Vol. 16 No. 1
Journal of Chongqing University English Edition [ISSN 1671-8224] March 2017

doi:10.11835/j.issn.1671-8224.2017.01.01

To cite this article: GUO Shao-xia, PEI Qiang. Application of short-time Fourier transform to high-rise frame structural-health monitoring based on change of inherent frequency over time [J]. J Chongqing Univ Eng Ed [ISSN 1671-8224], 2017, 16(1): 1-10.

Application of short-time Fourier transform to high-rise frame structural-health monitoring based on change of inherent frequency over time

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Received 7 June 2016; received in revised form 16 July 2016

Abstract: The high-rise frame structure has become more and more widespread, like its damage from the complication of the environment. The traditional method of damage detection, which is only suitable for the stationary signal, does not apply to a high-rise frame structure because its damage signal is non-stationary. Thus, this paper presents an application of the short-time Fourier transform (STFT) to damage detection of high-rise frame structures. Compared with the fast Fourier transform, STFT is found to be able to express the frequency spectrum property of the time interval using the signal within this interval. Application of STFT to analyzing a Matlab model and the shaking table test with a twelve-story frame-structure model reveals that there is a positive correlation between the slope of the frequency versus time and the damage level. If the slope is equal to or greater than zero, the structure is not damaged. If the slope is smaller than zero, the structure is damaged, and the less the slope is, the more serious the damage is. The damage results from calculation based on the Matlab model are consistent with those from the shaking table test, demonstrating that STFT can be a reliable tool for the damage detection of high-rise frame structures.

Keywords: short-time Fourier transform; fast Fourier transform; damage identification; shaking table test; time-frequency analysis

CLC number: TU313 Document code: A

1 Introduction

There are more and more high-rise frame structures around the world, and various damages occur in engineering systems during their service life. These damages may be caused by various factors such as natural disasters, excessive responses, wear and tear of working parts, impact of a foreign object, and cumulative crack growth [1]. They would inevitably lead to damage accumulation and resistance decrease [2]. Obviously, structural damage detection has been a more and more important research topic in civil engineering [3-5].

At present, the method of the damage detection is mainly based on dynamic damage detection [6]. There are three ways based on respectively dynamics [7], signals [8], and artificial networks [9]. The method based

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on signals is more popular than other methods in today's civil field.

The traditional ways of damage detection are based on the time domain [10], and the frequency domain [11]. The former directly uses temporal information to identify the modal parameters of a structure [12], and the latter uses the fast Fourier transform (FFT) [13-14] to transform the temporal information to the frequency domain. Because the response signals of the time domain are difficult to obtain, the fast Fourier transform may be subject to spectral leakage, mixing, frequency decomposition [15], and so on. Nevertheless, the method based on time-frequency analysis [16-18] is able to express the frequency spectrum property of the time interval using the signals within this interval. The short-time Fourier transform (STFT) [19] is widely used in damage detection as one of the time-frequency analysis methods.

This paper uses FFT and STFT to determine the data of analytic signals, the model built with Matlab, the shaking table test, and so on. The results indicate that STFT can reflect the change of frequency with the change of time, and it can detect the damage by the slope of the frequency-time shape. If the slope is equal to or greater than zero, the structure is not damage. If the slope is smaller than zero, the structure is damage; and the smaller the slope is, the more serious the damage is. The response is consistent with the test, which indicates that the proposal is a suitable reliable tool for the damage detection of high-rise frame structures.

2 Fundamentals of STFT analysis

The basic idea of STFT is windowing and shifting of observation signals and performing Fourier transform of windowed signals. A brief background on the Fourier transform (FT) and STFT analysis is described in this paper.

2.1 Fundamentals of FT

A general overview of FT can be expressed as

$$F\left(\mathrm{i}\omega\right)=\int_{-\infty}^{+\infty} f\left(t\right)\mathrm{e}^{-\mathrm{i}\omega t}\,\mathrm{d}\,t, \tag{1}$$

$$f\left(t\right)\overset{\text{def}}{=}\frac{1}{2\pi}\int_{-\infty}^{+\infty} F\left(\mathrm{i}\omega\right)\mathrm{e}^{\mathrm{i}\omega t}\,\mathrm{d}\,\omega, \tag{2}$$

where f is the signal; t is the time; $F(\mathrm{i}\omega)$ is the frequency function of $f(t)$, and $f(t)$ is the original function of $F(\mathrm{i}\omega)$; i is the imaginary unit; and ω is the frequency. Eqs. (1) and (2) are the FT and its inverse, respectively. FT can clearly respond to the frequency of the whole period of time and overlooks the temporal information completely. So FT is only suitable for stationary signals.

2.2 Fundamentals of STFT

To improve FT, Gabor put forward STFT in 1946. In 2006, Neild et al. [20] studied the relation between nonlinear vibration and the damage of the reinforced concrete beam using STFT. In 2003, Xu et al. [21] studied the modal parameters of the structure using STFT and HHT [22]. In 2014, Wu [23] identified the damage of wind turbine blades using STFT, and the result was considerable.

The principle of STFT is written as follows.

$$\mathrm{STFT}=\left(\omega,\tau\right)=\int_{-\infty}^{+\infty} g\left(t-\tau\right)f\left(t\right)\mathrm{e}^{-\mathrm{i}\omega t}\,\mathrm{d}\,t, \tag{3}$$

where $g(t)$ is the window function.

The processes of STFT are as follows [24].

Step 1. Cut off the signal using the window function;

Step 2. Use FT to process the signal in the window;

Step 3. Move the window along the time shaft;

Step 4. Use the FT to process the signal in the new window;

Step 5. Repeat Steps 3 and 4.

The gather of all signals after processing is STFT.

3 Analysis

The damage is bound to cause changes in modal parameters, such as inherent frequency, vibration mode, frequency response, and acceleration [25]. The most immediate index is the inherent frequency. Therefore, in this work we select the inherent frequency as the damage index.

To compare FFT with STFT, we choose two analytic signals: the first is a segmented signal with two different frequencies, and the other is a signal with a linearly changed frequency as time goes on. The two signal are presented as follows.

$$f\left(t\right)=\begin{cases}\sin\left(\dfrac{1}{5}\pi t\right) & t\le 500\ \text{s},\\ \sin\left(\dfrac{1}{10}\pi t\right) & 500\ \text{s}\le t\le 1\,000\ \text{s};\end{cases} \tag{4}$$

$$f\left(t\right)=0.4\pi t^2, \tag{5}$$

where *t* is the time.

The calculated frequency result of the signal described by Eq. (4) is 0.10 Hz when $t\le 500$ s and is 0.05 Hz when $500 < t \le 1\,000$ s; and that by Eq. (5) is 0.4*t*/s Hz. The signals processed with FFT and STFT are shown in Fig. 1.

It is shown in Fig. 1(a) that FFT and STFT both can recognize the frequency of signal described by Eq. (4), which is 0.10 Hz or 0.05 Hz. STFT can clearly present the relationship between frequency and time but FFT can not. In Fig. 1 (b), STFT clearly recognizes that the frequency of signal described by Eq. (5) is 0.4*t*/s Hz; whereas FFT hardly recognizes any frequency..

As shown in Fig. 1, FFT can recognize only the frequency of a stable signal, without any temporal information, and can hardly recognize any frequency of a non-stable signal which STFT can clearly recognize. During a structural damage, the frequency is inevitably changed; so, the signal is not always stable. Thus, STFT is more suitable for the damage detection of a structure than FFT.

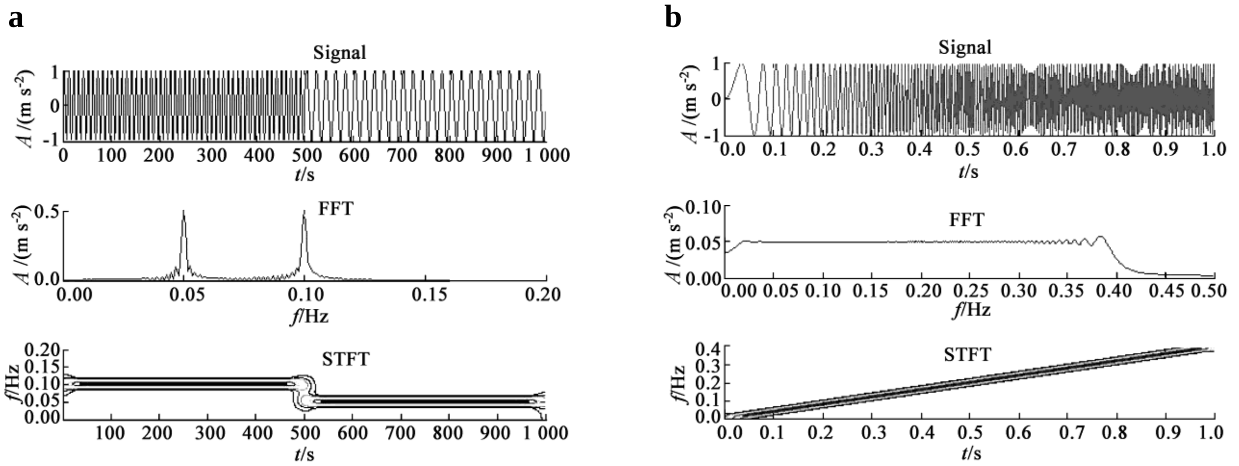

Fig. 1 Fast Fourier transform (FFT) and short-time Fourier transform (STFT) of signals described by a) Eq. (4) and b) Eq. (5), where *A* is the amplitude, *t* is the time and *f* is the frequency

4 Damage detection

4.1 Model built with Matlab

To explore the relationship of the damage with the figure of frequency and time, we build an architectural model of 12 stories using Matlab as shown in Fig. 2.

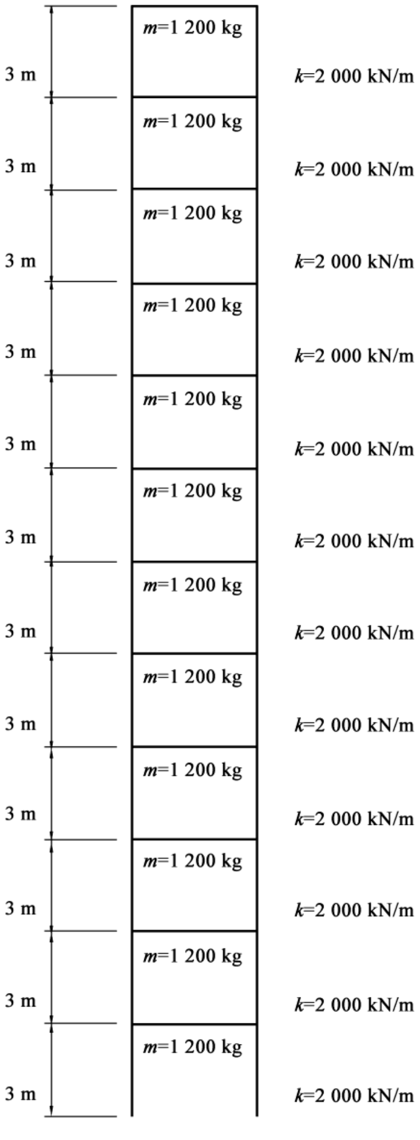

Fig. 2 Architectural model of 12 stories

We regard the first floor (1F) rigidity reduced 0%, 10%, 20%,…,80%, 90% as the damage degree 0%, 10%, 20%,…, 80%, 90%, respectively. Then we obtain the accelerations under these ten conditions and use FFT and STFT to analyze the accelerations. Because the relationship of frequency and time is not clearly presented in the STFT contour line, we extract the two-dimensional figure of the first inherent frequency and time, and the results are shown in Figs. 3 and 4.

In Fig. 3, it is difficult to see the change of frequency; whereas in Fig.4, it is easy to find that the line of frequency change over time is steeper with a larger damage degree. To further explore the relationship between frequency and damage degree, we list the first inherent frequencies of FFT and the slopes of STFT in Table 1.

The frequency is lower with a lower 1F rigidity only when the damage degree is larger than 40%; whereas the slope decreases with the decrease of rigidity in the whole damaging process. Obviously, the slope of the frequency-time pattern by STFT is more sensitive to a damage than that by FFT.

Hereinafter we use the data of a shaking table test from Tongji University to verify the effectiveness of the above conclusions.

4.2 Shaking table test

The shaking table test was conducted at Tongji University on a concrete-frame scale structure model of one bay and 12 stories which suffered four different earthquake waves, namely, El Centro (EL), Kobe (KB), Shanghai Artificial (SA), and Shanghai Bedrock (SB). The acceleration was received through inputting the four different earthquake waves from three directions X, Y, and Z. For simplifying the research, this paper only selects the direction of X of the SA wave. In this test, the damage information of the fourth floor was the most evident. So we use the data of the fourth floor for analysis.

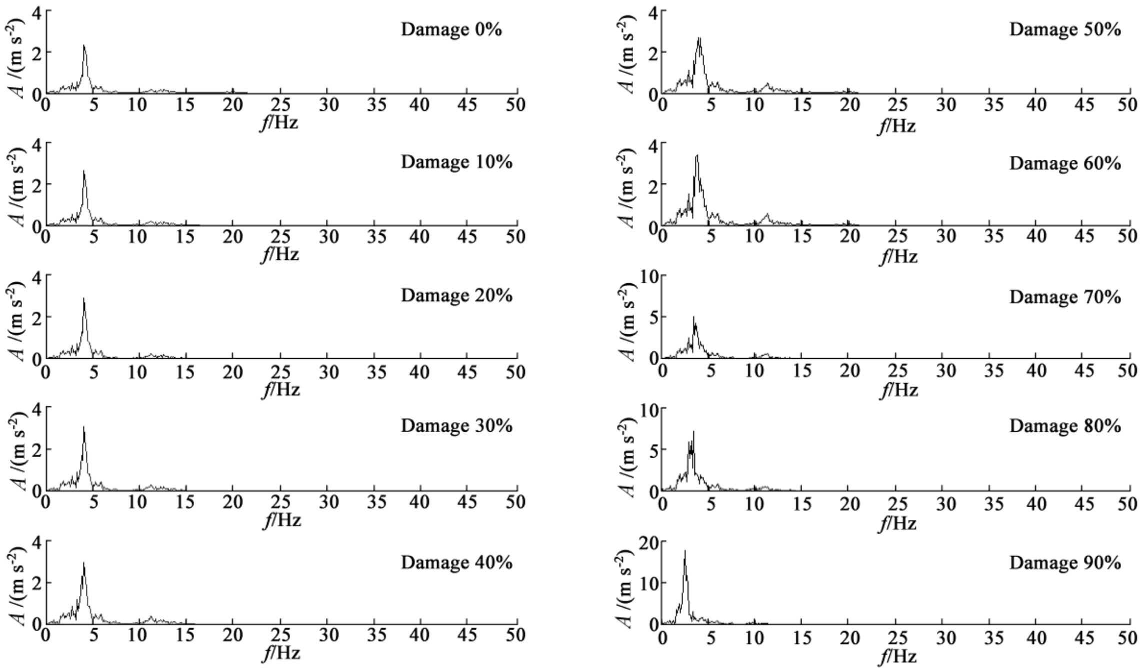

Fig. 3 Fast Fourier transform (FFT) of the architectural model, where *A* is the amplitude, and *f* is the frequency

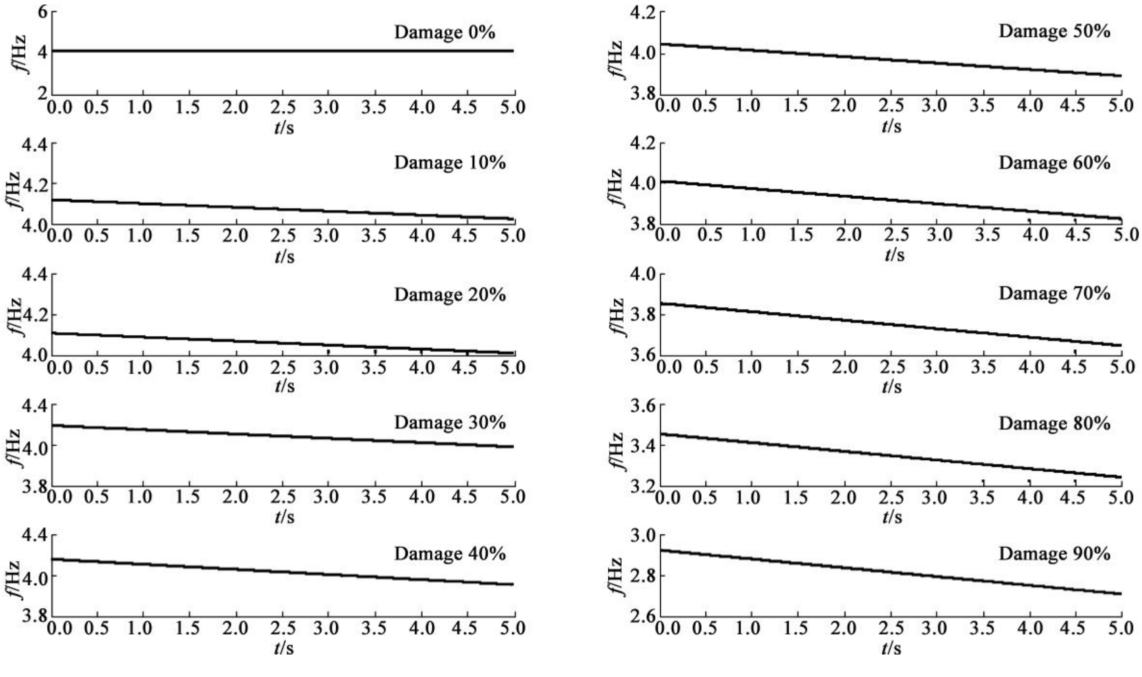

Fig. 4 Short-time Fourier transform (STFT) of the architectural model where *t* is the time, and *f* is the frequency

Table 1 Frequency of fast Fourier transform (FFT) and the gradient of short-time Fourier transform (STFT) of the Matlab model

Serial No.	Damage degree/%	Frequency of FFT/Hz	Gradient of STFT frequency- time line
1	0	4.125	0
2	10	4.125	–0.000 38
3	20	4.125	–0.000 39
4	30	4.125	–0.000 42
5	40	4.125	–0.000 50
6	50	3.875	–0.000 63
7	60	3.750	–0.000 75
8	70	3.375	–0.000 83
9	80	3.125	–0.000 85
10	90	2.500	–0.000 86

The experimental conditions are listed in Table 2.

Table 2 Experimental conditions

Description	Acceleration/(m s^{-2})	Earthquake size
SA1	0.090	Small
SA2	0.258	Medium
SA3	0.388	
SA4	0.517	Large
SA5	0.646	
SA6	0.775	

Note: SA is the Shanghai Artificial earthquake wave.

To prove that STFT is able to recognize the damage degree, we process the data of the six conditions with FFT and STFT. The results are shown in Figs. 5 and 6.

In a similar way to that for the analysis of the model built with Matlab, we use the first inherent frequency of FFT and the gradient of STFT, as listed in Table 3.

Table 3 The first inherent frequency of fast Fourier transform (FFT) and the gradient of short-time Fourier transform (STFT) for the shaking table test

Condition	Frequency of FFT/Hz	Gradient of STFT frequency-time shape
SA1	3.500	0.000 061 4
SA2	3.375	–0.000 200 0
SA3	2.000	–0.000 300 0
SA4	1.500	–0.000 330 0
SA5	1.375	–0.000 330 0
SA6	1.125	–0.000 330 0

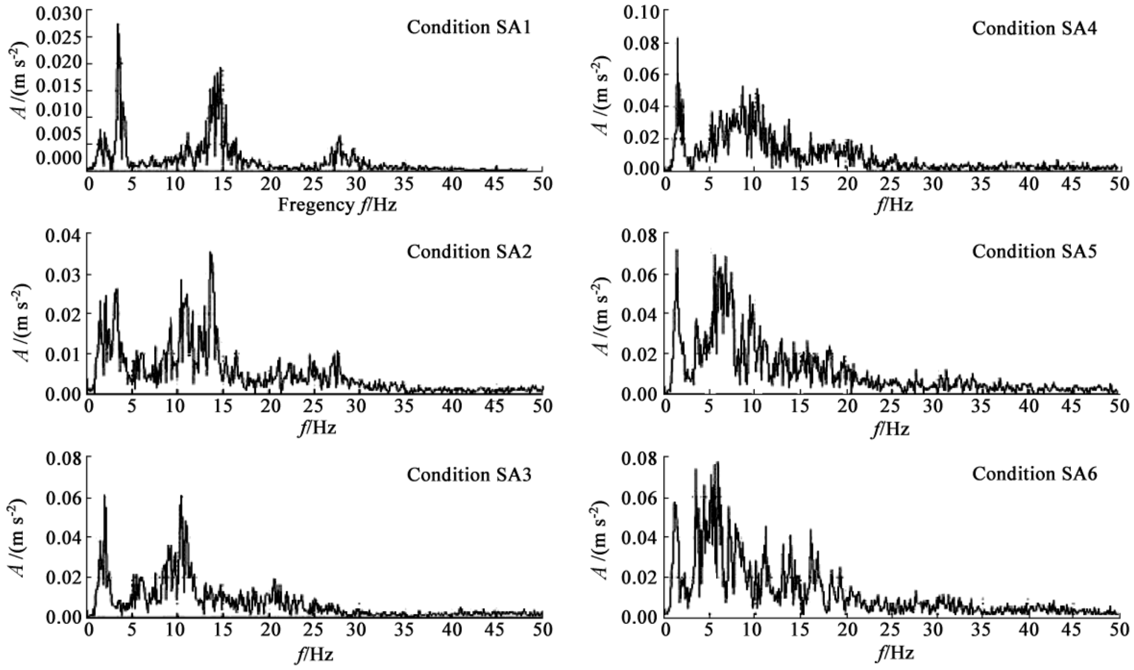

Fig. 5 Fast Fourier transform (FFT) of the shaking table test, where *A* is the amplitude, and *f* is the frequency

As shown in Table 3, with the earthquake size changing from small to large, the first inherent frequency of FFT decreases, indicating that the damage degree is more serious; and the STFT frequency-time gradient decreases too, suggesting that a lower frequency-time gradient is an indicator for a more serious damage. In the condition of SA1, the frequency-time gradient is positive, suggesting that the structure is not damaged in a small earthquake. From the condition SA2, the gradient is negative, showing that in a medium earthquake, the structure suffers a damage. In conditions SA4 to condition SA6, the gradient becomes lower, indicating that the damage is more serious in a large earthquake.

In the shaking table test, no crack happened in the condition SA1. In the condition SA2, there were some tiny cracks about 0.05 mm. In the condition SA3, the cracks were about 0.15 mm. In a large earthquake the cracks increased further, till the structure completely collapsed. The results of STFT agree with those obtained from the experiment. Obviously, STFT can clearly detect the damage degree.

4.3 Discussion

Compared with a traditional method for damage detection, STFT has the following advantages.

FT can detect the damage only when the original data are available, but STFT can detect the damage with the existing data without the need to compare with the original signal.

FT can obtain only the frequency for a complete period, but STFT can obtain the frequency at any time. So STFT can reflect the change of frequency with the change of time.

FT can detect only a large damage that the decrease of rigidity is larger than 50%, but STFT can detect smaller damages.

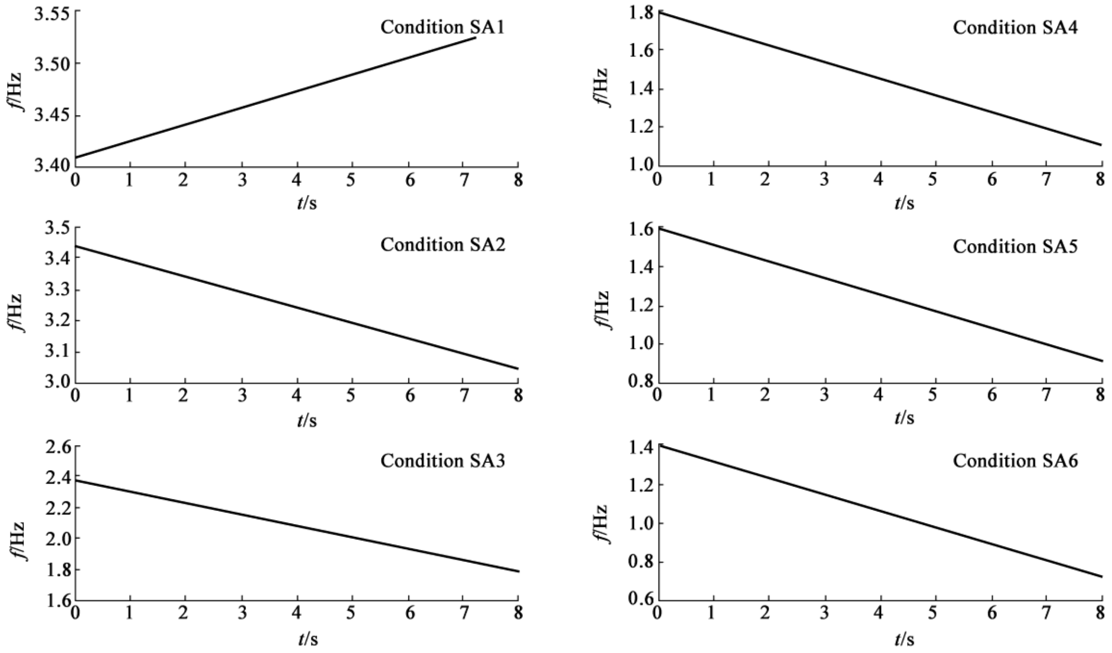

Fig. 6 Short-time Fourier transform (STFT) of the shaking table test, where *t* is the time and *f* is the frequency

Nevertheless, STFT cannot overcome the deficiencies of the Fourier transform, such as spectral leakage, frequency-mixing, and frequency-resolution. In essence, STFT is a method of single resolution because it uses an unchanged short-time window function.

5 Conclusion

In this paper, we use FFT and STFT to analyze two different signals, and demonstrate that STFT is easier to present the relationship between frequency and time than FFT. Then, we build a 12 story model with Matlab to research the damage degree with the frequency-time gradient obtained by picking up the two-dimensional chart of the first inherent frequency and time by using STFT. The results show that there is not any damage in a small earthquake, there is some slight damage in a medium earthquake, and there is a severe damage in a large earthquake. We also conduct a shaking table test on a concrete-frame scale structure model of one bay and 12 stories. The experimental results prove the correctness of the results on the Matlab model. Therefore, this paper provides a feasible method for the high-rise frame structural damage detection.

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