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Research on the deviation sensing of V-groove weld seam based on a novel two channel acoustic sensor

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Abstract: It is essential to sense the deviation of weld seam real-timely in robotic welding process. However, welding process always accompanied with high temperature, strong arc light and background noises, which significantly affects the application of sensors. In this study, a novel acoustic sensor was developed. This sensor consists of two microphones. Based on the sound signals collected by these two microphones, the deviation of weld seam was detected. The frequency response of the developed acoustic sensor was studied through simulation method firstly, and then the sensing performance of it was analyzed with experiments. The experimental results show that the developed acoustic sensor has a linear property for the deviation detection of V-groove weld seam. This research provides a novel method for weld seam tracking.

Keywords: Weld seam tracking; Acoustic sensor; Binaural effect; V-groove weld seam; Sound signals

1. Introduction

In robotic welding process, real-time seam tracking is essential for eliminating the welding path errors caused by heat-induced distortions of weld part. However, welding is a complicated physical process. It usually accompanied with high temperature, strong arc light and background noises, which significantly affects the application of sensors. For sensing the weld seam position real-timely, tactile sensors, arc sensors and vision sensors have been developed in the past few years.

Presem *et al.* [1] developed a tactile sensor to find and track three-dimensional trajectory of weld seam. Lei *et al.* [2] improved the structure of it to measure displacement and angular errors for tracking super narrow gap weld seam. Kim *et al.* [3] built a mathematical model of rotating arc sensor, and Shi *et al.* [4] improved this model for weld seam detection. Kodama *et al.* [5] studied the arc sensor sensitivity in short circuiting metal gas welding process. Gao *et al.* [6] adopted rotating arc sensor to detect the deviation and inclination of welding torch simultaneously.

Vision sensors also are extensively adopted in sensing the deviation of weld seam. There are two types of vision sensing methods: active vision and passive vision. In active vision, a low power laser is used to generate light stripes, and according to the projection images of light stripes on weld seam the tracking errors are obtained. Chen *et al.* [7] and Qin *et al.* [8] utilized active vision sensors to measure the deviations of weld torch. Wu *et al.* [9] adopted modified Hough-transform and Jia *et al.* [10] employed Kalman filter to extract the feature point of weld seam when the laser stripe was disturbed by heavy arc and welding splash. In passive vision, welding arc itself is used as the light source. Lee *et al.* [11] presented a passive vision sensor system in pulse laser welding process. For capturing clear images of weld pool, Chen *et al.* [12] and Xu *et al.* [13] adopted a narrow band optical filter with central wave length 630nm and 660nm respectively.

Arc sound signals contain abundant information of welding process, such as the stability and splash of it. Therefore, arc sound signals have been adopted recently to monitor welding process. Song *et al.* [14] utilized arc sounds signals to predict the penetration states of weld bead. Lv *et al.* [15] adopted arc sound signals to identify the penetration states in GTAW process. Zhang *et al.* [16] analyzed the frequency components of arc sounds and identified penetration states of aluminum alloy weld bead. Gao *et al.* [17] based on the human welder subjective assessments on arc sounds to identify the penetration states. Lan *et al.* [18] studied the

correlation of arc sound with arc position in narrow gap welding process. The offset distance from arc to sidewall of weld seam was detected according to arc sounds. Liu *et al.* [19] developed a swing arc sound sensor to detect the arc deviation for narrow gap weld seam tracking. The short-time energy of arc sound signals was selected as the feature for arc deviation sensing. Lv *et al.* [20] adopted a dual-microphone array to monitor the welding path in pulse metal-gas welding process.

Based on those previous studies, this paper develops a novel acoustic sensor to detect the V-groove weld seam position. This sensor consists of two microphones and based on the sound signals collected by these two microphones to sense the deviation of weld seam. Firstly, the structure of the developed acoustic sensor and the basic principle of it are explained. Secondly, with numerical simulation methods, the sensing properties of the developed sensor are analyzed. Subsequently, the sensing properties of the developed sensor are tested through a series of experiments, and the optimal frequency of it is acquired. Finally, some welding experiments are implemented to study the sensing capabilities of the developed acoustic sensor.

2. An acoustic sensor design

An acoustic sensor was designed in this study for sensing weld-seam position based on sound signals. The structure of it is shown in Fig.1, and the product of it is shown in Fig.2.

Fig.1 The structure of designed acoustic sensor

Fig.2 The picture of the acoustic sensor

As shown in Fig.1, the designed acoustic sensor consists of top cap, blimp, microphone, main chamber, bottom cap, sound source and fixed part. The sound source is a RY-LB woofer, and it is mounted in the center hole of the bottom cap to generate sound waves. Two microphones are packed in the two cavities that located on the two sides of the center hole symmetrically. In the interior of bottom cap, there are two small holes with diameter of 2mm and a center hole with diameter of 8mm. As shown in Fig.2, during welding process the acoustic sensor is mounted on the front of weld torch to detect the deviation of weld seam.

In sensing process, as shown with the red arrows in Fig.1, sound waves are generated by sound source firstly, and then propagate downward within the center hole and arrive at the surface of weld seam. Subsequently, these sound waves are reflected by weld seam and received by two microphones via two small holes, respectively. When the designed acoustic sensor locates at the center of weld seam, the propagation paths of sound waves that received by two microphones are symmetrical. If the the acoustic sensor locates at the right or left of the weld seam, the propagation paths of sound waves are no longer symmetrical. Therefore, the sound pressures that received by two microphones are different. Based on the differences of sound pressures of two microphones, the deviation of acoustic sensor is obtained.

3. Sensing property analysis with numerical simulation

3.1 Mathematical model

To simulate the transmitting process of sound waves in the designed acoustic sensor, the governing

equations are given as follows.

Continuity:

$$\frac{\partial(\rho_0 + \rho')}{\partial t} = -(\rho_0 + \rho') \nabla \cdot \mathbf{v} \quad (1)$$

Motion:

$$(\rho_0 + \rho') \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) = -\nabla(P_0 + P') \quad (2)$$

State:

$$\frac{P}{P_0} = \left(\frac{\rho}{\rho_0} \right)^\gamma \quad (3)$$

where, P_0 , ρ_0 are the sound pressure and air density in stationary state, respectively. P' , ρ' are the variation of sound pressure and air density caused by outside disturbance, respectively. $\mathbf{v}$ is the vibration velocity of particle. γ is a constant and equal to 1.402. From the governing equations, the acoustic wave can be expressed as equation (4).

$$\nabla^2 P' - \frac{1}{c^2} \frac{\partial^2 P'}{\partial t^2} = 0 \quad (4)$$

where, ∇ is a Lagrange operator. $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$. c is the velocity of sound waves, $c = \sqrt{\frac{\gamma P_0}{\rho_0}}$. Based on Fourier transform, an arbitrary vibration could be expressed as the integration of series simple harmonic oscillations. Therefore, the variation of sound pressure is expressed as equation (5).

$$P' = P(x, y, z) \cdot e^{j\omega t} \quad (5)$$

Substituting the expression of P' into equation (4), a Helmholtz equation is obtained.

$$\nabla^2 P(x, y, z) - k^2 P(x, y, z) = 0 \quad (6)$$

where, $k = \omega / c$, $\omega = 2\pi f / c$.

Fig.3 The finite elementary model of designed sensor

Fig.3a shows the finite elementary model of the designed acoustic sensor. In Fig.3a, S is the inlet boundary of sound source. T_1 and T_2 are the outlet boundary of sound waves. The faces of AHRI, ARNB, BCMN and AHGFEDCB are the boundaries of sound space. In these boundaries, there are no reflections when sound waves traverse through them. The faces of RIJQ, JQPK, PKLO and LONM are the surfaces of weld seam. They are assumed as fully reflecting surfaces. On these surfaces, the sound waves are totally reflected and there are no energy losses. The interior walls of sensor are supposed as fully reflecting surfaces too. In the numerical simulating process, tetrahedral mesh with size of 0.6mm is adopted. The geometry model after mesh generating is shown in Fig.3b. The numerical model boundary conditions of the designed acoustic sensor are listed in Tab.1. The distance from the bottom of sensor to the top surface of weld seam is set as 2mm in the simulation process.

Tab.1 Boundary conditions

Boundary	Pressure P/Pa	Impedance Zp(Kg/m ² /s)	Density ρ (Kg.m ⁻³)	Velocity c(m.s ⁻¹)
S	1	-	1.225	340
T ₁	-	416.5	1.225	340
T ₂	-	416.5	1.225	340
Sound space	-	416.5	1.225	340
Weld seam surface	-	-	-	-

3.2 Results and discussion

3.2.1 The influence of sound source frequency

The transmitting process of sound wave in a local space is shown in Fig.4a. The sound waves are generated by sound source on the inlet boundary S firstly. Then they propagate downward within a center hole and arrive at the surfaces of weld seam and are reflected by these surfaces. Afterward, the reflected sound waves enter two long small holes and received by two microphones at the outlet boundary T₁ and T₂.

Fig.4 The distribution of sound pressure with different frequencies

Usually, the distributions of sound pressure in space are significantly influenced by the frequency of sound waves. Fig.4 is the simulation result of distributions of sound pressure when the sound frequencies are 2001Hz, 6201Hz, 11601Hz and 17201Hz, respectively. In Fig.4, the distributions of sound waves are expressed by sound pressure levels (SPL). Sound pressure level is calculated with equation (7).

$$L_p = 20 \lg \frac{P_s}{P_{ref}} \text{ dB} \quad (7)$$

where, L_p is the sound pressure level, and the unit of it is dB; P_s is the sound source pressure; P_{ref} is the reference sound pressure, and the value of it is 2×10^{-5} Pa. Based on Tab.1, the sound source pressure on inlet boundary S is 1Pa, so the SPL of it approximately is 94dB.

As shown in Fig.4a, when the sound wave frequency is 2001Hz, the higher SPL only appears at the area within the center hole. And the SPL that received by two microphones are comparatively low (37dB). While as shown in Fig.4b-d, with the increasing of sound waves frequency, the SPL in the whole space accordingly increase. Moreover, the sound pressure in the two small holes demonstrates obviously periodical distribution. For example, in Fig.4c, there are two periods in the two small holes. While in Fig.4d, there are three periods. It is because with the increasing of frequency the wavelength of sound waves become small. From Fig.4b-d, it can be found that the highest SPL is generated in the middle of the two holes, other than in the outlet boundaries. Therefore, to acquire relatively high SPL on the outlet boundaries, it is particularly important to select the suitable frequency of sound waves.

It can be found that the gradient of sound pressure on the weld seam surface (top views of Fig.4) is increased with increasing of frequency. When the frequency increases to 11601Hz (Fig.4c) and 17201Hz (Fig.4d), the sound pressure shows an elliptical distribution, and the major axis of ellipse is parallel to the weld seam. Fig.4 also shows that the distributions of sound pressures are symmetrical with central line of weld seam. It is because in the simulation process the sound source locates at the center of weld seam.

If the sound wave that generated on the inlet boundary S is taken as input variable, and the SPL of sound wave that received by microphones on the boundaries of T_1 and T_2 are taken as output variables, then the frequency response of the designed sensor system could be acquired with simulating method. Fig.5 shows the simulating result.

Fig.5 The frequency response of the designed sensor

From Fig.5, it is observed that the SPL on the outlet boundaries T_1 and T_2 are nearly same and both change periodically with the increasing of frequency, and the period approximates 6000 Hz. Combined with the results of Fig.4, the frequency of sound wave in the range of 16-18KHz probably is suitable for sensing process.

3.2.2 The influence of relative position between acoustic sensor and weld seam

Fig.6 The relative position of acoustic sensor with weld seam

The relative position between acoustic sensor and weld seam is shown in Fig.6. The line ABC is a V-groove weld seam, and S is a sound source. T_1 and T_2 are two microphones that mounted on the two sides of sound source symmetrically. Fig.6a shows the sound source in the center of weld seam. Fig.6b shows the sound source at the right side of weld seam, and the deviation of it in X-axis is Δx , and rotating angles of it around Z and Y axis are α and β , respectively.

(a) The influence of weld seam deviation Δx

The purpose of designed acoustic sensor is to sense the deviations of weld seam. Therefore, the influence of weld seam deviation on the distribution of sound pressure is simulated and the results are shown in Fig.7. In this figure, the frequency of sound wave is set as 17.5KHz. It is observed that the distributions of sound pressure in the four sub-figures of Fig.7 are not symmetrical with central line of weld seam. The SPL in the right hole is obvious larger than the SPL in the left hole. Moreover, with the increasing of deviations the SPL in the right-hole increases accordingly, while SPL in the left-hole decreases gradually.

Fig.7 Distributions of sound pressure under different deviations

Fig.8 The frequency response of designed sensor under different deviations

Fig.8 shows the frequency response of the designed sensor system when the deviations of weld seam are 0.5mm and 1.0mm. From Fig.8, it is found that the SPL of T_1 and T_2 are same when the frequency less than 13KHz. It manifests that in this frequency range the designed sensor cannot detect the deviation of weld seam. When the frequency larger than 13KHz, the SPL of T_2 obviously larger than the SPL of T_1 . To further study the changes of SPL with the deviations of weld seam, the SPL differences of T_1 and T_2 are calculated out with a subtract operation. Under different deviation conditions, the SPL differences in the frequency range of 13-19KHz are shown in Fig.9.

Fig.9 SPL difference of sound waves that received by two microphones under different deviations

As shown in Fig.9, the deviations of weld seam are set as 0.3mm, 0.5mm, 0.8mm, 1.0mm, 1.5mm and 2.0mm. In the frequency range of 15-17KHz, the SPL differences are relatively large. However, the values of these SPL differences are not increased in sequence with the deviations of weld seam. For example, the SPL difference is largest when weld seam deviation is 1.0mm other than 2.0mm. Therefore, the frequency range of 15-17KHz is not suitable for detecting weld seam deviations. In the frequency range of 17-18KHz, the gaps between these SPL differences are also relatively large, and the values of these SPL differences are increased with the deviations in sequence. Therefore, this frequency range is comparatively suitable for the designed sensor. To find the specific suitable frequency, the changes of SPL differences with the deviations of weld seam are simulated and the results are shown in Fig.10. In this figure, the frequency range is 17.2-17.8KHz.

Fig.10 SPL differences with deviation of weld seam ($H=2.0\text{mm}$)

From Fig.10, it is observed that when the sound wave frequencies are 17.6, 17.7 and 17.8KHz, the relations between SPL differences and deviations of weld seam are non-linearly. When the sound wave frequencies are 17.2, 17.3, 17.4 and 17.5KHz, the SPL differences increase linearly with the deviations of weld seam.

(b) The influence of sensor height h

In this section, the sensor height is defined as the distance from the bottom of sensor to the top surface of

weld plate. Because the sound waves generated by sound source are reflected by weld seam surface firstly, and then received by microphones, so the height of sensor would significantly affect the distributions of sound pressure. The simulation result about the influence of sensor height on the SPL differences is shown in Fig.11.

Fig.11 SPL differences with heights of sensor

Fig.11 consists of four sub-figures. Each sub-figure represents the changes of SPL difference with the deviation of weld seam under one specific height. The heights of these four subfigures are 0.5mm, 1.0mm, 1.5mm and 3.0mm, respectively. From Fig.11, it is obvious that the SPL differences in these four subfigures linearly increase with the deviations of weld seam when the frequencies are 17.2 and 17.3 KHz. However, for other frequencies the linear relations between SPL differences and deviations are only exist in some of height conditions. It means that the influence of sensor height on the SPL differences is relatively small when the frequencies of sound wave are 17.2 and 17.3 KHz. Therefore, 17.2 KHz is selected as the frequency of sound source in this study.

(c) The influence of rotating angle α

The rotating angle of sensor around with Z-axis is defined as α in Fig.6. The influence of this angle on the distribution of sound wave is simulated in this section and results are shown in Fig.12 and Fig.13.

Fig.12 Distributions of sound pressure when rotating angles α are 4° and 10°

Fig.13 SPL differences with rotating angle α of designed sensor ($H=2.0\text{mm}$)

Fig.12 shows the distributions of sound pressure when rotating angles of sensor around with Z-axis are 4° and 10° . It is found that the distributions of sound pressure in these two channels are symmetric. Fig.13 shows the SPL differences of two microphones with the increasing of rotating angle α . It is observed that, under various of frequency, the SPL differences are less than 0.2dB. This result shows that the influence of rotating angle α on the sensing performance is negligible.

(d) The influence of rotating angle β

In this section, the rotating angle of sensor around with Y-axis is defined as β in Fig.6. The influence of this angle on the distribution of sound wave is simulated in this section and results are shown in Fig.14 and Fig.15.

Fig.14 Distributions of sound pressure when rotating angles β are 2° and 5°

Fig.15 SPL differences with rotating angle β of designed sensor ($H=2.0\text{mm}$)

Fig.15 shows the SPL differences of two microphones with the increasing of rotating angle β . It is observed that, under the frequencies of 17.2KHz and 17.3KHz, if β less than 5° then the maximum SPL difference less than 0.5dB. Therefore, the influence of β is relatively smaller than Δx .

4. Sensing property analysis of the developed sensor with experiments

4.1 Experimental system

The experimental system is shown in Fig.16. It consists of the developed acoustic sensor, work-piece, moving platform and data acquisition system. The work-piece and acoustic sensor are mounted on the moving platform. The deviation between acoustic sensor and weld seam is set before experiment. A RY-LB woofer is used as a sound source, and a NF WF1974 signal generator was used to supply sinusoidal electricity to this woofer. In the inside of this acoustic sensor, two CRY331 microphones are mounted to receive the sound waves that generated by this woofer, and a high-speed data acquisition card is used to collect the signals of these two microphones. The SPL differences of the sound waves received by two microphones are obtained and analyzed in a computer. During experiments, various frequencies sinusoidal electricity with same amplitudes are supplied to the woofer. Therefore, the sound waves that generated by woofer have different frequencies but same intensities. The performances of RY-LB woofer and CRY331 microphone are shown in Tab.2 and Tab.3, respectively.

(a) Acoustic sensor and work-piece

(b) Data acquisition system

Fig.16 Experimental system for sensing property analysis

Tab.2 Performances of RY-LB woofer

Rated power (W)	Rated impedance (Ω)	Sensitivity (dB/W)	Frequency range (Hz)	SNR (dB)	Directivity
2	8	95	0-20000	90	omnidirectional

Tab.3 Performance of CRY331 microphone

Sensitivity (mV/Pa)	Response frequency (Hz)	Polarization voltage (V)	Linearity range (dB)
12.5	3.15-20000	95	0-20000

Before experiments, the microphones used in this study are calibrated and the sensitivity of them are tested with a standard sound source device. The testing results show that the sensitivity of the microphone used in this study is 12.5mV. Generally, the output signals of microphone are voltage signals. The sound pressure can be acquired through these voltage signals based on the equation (8).

$$P_e = \frac{V_e}{V_{ref}} \quad (8)$$

where, P_e is the sound pressure; V_e is the voltage signals output by microphone; V_{ref} is the sensitivity of microphone, and it equal to 12.5mV.

4.2 The sound waves received by two microphones

In this section, the frequencies of sound waves generated by woofer RY-LB are 11 KHz, 14 KHz, 17 KHz and 19 KHz, while the amplitudes of these sound waves are same. Fig.17, Fig.18 and Fig.19 show the sound signals that received by microphone T1 and microphone T2 when the deviations of the developed acoustic sensor are set as 0mm, 0.5mm and 1.0mm, respectively. In these experiments, the height of acoustic sensor is set as 2.0mm.

Fig.17 Sound signals received by to microphones when deviation is 0mm

Fig.18 Sound signals received by to microphones when deviation is 0.5mm

Fig.19 Sound signals received by to microphones when deviation is 1.0mm

The results of Fig.17, Fig.18 and Fig.19 show that, compared to other frequencies, when the frequency is 17KHz, the amplitudes of sound signals that received by these two microphones are relatively high. It manifests that the designed acoustic sensor has a high sensitivity to the frequency of 17 KHz. As shown in Fig.17, when the deviation of the designed acoustic sensor is set as 0mm, the amplitudes of sound signals that received by microphone T1 and T2 are nearly same under all frequency conditions. However, as shown in Fig.19, when the deviation is set as 1.0mm, the amplitude of sound signals that received by microphone T1 is significantly smaller than T2 when the frequency is 17KHz. The results manifest that the suitable frequency for the developed acoustic sensor is nearby 17KHz, which is accordant with the results of simulation results in section 3. The SPL differences of two sound signals that received by microphone T1 and T2 in the frequency range of 12-20KHz are shown in Fig.20.

Fig.20 shows that the SPL differences are relatively high in the frequency range of 16-18KHz. Moreover, when the deviation is large the SPL differences are relatively high. For example, the SPL differences graph of deviation 2.0mm are generally higher than other graphs. Fig.21 shows the influence of the developed sensor heights on the SPL differences.

Fig.20 SPL differences of sound signals that received by microphone T1 and T2

Fig.21 SPL differences with deviation of weld seam under various heights

Fig.21 shows that, in general the SPL differences increase with the deviation of weld seam under various heights of sensors. However, the increase is not linear under some of frequencies. For example, as shown in Fig.21c, when the frequencies are 17.6KHz, 17.8KHz and 18.0KHz, the SPL differences are not increase linearly. Compared the four sub-figures of Fig.21, it is found that the SPL differences show a relatively stable linear relations with the deviation of weld seam under various heights when the frequency of sound wave is 17.2KHz or 17.4KHz.

5. Deviation sensing of weld seam with the developed sensor

5.1 Welding parameters

To test the sensing performance of the developed acoustic sensor in the detection of weld seam deviation, a series of welding experiments are implemented in this study. In the welding experiments, a NB315F inverter welder that produced by JASCI company is used as the welding power source, and a WF-21 wire feeder is used to feed welding wire with specific speed. The material of base metal is Q-235 mild steel. Argon gas with

purity of 99% is used as the shield gas in the welding process and its flow rate is set as 15L/min. The welding parameters are adopted in the experiments are shown in Tab.4.

Tab.4 Welding parameters in the experiments

Welding electricity current I/A	Welding electricity voltage U/V	Flow rate of argon gas Q/L.min ⁻¹	Welding velocity V/mm. min ⁻¹	Deviation of weld seam D/mm
210	21.9	15	200	-3.0, -1.5, -1.0, 0, 2.0, 2.5, 4.0

In the welding experiments, the height of the developed sensor is set as 2.0mm, and the deviations of weld seam are set as -3.0mm, -1.5mm, -1.0mm, 0mm, 2.0mm, 2.5mm and 4.0mm, respectively. Where, the negative deviation means the sensor deviates to the left of the weld seam, and the positive deviation means the sensor deviates to the right of the weld seam. The frequency of sound waves generated by RY-LB woofer is 17.2KHz in these welding experiments, and the sampling frequency is set as 40KHz during experiments.

5.2 The welding sound signals

In this study, the frequency of sound waves that generated by RY-LB woofer is 17.2KHz, and these sound waves are used to detect the deviations of weld seam. During welding process, the welding arc, shield gas, metal transfer and other sound sources usually emit various frequency sound waves. To extract the sound signals whose frequencies are nearby 17.2KHz, a Butterworth band-pass filter is designed, and the pass-band frequency of the designed filter is set as 17180-17220Hz. The sound waves after filtered with the designed pass-band filter are shown in Fig.22. The weld seam deviations in this figure are -3.0mm, 0.0mm, 2.0mm and 4.0mm.

It is observed from Fig.22, the amplitudes of sound signals collected by these two microphones have no obvious difference under various deviations. It means that the sounds generated by other sound sources in the welding process significantly affect the sounds emitted from RY-LB woofer. To detect the deviations of weld seam from the sound signals received by the developed sensor, the SPL of the welding sounds are calculated via equation (8) firstly, and then a limit range filter is designed, and finally the short time energies of the sound waves are obtained. Based on the short time energies of the two microphones, the deviations of weld seam are detected.

The limit range filter is designed as equation (9).

$$Y_n = \begin{cases} X_n & \max(|X_n - X_i|) \leq \Delta e \\ \left(\sum_{i=n-l/2}^{n+l/2} X_i \right) / l & \max(|X_n - X_i|) > \Delta e \end{cases} \quad (9)$$

where, Y_n is the sound signal after filtered; X_n is the sound signal before filtered; l is the length of the filter window, $l=100\text{ms}$; Δe is the maximum difference between adjacent data in the sound signals and $\Delta e=3\text{dB}$. The sound waves in Fig.22 are disposed with equation (9) and the results are shown in Fig.23.

Fig.22 The welding sound signals after filtered by a Butterworth band-pass filter

Fig.23 The welding sound signals after filtered a limit range filter

Fig.23 shows that, after disposed by the designed limit range filter, the sound waves that received by two microphones have different amplitudes with the changing of weld seam deviations. When the deviation is -3.0mm, as shown in Fig.23a, the amplitudes of sound wave that received by microphone T1 are apparently larger than microphone T2. However, when the deviation is 0mm, as shown in Fig.23b, the amplitudes of the two sound waves that received by microphone T1 and T2 are almost equal. When the deviation increases to 4.0mm, as shown in Fig.23d, the amplitudes of sound wave that received by microphone T2 become larger. Therefore, based on the sound waves in Fig.23, the deviations of weld seam probably can be detected.

5.3 Detection of weld seam deviation

To acquire the deviation of weld seam from the sound signals, a short time energy method is adopted to dispose the data in Fig.23. In general, in a time range of 80-100ms, arc sounds are usually considered as stable and time-invariant. The short time energy of the sound signals E_n in the n th frame can be expressed as equation (10).

$$E_n = \sum_{m=n-(N-1)}^n [x(m)\omega(n-m)]^2 \quad (10)$$

where $x(m)$ is the original signal of sounds, ω is a hamming window function and N is the width of it. In this study, the width of hamming window is set as 200ms, and the overlapping size of the window is set as 100ms.

The calculated results are shown in Fig.24.

Fig.24 The short time energy of sounds received by designed sensor

In Fig.24a, the short time energies of microphone T1 are apparently larger than microphone T2. When the deviation is 0.0mm, as shown in Fig.24b, the short time energies of microphone T1 and microphone T2 are almost equal. With the increasing of deviation, as shown in Fig.24c and Fig.24d, the short time energies of microphone T2 gradually larger than microphone T1. Therefore, based on the short time energy of the sound signals that received by two microphones the deviations of weld seam could be obtained.

To acquire the sensing property of the developed sensor, the difference values of short time energies of these two microphones are obtained through a subtract operation firstly. And then the mean value and square deviate of the difference value of short time energies in each experiment are calculated. In each experiment process, the deviation of weld seam is set as a specific value, and each experiment repeat five times. The results are shown in Fig.25.

In Fig.25, the horizontal axis is the deviation of weld seam and the vertical axis is the difference of the short time energy of sounds that received by two microphones. It is obvious that a linear relation between the deviations and short time energy differences. This results manifest that the developed acoustic sensor has a potential application in the weld seam detection.

Fig.25 The sensing property of designed sensor

6. Conclusion

In this study a novel acoustic sensor is developed based on binaural effect for detecting the V-groove weld

seam position real-time. The frequency response of it is studied through numerical simulation method and experiments. It is found that when the frequency of the sound wave is 17.2KHz the developed sensor has highest sensitivity. A series of welding experiments are implemented and the sound signals are collected by this developed sensor. A limit range filter is designed to dispose the sound signals, and then the short time energy of them are acquired. It is found that the linear relation exists in the short time energy differences of two microphones with deviations of weld seam. The developed acoustic sensor has potential applications in the area of weld seam tracking.

Declarations

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Conflicts of interest/Competing interests

The authors declare no competing interests.

Availability of data and material

Not applicable

Code availability

Not applicable

Ethics approval

Not applicable

Consent to participate

All the authors listed have participated in the preparation of the manuscript.

Consent for publication

This manuscript is approved by all the authors for publication. It is the original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

Authors' contributions

Yanfeng Gao: Conceptualization, Methodology, Writing- Original draft preparation, Funding acquisition.

Jianhua Xiao: Investigation, Data Curation, Visualization.

Genliang Xiong: Writing - Review & Editing.

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