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Application of several time-frequency analysis methods to the spectral analysis of rock fracture signals

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Abstract. *From a signal processing perspective, the acoustic emission and electromagnetic signals emitted by rocks are non-stationary signals. The Fourier transform, which is commonly used for spectrum analysis, is not suitable for analyzing such signals. To address this problem, we used various time-frequency analysis techniques, such as the short-time Fourier transform, continuous wavelet transform, generalized S transform, and Hilbert-Huang transform (HHT). It was found that HHT provides more accurate time-frequency information and reflects a better frequency aggregation effect comparing to the other methods for analyzing such signals.*

Keywords: *short-time Fourier transform, continuous wavelet transform, generalized S transform, Hilbert-Huang transform.*

Introduction

The use of solid dielectric materials in products requiring mechanical loads can cause defects, leading to product destruction. Non-destructive testing (NDT) methods, such as Fourier transform analysis, can monitor and control defects [1, 2]. However, these methods do not provide time domain data for non-stationary signals. This paper introduces four time-frequency analysis methods: the short-time Fourier transform, Continuous Wavelet Transform, Generalized S-transform, and Hilbert Huang transform (HHT), and compares them with synthetic signals to select the most suitable method.

Research methods

The Hilbert Huang transform, consisting of empirical mode decomposition (EMD) and Hilbert Spectral Analysis (HSA), decomposes the signal into Intrinsic Mode Functions (IMFs) and calculates the IMF using the Hilbert transform to obtain the instantaneous frequency. The signal f(t) is then represented as a time-frequency spectrum of amplitude (energy) after HHT.

The signal f(t) can be expressed by the sum of the nth-order IMF component and the residual r(t), as shown in the equation (1).

$$f(t) = \sum_{i=1}^{n} c_i(t) + r(t) \tag{1}$$

However, the EMD method faces an endpoint problem, causing divergence in the upper and lower envelope of the cubic spline function. To address this, the Mirror Extending method is used. The measured signal in this paper has a characteristic of a jump change, leading to modal confusion in the decomposition process.

Results

In acoustic emission (AE) detection of dielectric materials, sudden frequency change signalsare the most common. In the meantime, it is necessary to add a frequency mutation signal and pulse signal due to friction between the experimental specimen and the fracture occurring inside the material. The simulated synthesized signal is set as shown in Table 1, the sampling rate is 1000 Hz, the number of data samples is 1000, and the synthesized signal is shown in Fig. 1.

Table 1

Expressions of synthetic signal

Expression	Time/s
$(1 + 0.2\sin(20\pi t))\cos(60\pi t + 0.5\sin(30\pi t))$ $+ \sin(240\pi t)$	$0.5 \leq t \leq 1$
$\sin(400\pi t)$	$0 \leq t < 0.5$
-5	$t = 0.1$,$t = 0.2$
5	$t = 0.099$, $t = 0.199$

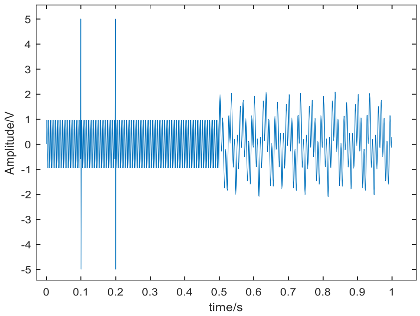

Fig. 1. Synthetic signal

As can be seen from Figure 2(A) (Fast Fourier Transform), the three frequency components of 60Hz, 240Hz and 400Hz contained in the signal are clearly identified, but do not show any frequency to time relation data. From Fig. 2(B), the three frequency components are well identified, and the time-frequency resolution remains consistent, but the display of the frequency mutation points is not clear, and the pulse signal cannot be effectively identified. From the wavelet transform time spectrum shown in Fig. 2(C) and the generalized S-transform time spectrum shown in Fig. 2(D), both can accurately distinguish the three frequency components and the two pulse components, with good time-frequency resolution, but the temporal aggregation of the pulse signal display is slightly worse. In Fig. 2(E), the three frequency components and the trend of the signal over time can be shown clearly, reflecting the sudden change of the signal at 0.5 s. The two pulse signals show at 0.1s and 0.2s respectively, but they are not clearly identifiable in the low frequency part of the figure due to their low frequency.

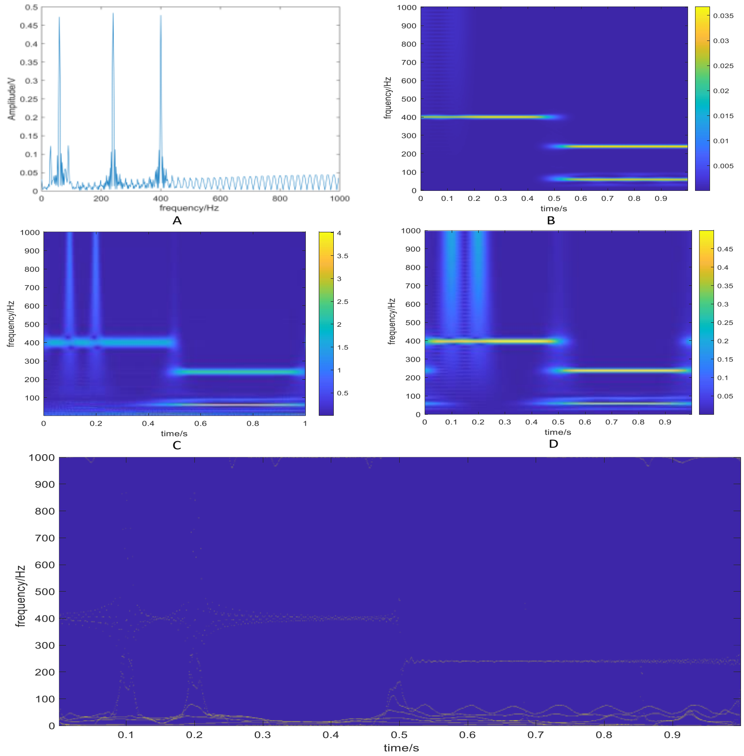

Fig.2. Effect of different time frequency analysis methods: (A) FFT (B) STFT (C) CWT (D) Generalized S-transform (E) HHT

Conclusion

Through the analysis of synthetic data simulation experimental results, the paper presents different time-frequency methods for rock measurement data. As can be seen from the graph HHT time-frequency spectrum (Fig. 2 E), both the low-frequency component and the high-frequency component show excellent time-frequency resolutions. It is evident that with HHT we can obtain more accurate time-frequency information and reflect better frequency aggregation compared with other time-frequency analysis methods. In future work, we will use the time-frequency method proposed in this article to conduct time-frequency analysis of measured rock acoustic emission and electromagnetic radiation data.

References

1. Griffin D., Jae Lim. Signal estimation from modified short-time Fourier transform // IEEE Transactions on Acoustics, Speech, and Signal Processing. – 1984. – Vol. 32, № 2. – P. 236–243.
2. Stockwell R.G., Mansinha L., Lowe R.P. // Localization of the complex spectrum: the S transform // IEEE Transactions on Signal Processing. – 1996. – Vol. 44, № 4. – P. 998–1001.