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Quantitative evaluation method of arc sound spectrum based on sample entropy

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ABSTRACT

Arc sound analysis is an effective way to evaluate the stability of the arc welding process. Current methods cannot effectively quantify the disorder of the process. By studying the characteristics of the arc sound signal, we found that low frequency random mutation of arc sound power resulted from unstable factors, such as splashes or short circuits, increased the complexity and randomness of the arc sound signals. Then the arc sound signals were visualized on time-frequency interface by means of spectrogram, and it was found that the max power spectral density (PSD) distribution of spectrogram was closely related to the stability of arc welding process. Moreover, a method based on sample entropy was proposed to further quantify the relation. Finally, considering the factors such as averages of max PSD and the standard deviations of sample entropy, a compound quantitative evaluation indicator, arc sound sample entropy (*ASSE*), which can avoid the influence of different parameters on the quantitative results, was proposed, so that the stability of arc welding process can be quantitatively presented. Testing results showed that the accuracy rate of the method was more than 90 percent.

1. Introduction

The stability of arc welding process is an important condition for assuring the quality of welding products. For decades, a lot of relative works were conducted to monitor the stability of welding process. Luksa et al. [1] online collected the process signals by an experimental platform, and then analyzed the welding quality by signal variations. Hermans et al. [2] also collected electrical signals during the welding process and analyzed the short circuit frequency, and then concluded that the welding process was stable when the short circuit frequency was the same as the frequency of weld pool oscillations. Adolfsson et al. [3] employed a repeated sequential probability ratio test (SPRT) algorithm to detect the sudden minor changes of weld voltage, and then concluded that it was possible to online detect changes in weld quality automatically. Though there were relative works considering the stability of welding process, those methods could only detect some abnormal phenomena during the welding process, instead of analyzing, especially quantifying the stability of a whole welding process. In addition, arc welding process is a highly nonlinear and multi-field coupled process, limited electrical signals cannot sufficiently

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present the characteristics. Hence, other signals which include abundant information of the process should be introduced to evaluate the stability, and then to help to achieve high quality welding production.

Arc sound signals contain a large amount of information generated during arc welding process [4–6]. Skilled welders were able to determine the stability of the welding process by means of arc sound alone. Čudina and Prezelj [7] studied the feasibility of online monitoring welding quality by arc sound in Gas Metal Arc Welding(GMAW), and thought that irregular changes of arc sounds were the reaction of the unstability of welding process. Liu et al. [6] extracted the arc sound features from four typical weld penetration statuses and analyzed the relation between weld penetration statuses and arc sound characteristics. Pal et al. [8] acquired current, voltage and arc sound signals synchronously and analyzed the correlation between electrical signals and arc sound signals in terms of time-domain and frequency-domain. Grad et al. [9] thought that the irregular of arc sound signal reflected the unstability of welding process. Hence, the arc sound signal is closely relative to the stability of arc welding process, and it can be employed to evaluate the stability of the process.

For decades, arc sound signals were usually described by time-domain, frequency spectrogram and power spectrogram. In such a case, the relation between time, frequency and power spectral density cannot be simultaneously presented and employed. Saini and Floyd [10] monitored weld quality online by kinds of indicators in time-domain and frequency-domain of the arc sound, and then proposed that the advantages of time-domain and frequency-domain should be combined, since the two analyses had their own advantages and disadvantages, no one could sufficiently show the signal characteristics alone.

Under this circumstance, sound spectrum analysis technology was developed. A spectrogram, or sonogram, is a visual technology, which can be employed to represent the variations of sound or other signals with time or other selected variables. In this work, spectrogram, which is also the sound spectrum figure, is a colorful plane figure obtained from spectral decomposition for sound signals. In the figure, time is in the x-axis, while frequency is in the y-axis, and each value of pixel denotes the power spectral density (PSD) of the signal at designated time and frequency. The information of signal stability could be obtained via sound spectrum analysis technology, due to varying information of the power spectral density and frequency waveform can be observed from the figure.

The spectrogram is one of the best-known time-frequency distributions suitable for analyzing signals whose power varies both in time and frequency. It was commonly employed to phonetically identify spoken words [11,12], or analyze various callings of animals [13]. Also, this tool was used extensively in the development of polyphonic piano transcription [14], sonar, radar, and speech processing [15,16], and so on.

According to corresponding researches and applications, it is feasible to employ the sound spectrum analysis technology to analyze the arc sound signal, and then obtain the information about stability during the process. However, due to the information in sound spectrum figure is in pixel form, and the information acquisition is determined by analyses' experiences and interpretation standards, large errors may be obtained during the process. In addition, the figure information obtained may have low repeatability, so that it is hard to analyze and after-treatment. These disadvantages seriously restrict the application of arc sound spectrum analyzing technology.

Entropy is a mathematical variable which can describe the stability of a system. It is extensively used to calculate phenomena of system disorder, that is, the degree of confusion of a system. Approximate entropy is proposed by Pincus et al. [17] to overcome the difficulty in solving the entropy in chaos. Approximate entropy is mainly employed to measure the probability of new model generated in the signal. The more complex the sequence, the greater the probability of generating a new model and the corresponding approximate entropy [18,19]. Approximate entropy was initially developed to analyze medical data, such as heart rate [18], and later its applications were spread to other areas, such as finance [20], psychology [21], and human factors engineering [22].

Recently, researchers have made some welding process stability studies by means of approximate entropy. Tolle et al. [23] found that the approximate entropy of arc voltage increased with the increasing of wire feed speed in GMAW. Cao et al. [24,25] proposed that approximate entropy can be used to quantify arc and welding process stability in short-circuiting GMAW. Nie et al. [26] used neural network to predict the approximate entropy of pulsed metal inert gas(MIG) welding of aluminum alloy and achieved good results. Zhang et al. [27] evaluated the effect of adaptive control by approximate entropy and thought that the smaller the approximate entropy, the better the adaptive control. The work showed that the approximate entropy and stability of welding signals have a certain relation but relatively poor consistency due to effects of data length and embedding dimension. Richman et al. [28] proposed a new time-series complexity measuring method on the basis of comparison between approximate entropy and sample entropy, and then concluded that the sample entropy can achieve better consistency and accuracy with faster computing speed than that of approximate entropy, because sample entropy excludes self-match values, and reduces approximate entropy errors.

So far, arc sound detections and corresponding researches were in analyzing stage instead of actual application, and the researches focused on exploring the arc sound characteristics and the relation between arc sound and welding quality. There was little work which employed the arc sound to quantitatively analyze the stability of welding process. Under this circumstance, at first, we collected the original arc sound signal by proposed experimental platform and processed the data using wavelet packet filtering tool, and then analyzed the corresponding sound spectrum figure using the sample entropy algorithm. Finally, the stability information of arc welding process can be quantitatively collected. In this work, we aim to explore a new method and design the quantitative indicators of evaluating arc sound stability of welding process by spectrogram and sample entropy. The work can achieve the goal that the stability of arc welding process can be effectively quantified.