Delamination Damage Detection in Laminated Composite by LDR-Based Multi-frequency Method

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(Received 5 June 2020; revised 14 September 2020; accepted 19 September 2020)

Abstract: Local defected resonance (LDR) is a recently-developed non-destructive testing method, which identifies damage by detecting the vibrational response of the structural surface under the wideband ultrasonic excitation. The concept of LDR is studied and applied for damage imaging of delamination in composite laminates. Aiming at the problem of poor anti-noise ability and inaccurate damage identification in traditional detection process, an LDR-based multi-frequency method is proposed. Experimental results show that the proposed method can realize the localization and imaging of delamination damage in composite materials.

Key words: carbon fibre reinforced polymer; local defect resonance (LDR); multi-frequency; non-destructive testing

CLC number: TP274;TB123 **Document code:** A **Article ID:** 1005-1120(2020)S-0028-07

0 Introduction

Composite materials are more and more widely used in advanced engineering structures due to high specific strength, light weight, resistance to fatigue/corrosion and flexibility in design[1]. In view of the particularity of the structure, various defects such as delamination and debonding are easily generated during manufacturing and service, which affect the structural integrity. To assure the structural performance of composite components, several NDT techniques have been developed and implemented over the last decades, including ultrasonic testing, eddy currents, acoustic emission, and thermography etc.[2-4].

Local defected resonance (LDR) is a newly developed acoustic vibration nondestructive testing technology in recent years[5-6]. The presence of a defect leads to a local decrease in rigidity for a certain mass of the material and therefore manifests in a particular characteristic frequency of the defect. A frequency match between the driving ultrasonic wave and this characteristic frequency provides a LDR and results in efficient energy pumping into the defect area[7]. The majority of all LDR-based methods can be divided into two main groups. The first group is based on the so-called derivative effects in acoustic wave-defect interaction. They include, for instance, nonlinear, thermal, acousto-optic responses also applied for NDE and acoustic imaging of damage[8-9]. The second group is mainly combined with laser vibration measurement technology to obtain the vibration response of the structure surface under wide-band stimulation[10-11]. The size and location of the damage are determined by analyzing the structural mode shapes and identify the LDR modal.

However, some real defects, in particular, delamination in composite laminates plate, the local vibration modes of the defects are complex, and the detection results are susceptible to noise interference. In this paper, a multi-frequency method based on near-LDR frequency band is proposed and used to detect defects. The results validate the delamination assessment capabilities of the methodology.

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How to cite this article: DENG Xingyu, QIU Jinhao, JI Hongli, et al. Delamination damage detection in laminated composite by LDR-based multi-frequency method[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(S): 28-34.

http://dx.doi.org/10.16356/j.1005-1120.2020.S.004

1 Experimental Setup

The LDR based laser vibrometry method is applied to a case study of composite laminate plates. Before the experiment, a specimen containing two delamination, as shown in Fig.1, has been manufactured. The composite plate has an in-plane dimension of 200 mm× 200 mm with a stacking sequence of $[0_2/90_2/0_2/90_2]$ and the nominal thickness is 1 mm. Delamination was introduced by laying down a 20 mm×20 mm×0.05 mm thick Teflon ply during layup. In #1 defect, delamination is placed in the corner, centering at 3/4 of each side, between the 2nd and 3rd layers. In #2 defect, delamination is moved to the middle of the plate, between the 4th and 5th layers.

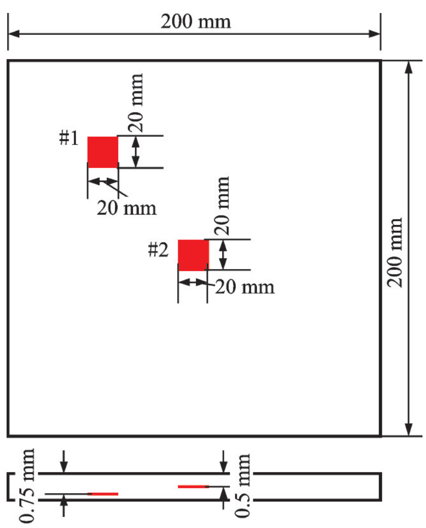


Fig.1 Delamination configuration

The experimental arrangement for NDT system is presented graphically in Fig.2. The composite plates were freely suspended using elastic cords. A piezoelectric transducer (r=5 mm), attached to the sample surface, was excited with a broadband periodic chirp signal with frequency bandwidth 62.5 kHz and forces the sample to vibrate accordingly. In the conducted experiments, the surface vibration response in a rectangular grid containing the delamination on the top surface of the sample was recorded by means of a laser Doppler vibrometer (LDV). The recorded signals are then transformed to the frequency domain using the fast Fourier transform (FFT) through the Polytec software[12-13]. The LDR corresponds to the resonance of damage area and modal analysis was used to identify the local resonance modes.

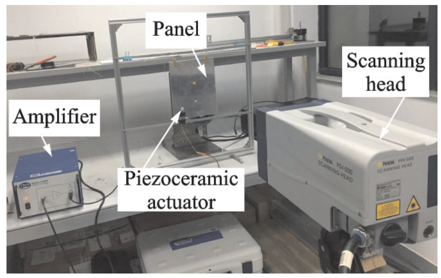


Fig.2 Experimental setup

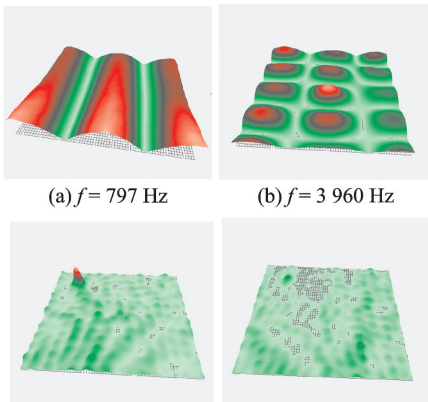
2 Results and Analyses

The defect is first detected using the traditional modal analysis method, and then the multi-frequency method is proposed and applied to damage imaging. Finally, the detection results of these two methods are compared.

2.1 Delamination damage detection based on modal analysis

Traditional LDR-based laser vibrometry method detects damage by analyzing the structural modal at different frequencies to identify the LDR modes and then images the defects according to the LDR mode shapes[14-15]. Fig.3 shows four typical modes of a laminate with delamination under the excitation of a wideband signal (0—62.5 kHz) in the experiment. We can find that in low frequency range, it represents the vibration modal of the whole structure (Figs. 3 (a) , (b)). As the frequency increases, when the frequency associated with the LDR frequency, the local vibration amplitude of the defect area increases dramatically, which is the LDR mode (Fig.3(c)). Under the excitation of other frequencies, the response of structural surface has no obvious features (Fig.3(d)).

After identifying the LDR mode, the location and shape information of the defect can be obtained. Fig. 4 shows the results of #1 delamination, the depth of defect is 0.75 mm. The fundamental LDR frequency was found at 40 kHz and the associated mode shape is illustrated in Fig.4(a). Here, the locally magnified amplitude can be clearly observed in

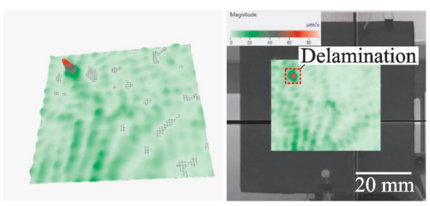


(a) f = 797 Hz (b) f = 3 960 Hz

(c) f = 39.4 kHz (d) f = 41.9 kHz

Fig.3 Typical vibration mode characteristics of the specimen

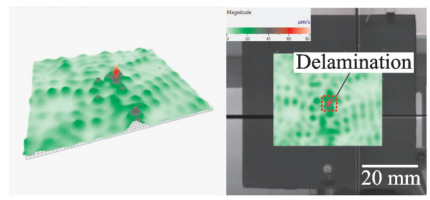
the corner of the plate, where the delamination was detected. According to the vibration mode, the 2D defect imaging result is shown in Fig.4(b). The calculated area of the delamination is about 142 mm^2, which is smaller than the actual damage area (400 mm^2), and the defect shape information is inaccurate.



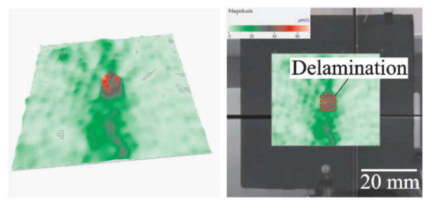
(a) f = 40 kHz (b) Damage imaging result

Fig.4 Results of 0.75 mm delamination in CFRP

For the #2 defect with a depth of 0.5 mm at the center of the composite plate, the same method can be used to identify the LDR modes and the results are shown in Fig.5. The first-order LDR mode and the corresponding LDR frequency is determined at 30.8 kHz. The defect shape is easily recognizable (see Fig.5(a)), but it is underestimated. The defect area is calculated to be 130 mm^2 approximately, which is much smaller than the actual damage size, with a relative error of 67.5%. The results indicate that only the position of the damage can be obtained while the damage shape is different from the actual damage. Subsequently, a second-order LDR mode occurs at 59 kHz in the high frequency range (Fig.5(b)). According to the second-order LDR vibration mode for 2D damage imaging, the damage area is calculated to be about 355 mm^2 with a relative error of 11.3%, which is better than the first-order LDR imaging result. At the same time, the damage location and shape information are more accurate. The analysis of resonance vibrations in different LDR modes has shown that the higher-order LDR is more sensitive to the boundary of the damage than the fundamental LDR modal.



(a) Vibration modes at the fundamental LDR (30.8 kHz) and 2D imaging



(b) Vibration modes at the second harmonic LDR (59 kHz) and 2D imaging

Fig.5 Results of 0.5 mm delamination in CFRP

2.2 Near LDR frequency band multi-frequency method

By analyzing the spectrum, we find that for a composite structural laminate containing a delamination defect, the resonant peak of the LDR is relatively flat, which is different from the spectrum characteristic corresponding to the overall vibration mode of the structural at a low frequency. Fig.6 is a portion of the spectrogram of the measured point located in the defect area, and the LDR resonance peak is marked. We define the LDR bandwidth Δf as the difference between the frequencies f_1 and f_2 corresponding to $V = 0.5V_{\text{LDR}}$ (-6 dB bandwidth) on both sides of the resonance peak. The LDR bandwidth is calculated to be approximately 3 kHz in this case, where the structure exhibits a local vibration mode limited to the defect area. Due to the complexity of delamination and the influence of noise, the LDR modes corresponding to different frequencies will not be same, which leads to poor anti-noise ability of traditional vibration-based methods and the detection result of the defect is seriously distorted.

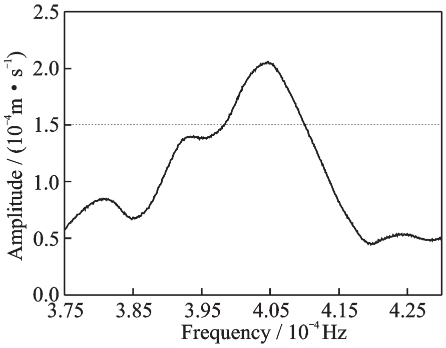


Fig.6 Frequency response of delamination in a CFRP plate

Based on the LDR effect, under the excitation of different frequencies in the LDR band, the vibration response of the measuring point at the defect dramatically increases compared with the point at healthy area. Therefore, superimposing the damage feature of all frequencies distributed in the LDR band can weaken the influence of single frequency and evaluate the health status of the point more accurately. Assuming that the velocity response signal of the point acquired by LDV is $F(f)$, the LDR band is Δf and FFT lines can be calculated by $n=\Delta f/r$ easily (r is the frequency resolution). Defining the damage factor $D_{\Delta f}$ as follows

$$D_{\Delta f}=\sqrt{\frac{\sum_{i=1}^{n}[\overline{F}(f_i)\cdot F(f_i)]}{n}}$$

where $\overline{F}(f_i)$ is the complex conjugate of $F(f_i)$. Eq.(1) first calculates the auto-power spectrum of $F(f)$, and then obtain the root mean square of different frequencies located in the LDR band. The obtained damage factor $D_{\Delta f}$ reflects the vibration energy of the measuring point within this bandwidth.

After identifying the LDR mode, the damage location can be determined and then the spectrum of the damage point can be obtained. For #1 delamination, the LDR frequency is found to be 40 kHz, and the bandwidth of the LDR is calculated about 4 kHz distributed in the frequency band of 38—42 kHz. Taking the points on the straight path pass through the damaged area as sampling, we draw the mode profile curve of different excitation frequencies in the LDR band (Fig.7).The defect is distributed in the x-coordinate in a range of 15—35 mm. We found that as the excitation frequency changes, the position and width of the resonance peak change due to the influence of noise.

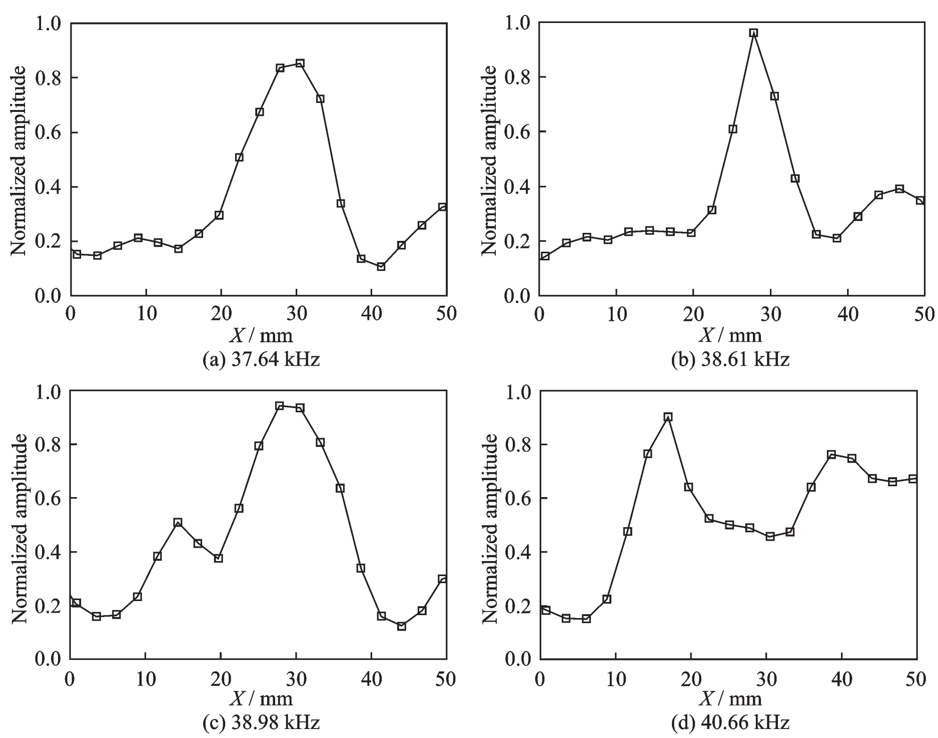


Fig.7 Normalized amplitude profiles of different LDR modes in #1 delamination

Using the LDR-based multi-frequency method, we calculate the damage factor $D_{\Delta f}$ of scan point on the straight path through the delamination area according to Eq.(1) and plot the $D_{\Delta f}$ amplitude curve. The results are shown in Fig.8, which reveals the location of defect (15—35 mm). It can be seen that when the measuring point located in the defect area, $D_{\Delta f}$ increases observably, and the amplitude curve of the damage factor is smoother than the mode profile at mono LDR frequency. It is indicated that the energy magnitude of the measuring point can accurately determine the health state of the measuring point.

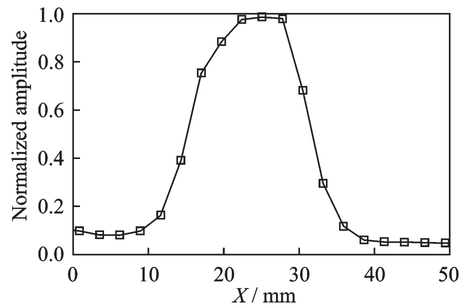


Fig.8 Normalized amplitude of $D_{\Delta f}$ pass through # 1 delamination

For composite structures, the surface reflection signal received by the LDV scanning head is weak, which leads to the fluctuation of detection results. For #2 delamination, the LDR bandwidth calculated from the damage point spectrum is about 5 kHz, distributed in the frequency band of 28—33 kHz. Arbitrarily taken four different frequencies in the LDR band, the corresponding mode profile curve is shown in Fig.9, and the defect is distributed in the x-coordinate with a range of 20—40 mm.

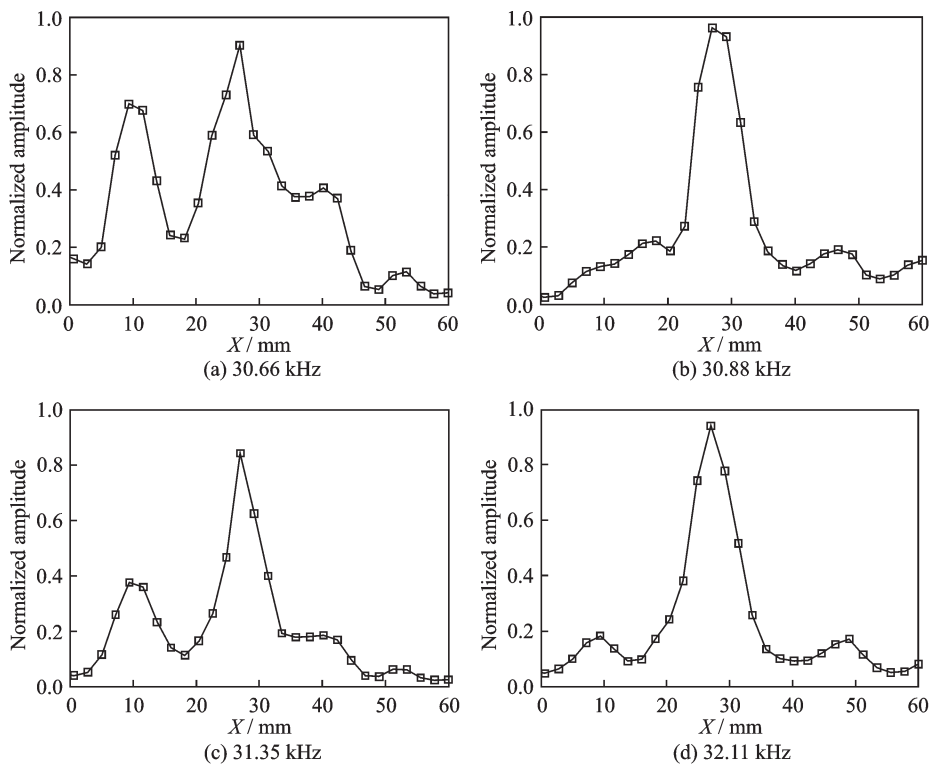


Fig.9 Normalized amplitude profiles of different LDR modes in #2 delamination

Under the exciting of 30.66 and 31.35 kHz, a small peak not belonging to the LDR occurs at the position $x = 10$ mm outside the defect area. This could have been expected as the poor quality of the individual measurement points. For the points on the same path, the multi-frequency method is used to calculate $D_{\Delta f}$ and the amplitude curve is shown in Fig. 10. Compared with the mono-frequency LDR mode profile curve, the unexpected values at some frequencies are suppressed. A smooth peak appears in the defect area of 20—40 mm, which can accurately obtain the health status of the measuring point and reflects the geometric information of the defect.

After obtaining the spectrum of all measure-

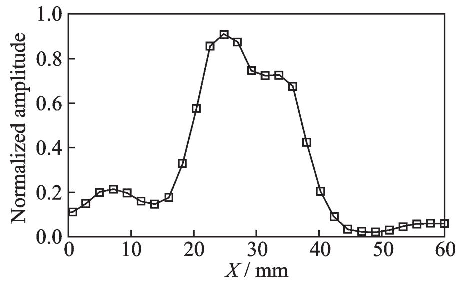


Fig.10 Normalized amplitude of $D_{\Delta f}$ passing through # 2 delamination

ment points in the entire scan area containing two defects, we calculate the normalization damage factors at 28—33 kHz and 38—42 kHz. The 2D damage imaging results of two different depth delaminations in the laminate based on $D_{\Delta f}$ are shown in Fig.11. The actual defect size is marked with a dotted line in Fig.11.

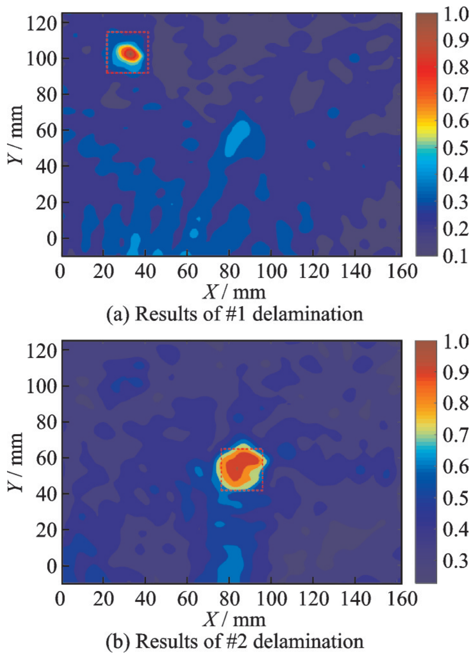


Fig.11 2D damage imaging based on $D_{\Delta f}$

The area of the detected damage region in #1 delamination is 319 mm^2 approximately. Comparing with the traditional mono-frequency mode method, the relative error of damage area is reduced by 44.2%. The area of the detected damage region in # 2 delamination is 436 mm^2 approximately, and the relative error is 9%. The results of two different damage imaging methods are shown in Table 1.

The results indicate that using the LDR-based multi-frequency method can weaken the influence of single frequency and significantly improve the anti-noise ability. The obtained shape information of the defects is more accurate.

Table 1 Results comparison of different imaging method

Domain	LDR mode		$D_{\Delta f}$	Error of $D_{\Delta f}$/ %
	Fundamental/ mm^2	Second-order/ mm^2		
Actual area	400	400	400	
#1 delamination	142		319	20.3
#2 delamination	130	355	436	9

3 Conclusions

The method for delamination detection is investigated in composite laminates plate based on multi-frequency LDR. Firstly, the defect is detected using the traditional modal analysis method and studies the vibration modal characteristics of the composite plate under wideband excitation. Aiming at the problem of poor anti-noise ability and inaccurate defect area identification, a near LDR frequency band multi-frequency method is proposed and used to detect defects. The results of experiment and analysis indicate that the method can effectively improve the anti-noise ability of the LDR method and detect the damage area more accurately.

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Acknowledgements This work was supported by the National Natural Science Foundation of China (Nos. 51875227, 51805261, 51775267), the Natural Science Foundation of Jiangsu Province (Nos. BK20181286, BK20180430), and the Aviation Science Fund (No. 20161552014). The authors realize that the time and space available for a review of such an ambitious subject are limited, thus, regretfully, we are unable to cover many important contributions. The authors would like to acknowledge Dr. TAO Congcong and Dr. XU Xiaojuan for their assistance, all with the State Key Laboratory of Mechanics and Control of Mechanical Structure, College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics.

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Author contributions Prof. **QIU Jinhao** and Mr. **DENG Xingyu** designed the study. Mr. **DENG Xingyu** performed most of the experiments. Dr. **ZHANG Chao** and Mr. **DENG Xingyu** performed the data analysis, data interpretation, and figure generation. Prof. **JI Hongli** and Mr. **DENG Xingyu** wrote the manuscript. All authors contributed to critical revisions and approved the final manuscript.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Tong)

基于LDR多频信息融合的复合材料分层缺陷检测

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摘要:缺陷局部共振(Local defect resonance,LDR)方法是近年来提出的一种基于结构振动特征识别的新型无损检测技术,通过检测结构表面在宽频超声信号激励下的振动响应特征来识别损伤。为此基于LDR效应,对有分层缺陷的复合材料层合板进行检测。针对传统的依据LDR振型进行损伤检测的方法抗噪能力较差以及缺陷面积识别不准确的问题,提出了近LDR频带的多频损伤信息融合方法。实验结果表明,利用所提出的方法可显著提高损伤识别过程中的抗噪能力,实现复合材料层合板中分层缺陷的准确定位和成像。

关键词:碳纤维增强复合材料;缺陷局部共振;多频;无损检测