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TIME–FREQUENCY ANALYSIS FOR NON-DESTRUCTIVE TEST SIGNAL OF ROCK BOLTS USING GENERALIZED S-TRANSFORM

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The length of rock bolt and grouting quality do not often meet the required design standards in practice because of the concealment and complexity of bolt construction. Non-destructive testing is preferred when testing a rock bolt's quality because of its convenience, low cost and wide detection range. Because of the complexity of multiple media, detecting the bolt length and the location of defect is still a technical challenge which needs to be studied further. This paper presents a time–frequency analysis for the non-destructive sound-wave test of rock bolts based on the generalized S-transform, which was adopted to extract reflection from the bolt end and grouted defect. Four experimental model tests with different location of defect were used to verify the feasibility of the generalized S-Transform. The results show that it is feasible and effective to use the generalized S-transform to identify the bolt length and grouted defect. The changes caused by the reflected wave significantly appear as peaks in the time-frequency spectrum calculated by generalized S-Transform, which has great advantage in identification for weak reflection and multiple reflections complex media.

Keywords: Non-destructive test, Bolt, Time–frequency analysis, Generalized S-transform.

1 Introduction

Rock bolts have been widely used in underground mining, tunneling and slope engineering to offer considerable support for structural safety (He, 2015). Full-length bonded rock bolts are commonly applied in practice because of their simple design and resistance to corrosion (MOHURD, 2009). However, the bolt length and grouting quality do not often meet the required design standards because of the concealment and complexity of bolt construction. Shortening bolt length leads to insufficient bearing capacity, while poor or incomplete grouting makes the bolts come into contact with water, leading to corrosion and fracturing (Beard and Lowe, 2003). Conventionally, the bolt quality is assessed by pull-out tests and over-coring, which are destructive and time consuming. Moreover, the standard compliance of tested bolts does not guarantee the quality of untested bolts (Cui, 2013). Therefore, economical and effective non-destructive methods for bolt testing are required.

Despite other attempts at other non-destructive bolt testing methods (Cui and Zou, 2012; Ivanović and Neilson, 2013; Yu et al, 2013), the sound-wave reflection method is the most commonly used in practice because of its clear principle, convenient operation, low cost and wide detection range (MOHURD, 2009). Currently, despite existing analysis methods to interpret reflection signals (Wu et al, 2012; Cheng et al, 2012; Lee et al, 2012), some problems regarding testing bolts must be solved: (1) identifying weak reflections from minor impedance differences between the reflected interfaces, (2) analyzing complex test signals that are caused by multiple media, and (3) interpreting multiple reflections from interfaces.

The generalized S-transform which was developed in 1994 for analyzing geophysics data (Stockwell and Mansinha, 1996) provides frequency dependent resolution while maintaining a direct relationship with the Fourier spectrum. The time–frequency distribution of a weak signal can be finely depicted by the generalized S-transform in time–frequency domain. (Mcfadden et al., 1999; Pinnegar and Mansinha, 2004). In this study, we take advantage of this characteristic of the generalized S-transform to identify the arrival times of the reflected wave in the bolt test signal. The location of the grouted defect or bolt end can be calculated according to the arrival times of the reflected wave. Four models with different grouted defect were used to verify the feasibility of generalized S-Transform.

2 Bolt Test Signal Analysis Method with The Generalized S-Transform

2.1 *Bolts Test*

In the sound-wave-reflection bolt test, the reflections from the bolt end and defects are extracted to calculate the bolt length and the location of the defects in the time domain. In practice, the sound-wave velocity and travel time in the protruding and bonded components are considered respectively. The bolt length and the location of the defects can be calculated according to Equation (1): (MOHURD, 2009).

$$L = L_1 + L_2 = L_1 + \frac{1}{2}\times t_2 \times C_2 = L_1 + \frac{1}{2}\times(\Delta t - 2t_1)\times C_2 = L_1 + \frac{1}{2}\times(t_r - t_d - 2\frac{L_1}{C_1})\times C_2 \tag{1}$$

where L is the distance from the reflection interface to the bolt top; L_1 and L_2 are the lengths of the protruding and bonded components, respectively; L_1 can be measured before the test. t_1 and t_2 are the travel times of the protruding and bonded components, and C_1 and C_2 are the sound-wave velocities of the protruding and bonded components. Δt is the travel time of the sound wave, which is the difference between the arrival time of the reflected wave t_r and the arrival time of the directive wave t_d.

C_1 and C_2 can be obtained by calibrating the sound-wave velocity, so Δt are crucial to calculating the corresponding length. This paper develops a sound-wave-reflection bolt-test signal-analysis method to identify Δt using The Generalized s-transform

2.1 *The Generalized S-TRANSFORM*

The generalized S-transform of the signal $x(t)$ is defined as (Pinnegar and Mansinha, 2004):

$$S(\tau, f) = \int_{-\infty}^{+\infty} x(t)\omega(\tau - t, f)e^{-i2\pi ft}\,dt \tag{2}$$

$$\omega(\tau, f) = \frac{|f|^p}{k\sqrt{2\pi}}\exp[-\frac{f^{2p}\tau^2}{2k^2}] \tag{3}$$

$$\sigma(f) = \frac{k}{|f|^p} \tag{4}$$

where, t is the time, τ is the position of Gauss's window function of Generalized S-Transform (ω) on the t-axis. f is frequency. $\sigma(f)$ is scale factor of Gauss's window function, p is a regulatory factor, k is a regulatory parameter. The time window will be widened with the increase of k and the decrease of p. The regulatory factor p has larger effect on the time window's shape (width and height) compared to regulatory parameter k. Thus, a wider time window can be adopted at low frequency to get a higher frequency resolution. A narrower time window can be used to obtain a higher time resolution in high frequencies.

According to the Fourier Transform, Convolution theorem and formulas above, the generalized s-transform can be expressed as below:

$$GST(\tau, f) = \int_{-\infty}^{+\infty} X(\alpha + f) e^{-\frac{2\pi^2\alpha^2k^2}{f^{2p}}} e^{-i2\pi\tau t} d\alpha \tag{5}$$

where, $X(\alpha+f)$ is the calculated from $x(t)$ using Fourier Transform and shifting.

we can derive the discrete time S-transform from formula (5) as below:

$$GST[j,n] = \sum_{m=0}^{N-1} X\left[\frac{n+m}{NT}\right] e^{-\frac{2n^2k^2m^2}{n^{2p}}} e^{\frac{i2\pi mj}{N}} \tag{6}$$

Where, $f = n/NT$, $\tau = jT$, T is the sampling interval and sampling frequency. Then the time–frequency distribution of test signal can be calculated by Formula (6).

When a grouted defect present under pile bottom, the reflected wave from grouted defect, and bolt end will change the wave pattern. The changes in the test signal significantly appear as peaks in the time-frequency spectrum. We can identify those peaks to detect the bolt length and grouted defect.

3 Experimental Test

Four full-length bonded-rock-bolt models with different grouted defects were designed to verify the generalized S-transform signal analysis method. The bolts were designed to be fully column grouted with the same total length (L in Fig. 1) and different location of defects. A summary of the geometry of all the bolt models is shown in Table 1.

Table 1 Geometry of test bolts model

Number		L0(mm)	Lm1(mm)	Lk(mm)	Lm2(mm)	L(mm)
Model 1	Bolt without defect	200	-	-	-	3000
Model 2	Bolt with defect	200	300	300	200	3000
Model 3	Bolt with defect	200	1300	300	200	3000
Model 4	Bolt with defect	200	2300	300	200	3000

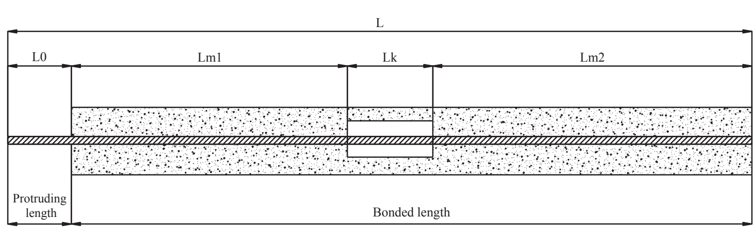

Fig. 1 Schematic diagram of a fully-grouted rock bolts

JL-MG(D) rock-bolt test instrument was used in the experiments. As shown in Fig.2, sound waves were excited by a transducer after regulating the transmitter energy. The sound waves reflected when reaching defects and bolt end in the propagation. The reflections were then received by an acceleration sensor that was fixed at the end of the protruding bolts. Finally, the signal was recorded on a computer and analyzed according to the generalized S-transform. The wave velocity in bonded part and protruding part are calibrated as 3980 m/s and 5100 m/s.

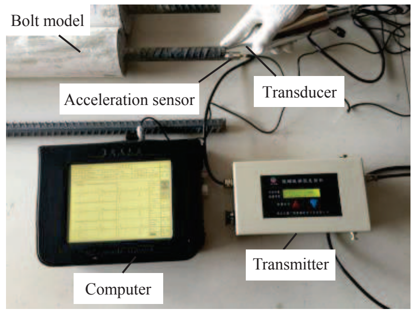

Fig. 2 Experimental schematic diagram of rock bolts test

4 Time-Frequency Analysis for Test Signal

Fig. 3 (a), (c), (e) and (g) are the test signal of models 1 to 4 in time domain. Fig (b), (d), (f) and (h) are the corresponding generalized S-Transform amplitude spectrums, which present the time-frequency characteristic of test signal.

In the model test 1 without defect, points A and B in Fig 3(a) correspond to the arrival time of directive wave and reflected wave. In the Fig. 3(b), it finds that the arrival of the directive wave and reflected wave will cause the peaks in the time-frequency spectrum (i.e. point A (0.388 ms) and B (1.923 ms) in Fig 3(b)). The bolt length can be calculated by the Eq. (1) according to the arrival times. The value is 3.098 m with an error of 3.267%, which may be caused by the calibrated velocity. The energy of the reflection can be evaluated by the color in the generalized S-Transform amplitude spectrum. It verifies that the generalized S-Transform can identify the arrival time of the reflected wave and the energy of it.

In the model test 2 with a grouted defect at 0.5m, the bolt length can be calculated as 3.059 m with an error of 1.959% according to the point A (0.368 ms) and B (1.903 ms) in the Fig 3(d). The reflection from the grouted defect can be roughly identified at the point C in Fig 3(c). But the multiple reflections from the defect can be found in time-frequency spectrum (point C (0.670 ms), D (0.938 ms) and E (1.206 ms) in Fig 3(d)). The location of defect can be identified based on the point C at 0.645 m.

In the model test 3 with a grouted defect at 1.5m, it is difficult to identify the reflection from the bolt end in the time domain (see Fig 3(e)). The reason is that the reflection from the grouted defect and its multiple reflections interfere the reflection from bolt end. But in the time-frequency spectrum, the reflections from defects and bolt end can be identified at point C (1.233 ms) and B (2.030 ms) in Fig 3(f). Thus, the location of grouted defect and bolt length can be calculated at 1.711 m and 3.297 m. It shows that the generalized S-Transform has advantage on the identification for the reflected wave interference from by multiple media.

In the model test 4 with a grouted defect at 2.5m, it is difficult to identify the reflection from grouted defect (point C in Fig 3 (g)) for its weak energy. In the time-frequency spectrum, the reflections from grouted defect and bolt end can be identified at point C (1.643 ms) and B (2.111 ms) in Fig 3(h). The location of grouted defect and bolt length can be calculated at 2.630 m and 3.564 m. Thus, it verifies that the generalized S-Transform method can make weak reflection significant in time-frequency spectrum.

The calculated bolt length and location of grouted defect and their errors are shown in Table 2. It shows that most relative errors of the identifications for bolt length is less than 10%. The biggest one is the model test 4. The reason is that the grouted defect in model 4 is very close to the bolt end, which largely affect the identification for the arrival time of reflection from bolt end. The absolute error of the identification for the location of defect is around 0.2 m. The calculated locations are all in the grouted defect part, since the size of grouted defect is 0.3 m.

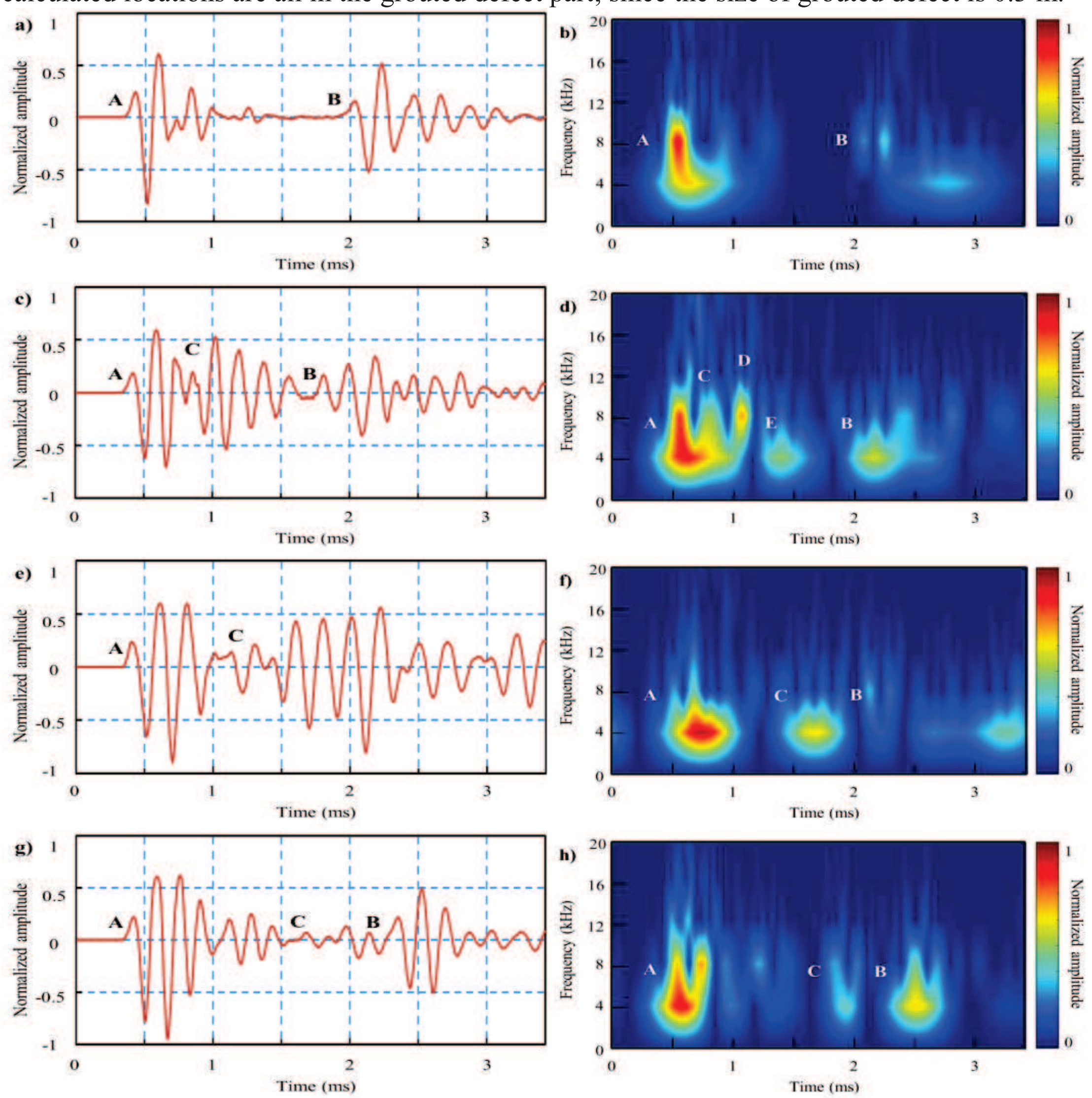

Fig. 3 Test signal and its corresponding amplitude of generalized S-Transform: (a) and (b) model 1; (c) and (d) model 2; (e) and (f) model 3; (g) and (h) model 4.

Table 2 Calculated results of bolt length and its error

Model	calculated bolt length (m)	Absolute error (m)	Relative error	calculated defect location (m)	Absolute error (m)	Relative error
1	3.098	0.098	3.267%	-	-	-
2	3.059	0.059	1.959%	0.645	0.145	29.000%
3	3.297	0.297	9.900%	1.711	0.211	14.060%
4	3.564	0.564	18.807%	2.630	0.163	5.200%

5 Conclusion

This paper provides an analysis method for the bolt test to identify the bolt length and grouted defect based on generalized S-Transform. Four experimental models with different location of grouted defect were conducted to verify this method. The following conclusions could be drawn:

(1) It is feasible and effective to detect the bolt length and grouted defect using the generalized S-transform. The changes caused by the reflected wave significantly appear as frequency peaks or enhancement of energy in the time-frequency spectrum.

(2) Time-frequency analysis using the generalized S-transform has great advantage in extracting weak reflections from defects or bolt end and could be considered as an automatic process. The energy of the reflection from deep grouted is relatively weak, which cannot be identified directly in time domain. But the generalized S-transform method can make the weak reflection significant.

(3) The multiple reflections from the grouted defect has large effect on the identification for the bolt length. It is difficult to identify the reflection from bolt end in original test signal if there is an interference from the multiple reflections from defect. The generalized S-transform method can identify reflected wave from by multiple media according to the frequency peaks or enhancement of energy in the time-frequency spectrum.

(4) Only different locations of grouted defect are considered in this study for the limited length of this paper. The protruding length, bolt length and the size of defect will be studied in the future. The test signal of field experiment will be introduced to study the method as well.

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