient Excitation Operational Modal Measurement

In modal testing, excitation can be categorized into transient and continuous excitations based on the duration of the applied force on the structure. Transient excitation refers to a method where the structure is excited into free vibration using a pulse or another short-duration signal. The hammer impact method is a typical example of transient excitation.

In this context, transient excitation differs from hammer impact by using the ejection or projection of a rigid object to excite the structure without measuring the excitation force signal and measuring the response signal separately over time. A steel ball is generally used as the projectile, as its impact pulse has a broad frequency range that fully meets the experimental requirements. In this test, the test piece was mounted on the side wall of the traveling wave tube. A simple pendulum system was used, where a steel ball was suspended from the lower end of a rigid rope, and the kinetic energy of the swinging steel ball was used to impact a fixed position on the test piece's surface to achieve excitation. A single-point laser vibrometer measured the velocity response at the central location of the test piece's surface, obtaining the PSD curve of the velocity response. By analyzing the peak frequencies in the PSD curve, the resonant frequencies of the test piece were determined.

In the experiment, a steel ball with a diameter of 12 mm and a mass of 30 g was used as the impactor, suspended by a soft rope. The steel ball was raised to approximately 15° and then released, allowing gravitational potential energy to convert into kinetic energy, accelerating the ball to impact the surface of the test piece for excitation. A photograph of the transient excitation test is shown in Figure 4.

Figure 4 Photograph of Transient Excitation Test

2.5.3 Exciter Operational Modal Measurement

The transient excitation method is mainly suitable for small test pieces with stable temperature environments. If the structure under test is surrounded by a high-temperature zone and the test process includes a non-steady heating phase, an exciter can be used to apply a stable random load to elicit structural response, providing a convenient and effective solution for thermal modal tests of such structures.

The test piece was mounted on the side wall of the traveling wave tube. A nut was attached to the surface of the test piece, and the excitation rod was screwed onto the test piece's surface. The excitation rod was connected to a force sensor in the middle and to the exciter at the back end. The exciter was suspended with an elastic rope so that the excitation direction was perpendicular to the structure's surface. During the test, the exciter continuously applied a wideband signal of 50Hz~1000Hz, and a scanning laser vibrometer was used to measure the forced vibration response of multiple points on the structure's surface over time, resulting in modal measurement data. A photograph of the exciter operational modal test is shown in Figure 5.

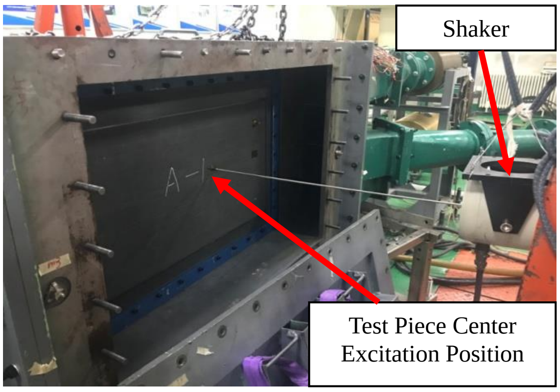


Figure 5 Schematic of shaker excitation position

2.5.4 Random Noise Excitation Operational Modal Measurement

The random noise excitation method is a type of continuous excitation. Unlike exciter excitation, this method uses broadband noise for excitation. The structural response is captured by a laser vibrometer, and modal parameters are obtained using phase separation techniques. The system diagram of the random noise excitation method is shown in Figure 6, and the experimental site photo is shown in Figure 7.

The test piece was mounted on the side wall of the traveling wave tube, and a noise load with a total sound pressure level of 137 dB was applied. A scanning laser vibrometer was used to measure the forced vibration response of multiple points on the structure's surface, and modal measurement data were analyzed. The modal parameters were identified by applying the phase separation method to the measured signals, thereby obtaining the natural frequencies, mode shapes, and damping ratios.

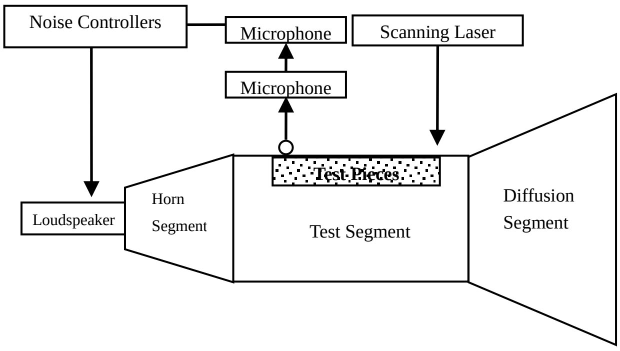


Figure 6 Block diagram of the system of random noise excitation method

Figure 7 Test Photograph of random noise excitation method

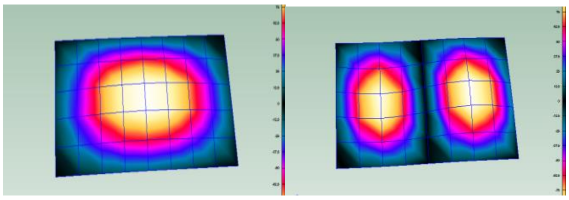
3. Test Results

3.1 Hammering Method Measurement Results

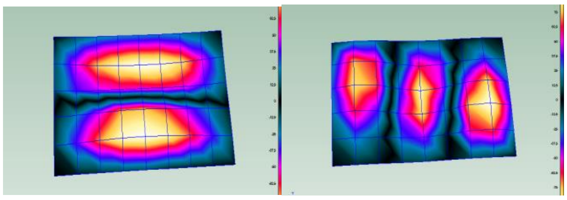
The modal measurement results of the test piece using the hammering method are shown in Table 3. The mode shapes are illustrated in Figure 8. A total of 6 modes were identified within 1000Hz, with their corresponding mode shapes also shown in Figure 8.

Table 3 Modal Frequency and Damping Ratio Measurement Results Using the Hammering Method

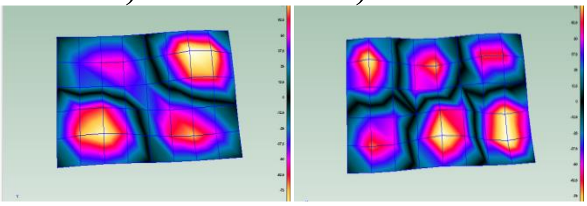
Modal Order	Modal frequency Hz	Damping ratio %
1 order	243.99	5.77
2 order	449.24	4.10
3 order	637.70	3.15
4 order	736.64	3.47
5 order	752.03	3.04
6 order	960.04	1.54



a)2st order *b)2nd order*



c)3rd order d)4th order



e)5th order f)6th order

Figure 8 Measurement results of modal shapes by hammering method

3.2 Transient Excitation Method Measurement Results

The transient excitation method uses the kinetic energy of a small metal ball as the excitation source. The ball periodically strikes the same position on the test piece's surface, and a scanning laser vibrometer is used to scan each point on the surface for modal analysis. Each time the laser scans a point, the ball strikes the same position on the test piece. The analysis software used was VibroLink. During testing, a single-point laser vibrometer was used to measure the vibration at a single point on the surface of the test piece as a reference point. Both the test channel and the reference channel employed automatic phase compensation. Modal frequencies were determined by observing the peak frequency of the acceleration response, while the mode shapes were derived by combining the z-axis vibration vectors displayed within a 50Hz bandwidth centered on the acceleration response peak frequency. The photo of the laser scanning point using transient excitation method is shown in Figure 9.

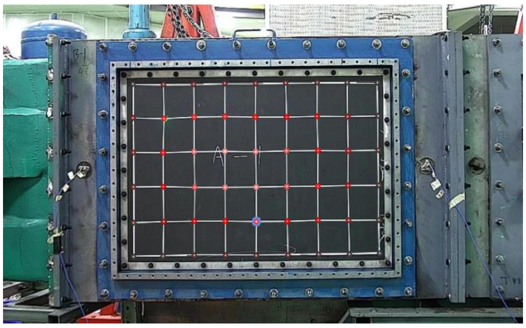


Figure 9 Photograph of the Laser Scanning Points Using the Transient Excitation Method

3.2.1 Left Side Ball Impact Laser Scanning Modal Test

The modal parameter measurement results are listed in Table 4.

Table 4 Measurement results of modal parameters on the left side of the ball-strike test piece

Modal Order	Modal frequency Hz	Damping ratio %
1 order	253.75	2.51
2 order	459.37	2.21
3 order	748.75	1.76

3.2.2 Central Ball Impact on the Test Piece

The modal parameter measurement results are listed in Table 5.

Table 5 Measurement results of the center modal parameters of the ball-impacted test piece

Modal Order	Modal frequency Hz	Damping ratio %
1 order	253.75	2.28
2 order	455.63	3.45
3 order	747.50	2.34

3.2.3 Right side of the ball-striking test piece

The modal parameter measurements are shown in Table 6.

Table 6 Measurement results of modal parameters on the right side of the ball-striking test piece

Modal Order	Modal frequency Hz	Damping ratio %
1 order	253.75	2.79
2 order	460.62	2.60
3 order	748.12	2.09

The measured modal frequencies for the three ball-strike positions are summarized in Table 7.

Table 7 Comparison of modal frequency results for different parts of the ball-striking test piece

Modal Order	Left side of the test piece	Center of the test piece	Right side of the test piece
1 order	253.75	253.75	253.75
2 order	459.37	455.63	460.62
3 order	748.75	747.50	748.12

From the measurement results in Table 7, it can be seen that the modal frequencies measured from different ball impact positions are highly consistent, and the corresponding modal shapes are also highly consistent. This indicates that using the single-point transient periodic excitation method, the different excitation positions have virtually no effect on the modal test results.

3.3 Modal Measurement Results with Exciter Excitation

The exciter is suspended using elastic ropes, with the excitation end connected to the convex surface of the test piece via a rigid screw. On the other side of the test piece, a scanning laser vibrometer is used to measure vibrations across the flat surface of the test piece.

3.3.1 Corner Position Excitation with 100Hz~1000Hz Broadband Random Signal

For the choice of excitation position on the test piece, two excitation positions were set. The first excitation position is located at the upper right corner of the convex surface of the test piece, referred to as the "corner excitation." The second excitation position is at the center of the convex surface of the test piece, referred to as the "center excitation." The exciter's head was first installed at the corner of the test piece. A broadband random signal ranging from 100Hz to 1000Hz was continuously applied, and the vibration response was captured using a laser vibrometer for modal analysis. The modal measurement results are listed in Table 8.

Table 8Measurement results of 100Hz~1000Hz broadband excitation at the corner of the shaker

Modal Order	Modal frequency Hz	Damping ratio %
1 order	221.875	2.78
2 order	458.125	4.37
3 order	768.125	3.50

3.3.2 Corner Position Single Sweep Frequency from 100Hz to 1000Hz

At the corner position, the exciter was used to apply a sine wave signal sweeping from 100Hz to 1000Hz slowly. The sweep frequency time was controlled to match the total time required for the laser vibrometer to scan all vibration pickup points on the test piece. The laser vibrometer was used to capture the vibration response for modal analysis.

From the figure, it can be seen that when using a single sweep frequency signal for excitation, the scanning laser vibrometer was unable to analyze the structure's frequency response curve, making it impossible to determine the modal frequencies. The main reason for this phenomenon is that during a single sweep frequency, the test piece is in a transient vibration state, and the scanning laser vibrometer cannot obtain steady-state vibration measurement results.

3.3.3 Corner Position 100Hz~1000Hz, 1.6s Cyclic Sweep Frequency

In this experiment, the exciter was used to repeatedly apply a sine wave sweep signal from 100Hz to 1000Hz at the corner of the test piece, with each sweep lasting 1.6 seconds. The sweep was continuously cycled. It is important to note that the selected 1.6-second sweep period does not directly correspond to the laser vibrometer's point-by-point scanning frequency, where the interval between each point scan is approximately 5 seconds.

The laser vibrometer was used to capture the vibration response for modal analysis. The modal parameter measurement results are presented in Table 9.

Table 9 100Hz~1000Hz Cyclic Sweep Frequency Response Measurement of Shaker at Angle Position

Modal Order	Modal frequency Hz	Damping ratio %
1 order	222.50	2.58
2 order	463.75	4.31
3 order	783.12	3.52

Based on the experimental results, it can be concluded that using a single sweep of the exciter combined with vibration measurement via a scanning laser vibrometer is ineffective in obtaining the modal frequencies of the structure. However, by employing cyclic frequency sweeps with the exciter in conjunction with the scanning laser vibrometer, the structural modal frequencies can be effectively measured.

3.3.4 Center Position 100Hz~1000Hz, 1.6s Cyclic Frequency Sweep

The exciter was moved to the center of the test piece. A sinusoidal sweep signal from 100Hz to 1000Hz was repeatedly applied, with a single sweep time of 1.6 seconds in a cyclic manner. Vibration responses were captured using a laser vibrometer for modal analysis. The modal measurement results are presented in Table 10.

Table 10 100Hz~1000Hz Cyclic Frequency Sweep Measurement at Shaker Center Position

Modal Order	Modal frequency Hz	Damping ratio %
1 order	221.87	2.05
2 order	462.50	3.47
3 order	763.75	4.29

From the comparison of the experimental results in Section 3.3, it can be seen that the modal measurement results of the cyclic frequency sweep laser scanning modal test are independent of the exciter's excitation position.

3.3.5 Center Position Exciter 100Hz~1000Hz Broadband Random Signal

At the center position, a continuous broadband random signal ranging from 100Hz to 1000Hz was applied using the exciter. The vibration response was captured using a laser vibrometer for modal analysis. The modal parameter measurement results are presented in Table 11.

Table 11 Results of 100Hz~1000Hz Broadband Random Signal Excitation Method at Center Position

Modal Order	Modal frequency Hz	Damping ratio %
1 order	222.50	2.25
2 order	471.50	3.89
3 order	766.87	3.68

A comparison of the modal parameter measurements of the shaker excitation method is shown in Table 12.

Table 12 Summary of Measurement Results of Shaker Excitation Method

Modal Order	100Hz~1000Hz broadband excitation at corner position	100Hz~1000Hz single sweep at corner position	100Hz~1000Hz cyclic sweep at corner position	100Hz~1000Hz cycle sweep at center position	100Hz~1000Hz broadband random at center position
1 order	221.875	Modal frequency cannot be obtained	222.50	221.87	222.50
2 order	458.125		463.75	462.50	471.50
3 order	768.125		783.12	763.75	766.87

As shown in Table 12, the modal frequency measurement results are relatively consistent when using the same excitation method, regardless of the exciter's position. Additionally, the modal frequencies measured using both broadband random and cyclic frequency sweep excitation methods are also quite consistent. However, when using a scanning laser vibrometer for vibration pickup, it is not possible to analyze and obtain the structural modal frequencies with a fixed-frequency sinusoidal signal or a single sinusoidal sweep signal from the exciter.

3.4 Modal Measurement Results Using Random Noise Excitation Method

The test piece was mounted on the sidewall of the traveling wave tube and continuously subjected to broadband noise excitation ranging from 50Hz to 800Hz. A scanning laser vibrometer was used to measure the surface vibrations of the test piece for modal analysis. The modal measurement results are presented in Table 13.

Table 13 Measurement results of random noise excitation method

Modal Order	Modal frequency Hz	Damping ratio %
1 order	256.25	3.90
2 order	458.12	2.62
3 order	746.25	2.68

Using broadband noise excitation in the 50Hz~800Hz range, the scanning laser vibrometer can measure the acceleration frequency response curve of the test piece, allowing for the determination of the primary working modal frequencies. However, it is not possible to obtain the modal shapes.

4. Experimental Results Analysis

The modal measurement frequencies obtained using different excitation methods are shown in Table 14. The modal orders were redefined based on the mode shapes, using the impact hammer test results for comparison. Except for the impact hammer test, all other excitation methods involved vibration measurements taken by point-by-point scanning with a scanning laser vibrometer. A comparison of the modal frequency measurement results from various excitation methods is presented in Table 14.

Table 14 Comparison of Modal Frequency Measurement Results of Various Excitation Methods (Unit: Hz)

Modal Order	Force hammer method	Transient excitation method			Shaker excitation method				Random noise excitation method
	Hammer Strike	Ball strike left	Ball Strike Center	Ball strike right	Corner position 100Hz~1000 Hz wideband random	Center position 100Hz~1000 Hz wideband random	Corner Positions 100Hz~1000 Hz Cyclic Sweep	Center position 100Hz~1000 Hz cyclic sweeping	50Hz~800Hz wideband noise
1 order	243.99	253.75	253.75	253.75	221.88	222.5	222.50	221.87	256.25
2 order	449.24	459.37	455.63	460.62	458.13	471.5	463.75	462.50	458.12
3 order	637.70	/	/	/	/	/	/	/	/
4 order	736.64	748.75	747.5	748.12	/	/	/	/	746.25
5 order	752.03	/	/	/	768.13	766.87	783.12	763.75	/
6 order	960.04	/	/	/	/	/	/	/	/

As shown in the comparison of results in Table 14, the modal frequencies measured using transient excitation and random noise excitation are quite close to those obtained using the impact hammer method. However, the first-order modal frequency measured using the exciter excitation method is significantly lower than that obtained by other methods. This discrepancy is likely due to the exciter altering the overall mass of the test system, thereby changing the original modal frequencies of the test piece.

5. Conclusions

This research focused on modal testing of a typical honeycomb sandwich structure using four different excitation methods: impact hammer excitation, transient excitation, pulse sequence excitation, and random noise excitation. The study verified the feasibility of conducting modal analysis with the last three excitation methods in conjunction with a scanning laser vibrometer. Based on the comparison of 10 different test conditions, the following conclusions were drawn:

a) When using a scanning laser vibrometer to capture vibration signals, the excitation position does not affect the modal measurement results as long as the nodal lines are avoided.

c) The modal frequencies measured using transient excitation and random noise excitation are slightly higher than those obtained using the impact hammer method. The first-order modal frequency measured with the exciter excitation method is significantly lower than that obtained by the other two methods.

d) Overall, the modal frequency results from transient excitation are the closest to those from the impact hammer method, with a frequency deviation of about 4.1%. The frequency deviation for the random noise excitation method is around 4.9%, which is relatively small. The deviations in these two modal testing methods are within the acceptable range for engineering applications.

e) The modal damping values obtained using transient excitation, pulse sequence excitation, and random noise excitation in this experiment show significant differences from those measured by the impact hammer method. The reasons for these differences require further investigation.

f) The modal measurement methods used in this study still have several limitations. When capturing vibration signals with a scanning laser vibrometer, the lack of specialized analysis software for modal analysis resulted in the failure to identify many modal orders. In future research, it is planned to use specialized modal analysis software to further analyze the measurement results and identify the missing modes.

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