Damage detection of multi-source excitation based on FBG sensor

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Abstract. The vibration detection is one of the key technologies of structural reliability. Traditional detection methods mainly focus on the analysis under single excitation, while the actual engineering problems mostly present the resonance phenomenon of multi-source excitation. Therefore, in this paper, based on the characteristics of FBG sensor, the vibration response characteristics under multi-source excitation are studied, including theoretical simulation and experimental research under multi-source excitation. On this basis, the experimental system for damage detection is built and its results show that this method by multi-excitation detection is feasible and it is sensitive to crack damage.

1. Introduction
The vibration responses of mechanical components in complex structure are actually joint action of vibration sources. So the vibration detection under multi-source excitation is a key technique for reliability of the complex structures. While traditional nondestructive testing methods are used in the specific occasion only considering an incentive with their limitations[1]-[2]. In fact, most of engineering problems are nonlinear under multi-source excitation. In recent years, many scholars have put forward some methods for multi-excitations. Wang developed a measurement technique for measuring vibration responses of different cylindrical structures under multi-excitations by experimental study[3]. Chen designed the experiment under multiple excitations by a shell structure[4]. Hu detected the closed crack by vibro-acoustic modulation experiment[5]. Non-destructive sensing system has been researched in structural health monitoring[6]-[9]. But these studies often focused on the simulation or on the experiment, comparative study on the simulation and experiment is few. In addition, generally multiple actuators or sensors are easy to bring a nonlinear factor. Therefore, the thin element should be considered. Meanwhile, Optical fiber Bragg grating (FBG) sensor has many advantages such as simple structure, small volume, light weight, etc., and it is convenient to use wavelength division multiplexing technology to avoid self weight load of electrical sensors and the influence of electromagnetic field and other various factors compared with the general electric sensor. So FBG sensor is selected to detect strain in our multi-excitation system.

This paper mainly focuses on the multi-excitation vibration responses of the plate structure based on FBG sensor. And the key contribution is to provide more data by theoretical simulation and experimental research for multi-excitation vibration responses and develop a corresponding damage detection method by nonlinear coefficients. This paper is structured as follows. Section 2 introduces the principle of multi-source excitation, which provides a theoretical basis for analysis of nonlinear coefficient. In section 3, the simulation analysis under the multi-excitation in COMSOL software are carried out. These results lay the foundation for the later experiment. In Section 4, the experimental
system is built and response analysis under the excitations with different parameters are given. Meanwhile, the output signals reveal an extremely efficient amplitude modulation and multiple frequency side-bands through crack damage, which show that this method is feasible and it is sensitive to crack damage.

2. Measuring principle
Assuming that the system has multiple inputs and multiple outputs:

\[ Y_i(f) = \sum_{j=1}^{n} H_{ij}(f) X_j(f) + N_i(f) \quad (i = 1, 2, 3, ... m) \]

where \( i \) represents for measurement point of vibration response, while \( j \) represents incentive points. \( Y_i(f) \) is the output, \( X_j(f) \) is the input, \( H_{ij}(f) \) is response function, \( N_i(f) \) is the noise. In order to simplify the multi excitation model, it is assumed that there are only two excitation sources, whose waveforms are sine signals. In this case, on the basis of the existing model, we can obtain the relationship between the input and the output. Here if the input \( X \) contains two harmonic component signals with different frequencies \( f_1, f_2 \), then the output \( y \) can be simplified to the following two order equation by Brouche[6] as follows:

\[
Y = -i\frac{\alpha A_1}{2} \delta(f_1 - f)e^{\omega_1} - i\frac{\alpha A_1}{2} \delta(f_2 - f)e^{\omega_2} - i\frac{\beta A_1^2}{4} \delta(2f_1 - f)e^{\omega_1} + i\frac{\beta A_1^2}{4} \delta(2f_2 - f)e^{\omega_2} + i\frac{\beta A_1^2}{2} \delta(f_2 - f_1 - f)e^{i(\omega_1 - \omega_2)} + i\frac{\beta A_1^2}{2} \delta(f_2 + f_1 - f)e^{i(\omega_1 + \omega_2)}
\]

(2)

Where \( \alpha \), \( \beta \) is the constant. From the formula (2), stress-strain relation coefficient is basically a non-linear response relationship through the analysis of the response signals. The amplitude changes caused by a damage can be obtained by calculating the nonlinear parameter \( \gamma \) according to the following formula.

\[
\gamma = \frac{4}{k_1k_2d} \frac{A(f_1 \pm f_2)}{A(f_1)A(f_2)} = \frac{c_1c_2}{\pi^2 f_1 f_2 x} \frac{A(f_1 \pm f_2)}{A(f_1)A(f_2)}
\]

(3)

Where \( k_1, k_2 \) are wave numbers, and \( d \) is the distance for detection. \( A(f_1), A(f_2) \) represent the amplitudes corresponding to the frequency components of the excitation signal. \( A(f_1 \pm f_2) \) represents the amplitude of the frequency sum component or the frequency difference component.

3. Vibration simulation under multi-excitation
In order to simplify the calculation, we assume that two excitations are placed directly on the plate without the adhesive layers. First, a geometric model is built in COMSOL software, model size of the plate is 400*400*1mm\(^3\) (as shown in figure 1a). The two circles ‘A’, ‘B’ (as shown in figure 2a) represent the piezoelectric sheets, whose diameters are 20mm and 10mm respectively and thickness are both 1mm. The acoustic field distribution under the multi-source excitation is shown in figure 1b.
Fig. 1. Displacement and pressure distribution of the healthy plate

a-displacement distribution; b-pressure distribution

The material parameters of the plate are specified: elastic modulus is 72 GPa, poisson coefficient is 0.33, density is 2700 g/cm³. And two different excitation signals are applied on ‘A’, ‘B’: the center frequencies are respectively 5kHz, 21kHz, and the voltage amplitudes respectively are 20V, 50V. In this way, the calculation results can be obtained after the mesh processing, such as the displacement field and the acoustic field distribution under the multi-source excitation, as shown in figure 1, from which we can observe the variation of displacement field at different time and the acoustic field on the different location.

We can establish two different plate models: a health plate(as shown in figure 2a) and a damaged
A plate (as shown in figure 3a). ‘A’, ‘B’ are piezoelectric elements, while ‘M’, ‘N’ are detection points on the plate. ‘M’ is near to ‘A’, while ‘N’ is close to ‘B’. There is a crack damage, whose dimension is 20mm * 1mm * 1mm on the vertical lines away from the center line from ‘A’ and ‘B’ on the damaged plate. By comparing the responses of the health plate and damaged plate, we can see that the amplitude of the detection signal will have a little change owing to the damage effect as shown in figure 2b and 3b, especially on the frequency points, such as 5k, 10k, 15k, 20k, 25k, 40k, roughly corresponding frequencies \( f_1, 2f_1, f_2 \pm f_1, f_2 \pm f_1, 2f_2 \) in the formula (3). The blue curve shows the response to the detection point ‘M’, and the green curve shows the response to the detection point ‘N’. The amplitude of the detection signal near the excitation point will appear the following changes: the low frequency signal component is stronger which is close to the low-frequency excitation, while if the monitoring point is near the high frequency excitation, high frequency component will strong, too.

![Harmonic responses of the healthy plate](image1)

**Fig. 2.** Harmonic responses of the healthy plate

- a- M,N point distribution  
- b- Harmonic responses of two points

![Harmonic responses of the damaged plate](image2)

**Fig. 3.** Harmonic responses of the damaged plate

- a- M,N point distribution  
- b- Harmonic responses of two points

Overall, the damage effect are as follows: the maximum amplitude of monitoring point near the damage is greater than that of the healthy plate, and at the same time, there is a relatively increase in harmonic components of high frequency signal by comparing the figures 2b and 3b. This means that the damage will cause sound wave reflection, which could affect monitoring points around the damage. We can observe the change of these points to determine the damage evolution.

4. Multi- excitation test

According the above simulation results, the detection system of the multi-excitation was shown in fig.4 (a) , where piezoelectric patches are used for the excitation, while FBG sensor is used for detection response. And the layout is shown in fig. 4 (b), where the plate’s dimension is 400mm * 400mm * 1mm, and circles ‘A’, ‘B’ represent the piezoelectric patches with diameter 20mm, 10mm.
The distance between FBG sensor and incentive ‘B’ is 60mm. The FBG wavelength are 1300.650nm. The vertical line ‘X’ represents crack damage, whose dimension is 20mm*1mm*1mm on the vertical lines away from the center line from ‘A’ and ‘B’. The signals from piezoelectric patches were transmitted to the plate structure, and FBG pasted on the board structure detected the strain. The demodulation system was composed of a tunable laser, an optical coupler and a photodetector. The tunable laser inspired a beam of light to the FBG through an optical coupler. Then the reflected light from the FBG propagated to the photodetector through the coupler. If the central wavelength of the laser beam was tuned to near to that of the FBG at free strain, the wavelength change of the FBG could be measured by the photodetector, which can display on digital oscilloscope after the photoelectric conversion.

According to the simulation analysis, we can see that the incidence waves with different frequencies have different responses, therefore, we choose the appropriate incentive parameters in our experiments: excitation frequencies are 5 kHz, 21 kHz and corresponding excitation voltages are 20V, 50V. In order to further obtain the response information, we can perform FFT transform on the signals to obtain the frequencies and amplitudes of harmonic components more clearly. Through the comparison of the response spectrums for healthy plate and damaged plate, the sidelobe signals with other frequencies appear on both sides in the center frequency because of the damage effect, whose experimental results are shown in table 1. These experimental data are different from simulation data because the experiment involves the transfer efficiency of the glue, which is not considered in the simulation process in order to simplify the calculation. As a whole, the overall relative change trends of the experimental data are basically consistent to the simulation results. This phenomenon can be seen in table II by calculated nonlinear coefficients. On the basis of the experimental data, combined with the known parameters such as velocity, wave number, detection distance, we can calculate the nonlinear coefficients by the formula (3), whose calculation results are shown in table 2.

| Comparison | f1 (5 kHz) | 2f1 (10 kHz) | f2-f1 (16 kHz) | f2 (21 kHz) | f2+f1 (26 kHz) |
|------------|------------|--------------|----------------|-------------|----------------|
| Healthy area(mV) | 35.28 | 4.35 | 2.91 | 15.68 | 3.09 |
| Damaged area(mV) | 16.1 | 0.49 | 5.84 | 5.88 | 0.32 |

| Table 2. The calculated nonlinear coefficients |
|-----------------------------------------------|
| nonlinear coefficients | γ₁ | γ₂ |
| Healthy area | 3.15 | 2.97 |
| Damaged area | 19.28 | 34.8 |
| Incremental ratio | 5.12 | 10.72 |

It can be seen from table II, there is a certain degree of nonlinear effect in healthy plate since of the boundary factors. But it can be ignored because it is very smaller than nonlinear effects caused by crack damage. The frequency difference between the two harmonic components is \( f_2 - f_1 \), whose
incremental ratio of that of the output signal in damaged area is 10 times than that of the output signal in healthy area. The sum of two frequencies is \( f_1 + f_2 \), whose incremental ratio of that of the output signal in damaged area is 5 times than that of the output signal in healthy area. By comparing the nonlinear coefficients, we can draw a conclusion that the nonlinear coefficients increase in damaged area significantly. That is mean that damage will strengthen the nonlinear phenomena. So we can determine there is damage in the plate structure according to the nonlinear coefficient.

5. Conclusion

This paper mainly focuses on the vibration responses of the structure under multi-excitation, including the theoretical simulation and the experimental research. The influence of frequency and phase on the response characteristics of structures under multi-excitation is analyzed by taking the plate structure as the object. The experimental results reveal the phase of multi-source excitation has obvious effect on vibration response of structure by calculating nonlinear coefficients. It proves the feasibility of this multi-source detection method, laying the foundation for further study on damage detection based on FBG sensors. The key contribution is to provide more data by theoretical simulation and experimental research for multi-excitation vibration responses and develop a corresponding measuring method.

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