Application of the Stockwell transforms to test the welding crack acoustic emission signal

Baoshan Huang [1*], Kuanfang He[2,3] Qinghua Lu[2] Kai Wang[2]

1 School of Industrial Automation, Beijing Institute of Technology, Zhuhai，519088, China
2 School of Mechatronics Engineering, Foshan University, Foshan, 528000, China.
3 Hunan Provincial Key Laboratory of Health Maintenance for Mechanical Equipment, Hunan University of Science and Technology, Xiangtan, 411201, China

Abstract: The welding crack acoustic emission (AE) signal process is analyzed by the S transform. Combining with welding crack AE signal test experiment, the time domain AE signals is converted to be the time frequency distribution diagram by the S transforms. The time frequency characteristic of the S transform applied for welding crack AE signal is analyzed by comparing the results of the short-time Fourier transform (STFT) and continuous wavelet transform (CWT). The results indicate that the time-frequency diagram of the AE signal obtained by S transform has the characteristics of adaptive multi-resolution and aggregation of time frequency. The extracted feature quantity obtained by S transform is not sensitive to noise, which provides an effective way to realize the AE detection of welding crack.

Keywords: Stockwell transforms; welding crack; AE signal; time frequency analysis

1 Introduction

In welding process, deformation, solidification, dislocation motion and crack propagation of the metallic materials release an elastic wave, which is AE signals. In fact, the AE signal is interfered by the noise generated by test machine and friction between sample and clamp in the AE test process, the collected AE signals contain a lot of noise components and present weak characteristic under the complex noise background, which is a typical non-stationary signal [1-3]. Time frequency analysis method is currently the powerful tool to analyze non-stationary signals. The common time frequency analysis methods have short time Fourier transform (STFT) [4], continuous wavelet transform (CWT) [5, 6], Wigner-Ville distribution[7,8] and so on [9-11]. However, there are some shortcomings in the above time frequency analysis methods. For examples, STFT has the fixed resolution once the window function is selected, which is not suitable for non-stationary signals with changing of the large frequency range. Due to there is no direct relationship between the scale factor and the frequency, so the

* Corresponding author (jetson_sbs@163.com)

ISSN 2572-4975 (Print), 2572-4991 (Online)

result of wavelet transform is not a real time frequency spectrum, of which the frequency is not obviously shown in the wavelet transform. The Wigner-Ville distribution has cross item interference for multi-component signals, which brings difficulty to the processing and interpretation of the AE signal.

In view of the defects of the above time frequency analysis method, American geophysicist proposed Stockwell transform in 1996[12]. Stockwell transformation is a time frequency analysis method based on STFT and wavelet. Stockwell transform adopts the Gauss window function with the width is proportional to the reciprocal of the frequency, which eliminates the selection of the window function and improves the fixed defects of the window width. The phase spectrum of each frequency component in the time frequency diagram is directly related to the original AE signal. Meanwhile, the inverse transformation of the Stockwell transform is Fourier transform, which is the lossless reversibility like that of the Fourier transform. Furthermore, Stockwell transform is a linear transformation to multicomponent signals, which does not exist the cross term of the time frequency distribution of Wigner-Ville, and has a good time-frequency resolution. Stockwell transform is widely used in many fields, such as signal processing, image processing, medical imaging, atmospheric science and so on[13-15]. Therefore, this paper performs the Stockwell transform to the time frequency analysis of AE signals in the welding process, which convert the time domain AE signals into the time frequency distribution diagram. The time frequency characteristic of the S transform applied for welding crack AE signal is analyzed by comparing the results of the STFT and CWT.

1 S Transform Algorithm

S transform is a kind of signal analysis method that can transform one-dimensional time domain signal into two-dimensional time-frequency one. The S transform of the signal *h*(t) can be defined as follows[13].

$$S(\tau, f) = \int_{-\infty}^{\infty} h(t) \frac{|f|}{\sqrt{2\pi}} \times e^{\left[\frac{-f^2(\tau-t)^2}{2}\right]} e^{-2\pi ift} dt \cdot \quad (1)$$

S is the *S* transform of *h*(t), *f* is the frequency, *t* is the time respectively, τ is the position of the Gauss window on the time axis.

The continuous inverse transform of (1) is as follows.

$$h(t) = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} S(\tau, f) d\tau \right] e^{i2\pi ft} df \ . \quad (2)$$

The difference between *S* transform and STFT is that the height and width of the Gaussian window can be adjusted as the frequency. The S transformation does not have the problem that the height and width of the Gauss window is fixed. The S transform of the signal *h*(t) can be also obtained by a CWT of the special mother wavelet multiplying a phase factor.

$$S(\tau, f) = e^{i2\pi f\tau} W(\tau, d) \ . \quad (3)$$

Where $W(\tau, d)$ is expressed as follows.

ISSN 2572-4975 (Print), 2572-4991 (Online)

$$W(\tau, d) = \int_{-\infty}^{\infty} h(t) w(t-\tau, d) dt \; . \quad (4)$$

The mother wavelet in (4) is defined as follows.

$$w(t,\ f) = \frac{|f|}{\sqrt{2\pi}} e^{\frac{t^2 f^2}{2}} e^{-i2\pi ft} \quad (5)$$

In (4), $W(\tau, d)$ is basic wavelet. $e^{i2\pi ft}$ is a phase factor that is the correction to wavelet transform, which owns a characteristic that conventional wavelet transform does not have. $1/f$ is equivalent to scale factor, and the τ is equivalent to the shift factor of the wavelet transform.

The basic wavelet shape of standard S transform is fixed, which is limited in practical application. Therefore, many scholars have made improvements of the standard S transform. Two adjustable parameters are introduced to adjust the speed of the window function size as changing of frequency, which has better flexibility and adaptability in the practical application. The expression of the improved S transform is as follows.

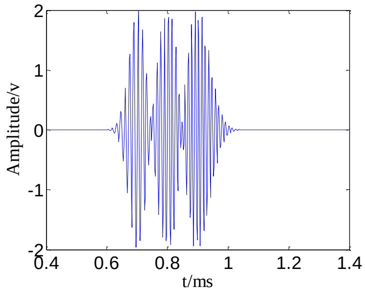
$$GST(\tau,\ f) = \int_{-\infty}^{\infty} x(t) \frac{\lambda |f|^p}{\sqrt{2\pi}} \exp\left[-\frac{\lambda^2 f^{2p} (\tau - t)^2}{2} \right] \exp(-j2\pi ft) dt. \quad (6)$$

In (6), $\lambda > 0$, $p \in (\frac{1}{2}, \frac{3}{2})$. The changing speed of Gaussian window size becomes inversely proportional faster as frequency when *p* is constant and $|\lambda| > 1$, it is contrary when $|\lambda| < 1$. Equation (6) is the standard S transform when $\lambda = 1, p = 1$. Therefore, the reasonable values of λ and *p* are chosen to adjust and improve the time frequency resolution of the S transform, which make it more flexible in practical applications.

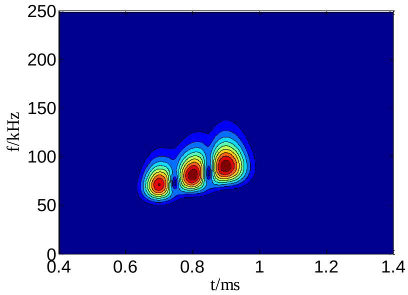
The transient signal composed by three sinusoidal signals with the amplitude modulated by Gaussian function is adopted to be calculated and analyzed, which is expressed as follows.

$$\begin{aligned} x(t) &= 2[\exp(-2\pi((t-t_1)/\alpha_1)^2)]\sin(2\pi f_1(t-t_1)) \\ &+2[\exp(-2\pi((t-t_2)/\alpha_2)^2)]\sin(2\pi f_2(t-t_2)) \\ &+2[\exp(-2\pi((t-t_3)/\alpha_3)^2)]\sin(2\pi f_3(t-t_3)) \end{aligned} \quad (7)$$

The AE simulation signal consists of three pulse signals. f_1, f_2 and f_3 are the frequencies of the three harmonic signals respectively. The values of the parameter are $f_1 = 70kHz$, $f_2 = 80kHz$, $f_3 = 90kHz$, $t_1 = 0.2ms$, $t_2 = 0.4ms$, $t_3 = 0.6ms$, α_1 =0.0001, α_2 =0.00015 and α_3 =0.0002. The sampling frequency is $500kHz$, the waveform of the AE simulation signal and the time-frequency diagram are shown in Fig.2.



(a) AE simulation signal waveform



(b) the time-frequency diagram

Fig.1. The AE simulation signal waveform and the time-frequency diagram

Figure 1 is the time frequency diagrams with different parameters. It can be seen that the AE simulation signals are mainly distributed at the time points of 0.7ms, 0.8ms, and 0.9ms in the time domain. The frequency is mainly distributed at the 70 kHz, 80 kHz and 90 kHz. The time-frequency aggregation of the simulation signal is strong.

2 Application of S transform to test welding crack signal

2.1 experimental condition

The welding AE signal testing experiment platform is shown in Fig.2. The welding method of the experiment is manual electric arc welding, the welding wire brand is J422, wire diameter is 2.5mm, welding current is 100~130A, welding voltage is 380V, the base material is HT200 with plate thickness of 7mm. The parameters set of the acoustic emission acquisition system are shown in Table 1. The specific size of the weldments and AE sensor layout is shown in Fig.2(b). The specific size of the weldments and AE sensor layout is shown in Fig.2(b). The weldment is fixed on the restrictable testing device. The effect of restraint device makes the weldment produce elastic, plastic deformation and cold cracking. The corresponding AE signals are collected by the sensors and the acquisition system, which are transmitted to the computer for analysis and processing.

ISSN 2572-4975 (Print), 2572-4991 (Online)

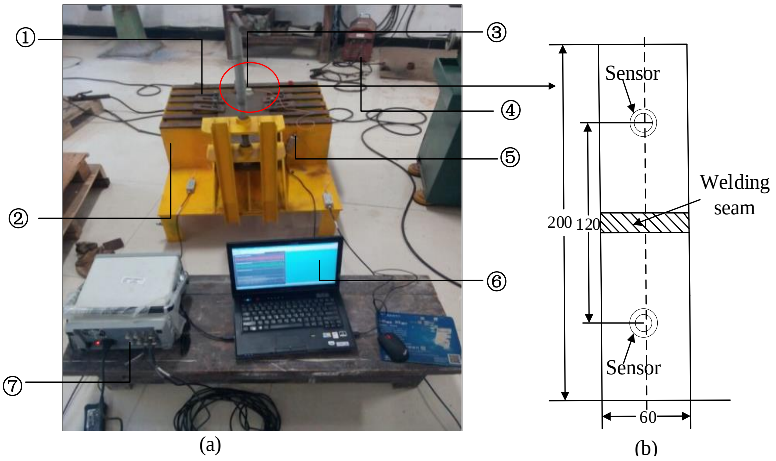


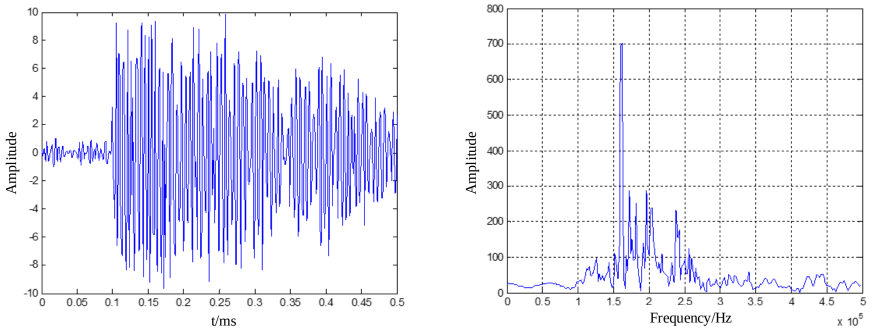
Fig.2. The physical map of welding AE signal test platform and the AE sensor layout in weldment: (a) The physical map of welding AE signal test platform: ① Weldment installation fixture ② Main platform of testing experiment ③ AE sensor ④ Manual arc welding machine ⑤ Preamplifier ⑥ PC machine ⑦ Acquisition system (b) The structure diagram of the weldments and AE sensor layout

TABLE 1. The parameters of acoustic emission system

Parameter term	Sampling frequency /kHz	Sampling length	Hit demention time /us	Parameter threshold /db	Hit locking time /us
Setting value	2500	2048	1000	45	2000

2.2 Test results and analysis

Fig.3 is the welding crack AE signal waveform and the amplitude frequency diagram. The welding crack AE signal is a kind of instantaneous, abrupt and non reproducible signal, which is a kind of non stationary signal. As can be seen from Fig.3 (b), the frequency distribution of the AE signal is mainly concentrated in the 100~300 kHz.



(a) Acoustic emission time domain waveform (b) Amplitude spectrum

Fig.3 Welding crack AE signal waveform and amplitude frequency diagram

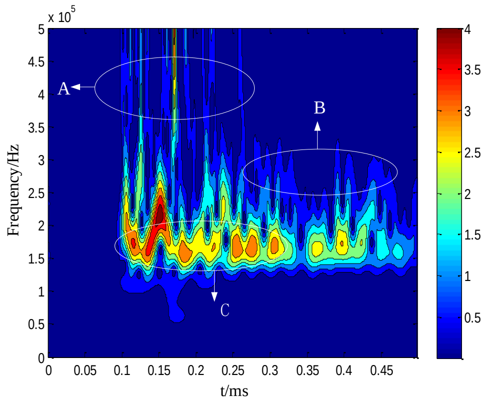


Fig.4 Time-frequency diagram of welding crack AE signal by S transform

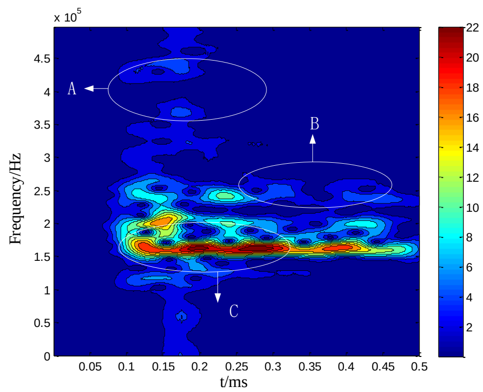


Fig. 5 Time-frequency diagram of welding crack AE signal by STFT

ISSN 2572-4975 (Print), 2572-4991 (Online)

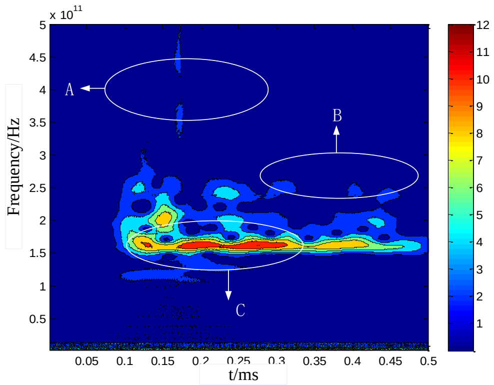


Fig.6 Time-frequency diagram of welding crack AE signal by CWT

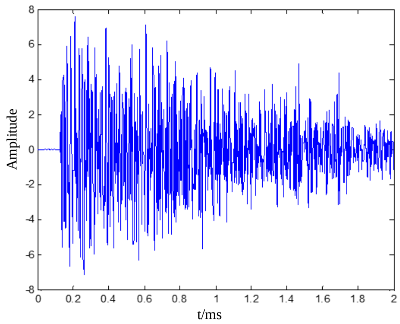
Fig. 4 is the time frequency diagram of welding crack AE signal by S transform, which shows that the resolution distribution of the AE signal in the time frequency domain is different at each frequency segment. In the region A, the frequency rang above 350kHz has a certain resolution, of which the time characteristics is more obvious. In region the B, the frequency range between the 250~300 kHz is another resolution, which has not so obvious feature over time. The resolution of the frequency range between the 100~200 kHz is different from the resolution of the AE signal in the regions A and B, of which the frequency characteristic in region C is more obvious. The result of the AE signal fully indicates the adaptive characteristic of S transform, which has good time resolution at high frequency and a good frequency resolution at the low frequency.

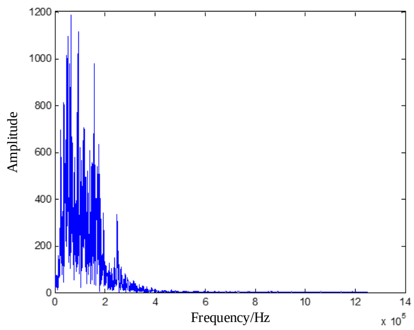
In order to further validate the S transform that is applicable to analyze the AE signal of welding crack, the STFT and CWT are adopted to perform time frequency calculation to the welding crack AE signal, of which the results are shown in Fig.5 and Fig.6. As can be seen form Fig. 5, the three marked regions of A, B and C show only a frequency resolution without no changing of the time resolution, STFT is a single resolution time frequency analysis method that is difficult to describe and depict the details of the AE signal.

As can be seen form Fig. 6, the time resolution displayed in the region A is not very good, and AE signal in regions B and C present a strong frequency resolution, but the time resolution is not very obvious. CWT is also a multi-resolution time frequency analysis method, which can be used to describe the details of the AE signal, however, the high time resolution and frequency resolution of the AE signal analysis results are difficult to be considered at the same time, the adaptability of CWT is not very obvious for AE signal.

In addition, the characteristics of the signal in the region C can be observed from the time frequency diagram of welding crack AE signal in Fig.4. There is a signal energy accumulation in the 100~200 kHz frequency range at the time of 0.1~0.12ms, and a small amount of energy is released that may be caused by a micro crack. At the time of 0.12 ms~0.15ms, it results in crack fracture when the size of the crack is greater than the critical length as the crack growth, the time frequency aggregation is the strongest and the energy released is the most. A small amount of energy is released at the time points of 0.18ms, 0.25ms and 0.3ms, which may be the formation of a small amount of micro cracks at the process of crack formation. According to the time frequency diagram of AE signal by STFT, there is energy accumulation in region C, but the time frequency clustering is relatively poor, and it is difficult to see the crack initiation and propagation to the fracture process by the energy distribution of the AE signal in Fig. 5. It can be seen from Fig. 6, time-frequency of welding crack AE signal by CWT has the same results with STFT. The time-frequency aggregation by CWT is better than that of STFT in the region C, which is impossible to be clearly distinguished in the process of crack initiation and propagation to fracture.

Fig.7 is a welding crack AE signal waveform and its amplitude frequency diagram. It is a typical burst type AE signal. The frequency of the AE signal is mainly distributed between 20～250kHz. Because the frequency of AE signals of the metal fatigue crack is distributed between 100～400kHz[16], the AE signal components below the frequency 100kHz is the interference or noise signal.





(a) Time domain waveform of the welding crack AE signal (b) Amplitude spectrum

Fig. 7 Welding crack AE signal waveform and amplitude frequency diagram

Fig.8 is the frequency diagram of the welding crack AE signal by S transform, which exists the high and low frequency distribution in the diagram. Although the entire time-frequency diagram distributes along with a lot of noise, it is not a great impact on the accurate expression of the signal characteristics. The AE signal energy is mainly concentrated between 100 kHz and 200 kHz, and there exist a large energy distribution released by the welding crack. It indicates that the S transform has a certain anti-noise performance. Fig.9 and Fig.10 are time-frequency diagrams of the welding crack AE signal by STFT and CWT respectively, the noise signal is eliminated, and the characteristic of the welding crack AE signal is also disappeared. The reasons for this situation may be the improper selection of the window function, it leads to the frequency or time resolution is the best, which result in the characteristic of the welding crack AE signal is eliminated. This indicates that the time frequency diagram by the S transform is not sensitive to noise, and has good noise immunity, while STFT and CWT do not have this characteristic.

 ISSN 2572-4975 (Print), 2572-4991 (Online)

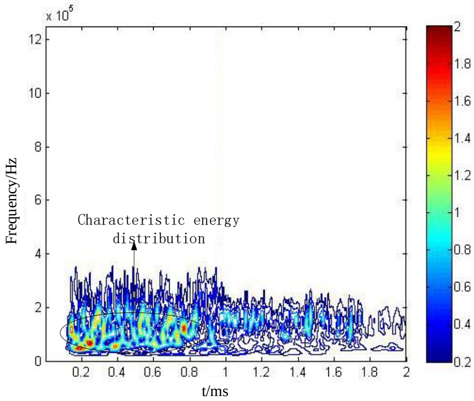


Fig. 8 Time-frequency diagram of welding crack AE signal by S transform

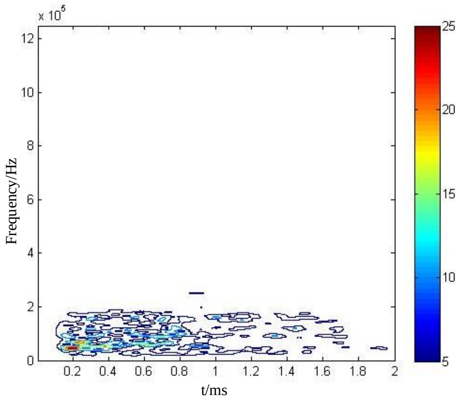


Fig. 9 Time-frequency diagram of welding crack AE signal by STFT

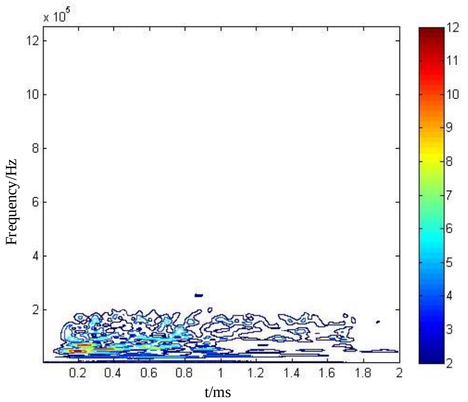


Fig.10 Time-frequency diagram of welding crack AE signal by CWT

As a result of the above analyses, S transform is a time-frequency analysis method of multi-resolution and high time frequency aggregation, which is suitable for the welding crack AE signals. The time frequency diagram obtained from AE signals can directly show the dynamic evolution process of the structural crack formation and expansion in welding process. Furthermore, the detection of the structural crack in the welding process can be realized according to the time frequency diagram of the acquired AE signal.

3 Conclusions

(1) The S transform has been adopted to describe and extract the energy time frequency distribution characteristics of AE signal in the welding process. Combining with welding crack AE signal test experiment, the time domain AE signals is converted to be the time frequency distribution diagram by the S transforms. The time frequency characteristic of the S transform applied for welding crack AE signal is analyzed by comparing the results by STFT and CWT. The results indicate that the time-frequency diagram of the AE signal obtained by S transform has the characteristics of adaptive multi-resolution, aggregation of time frequency, noise resistance and obvious characteristic information.

(2) Application of the S transform to welding crack AE signal can obtain more precise, higher resolution and more centralized frequency diagram of energy distribution, which greatly improve the readability of the time frequency. S transform is a time-frequency analysis method of multi-resolution and high time frequency aggregation, which is suitable for the welding crack AE signals. The time frequency diagram obtained from AE signals can directly show the dynamic evolution process of the structural crack formation and expansion in welding process. The detection of the structural crack in the welding process can be realized according to the time frequency diagram of the acquired AE signal.

ACKNOWLEDGMENTS

This work is supported by Hunan Provincial Natural Science Foundation of China (2017JJ1015, 2017JJ2086) and National Natural Science Foundation of China (51475159), are gratefully acknowledged.

References

[1] He K, Li Q, Yang Q. Characteristic Analysis of Welding Crack Acoustic Emission Signals Using Synchrosqueezed Wavelet Transform[J]. Journal of Testing & Evaluation, 2018, 46(6):20170218.

[2] Kuanfang He, Xiangnan Liu, Qing Yang, Yong Chen. An extraction method of welding crack acoustic emission signal using harmonic analysis[J]. Measurement, 103 (2017):311–320.

[3] Kuanfang He, Zhi Tan, Yong Cheng and Xuejun Li. Acoustic emission propagation characteristics in plate structure with various materials, cracks and coating metal[J]. Proceedings of the Institution of Mechanical Engineers, Part C- Journal of Mechanical Engineering Science, 2016, 203-210:1989-1996.

ISSN 2572-4975 (Print), 2572-4991 (Online)

[4] Portnoff MR. Time-frequency representation of digital signals and systems based on short-time fourier analysis[J]. IEEE Transactions on Acoustics, Speeeh,and Signal Processing, 1980, ASSP-28(1).

[5] Morlet J, Arens G, Fourgeau E, Giard D. Wave progagation and sampling theory-part I:Complex signal and scattering in multilayered media[J]. Geophysics, 1982,47:203-221.

[6] Morlet J, Arens G, Fourgeau E, Giard D. Wave progagation and sampling theory-part II: Sampling theory and complex waves[J]. Geophysics, 1982,47(2):222-236.

[7] Wigner E. On the quantum correction for thermodynamic equilibrium[J]. Phys.Rev s, 1932, 40:749-759.

[8] Ville. Theorie et applications de la notion de signal analytique[J]. Cables et Transmission,2,1948.

[9] Kuanfang He, Xuejun Li. A quantitative estimation technique for welding quality using local mean decomposition and support vector machine [J]. Journal of Intelligent Manufacturing, 2016, 27:525–533.

[10]. K. F. He, Q. Li, and J. Chen. An arc stability evaluation approach for SW AC SAW based on Lyapunov Exponent of welding current[J]. Measurement, 2013, 46:272-278.

[11] Kuanfang He, Zhuojie Zhang, Siwen Xiao, Xuejun Li. Feature extraction of AC square wave SAW arc characteristics using improved Hilbert–Huang transformation and energy entropy[J]. Measurement, 2013,46:1385–1392.

[12] Stockwell R G. A basis for efficient representation of the S-transform[J]. Digital Signal Processing, 2007, 17(1):371-393.

[13] Stockwell R G, Mansinha L, Lowe R P . Localization of the Complex Spectrum: The S-Transform[J]. IEEE Transactions on Signal Processing, 1996, 44(4):998-1001.

[14] Pinnegar.Comments on the inverse S-transform in filters with time-frequency localization[J]. IEEE Trans on Signal Process, 2007,55(10):5117-5120.

[15] Dash P K, Panigrahi B K, Panda G. Power quality analysis using S-Transform[J]. IEEE Trans. on Power Delivery, 2003, 18(2):406-411.

[16] Gang Qi. Wavelet-based AE characterization of composite materials[J]. NDT&E International. 2000,33:133-144.