Development of on-line nondestructive testing device for welding cracks based on piezoelectric ceramic excitation

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Abstract. Perform real-time non-destructive testing of weld damage in various welded structures of steel to determine the degree of weld damage in order to make timely safety warnings to protect human life and property safety. In this paper, piezoelectric ceramics are arranged on both sides of the weld to find the best frequency of the excitation system. The sine signal of this frequency excites the piezoelectric ceramics on one side, and receives and analyzes the response signals of the piezoelectric ceramics on the other side. This paper uses direct digital frequency synthesis technology (DDS), power management circuit, differential amplifier circuit, band-pass filter circuit, phase detection circuit, amplitude detection circuit, etc. to design a system that can perform real-time nondestructive testing. The whole system can measure the changes of these signals in real time, and send the signals to the upper computer remotely. Analysis of these signals can initially determine the size and location of weld damage. The research results show that when the weld in the steel is damaged, the amplitude of the sinusoidal signal propagating through the weld will be attenuated, and the phase difference between the transmitted signal and the received signal will increase. This change is positively correlated with the degree of damage.

1. Introduction

In the weld joint, the fusion zone is its weak link, it is actually an area where the melting is uneven. Some defects in welds such as cold cracks, reheat cracks and brittleness often originate here [1]. Defects in the weld may cause property damage, personal injury or death. In addition to the external defects visible to the naked eye, there are many internal defects that are difficult to find in the welded structure, such as cracks, pores, slag inclusions, incomplete penetration. Among them, cracks have the greatest impact on brittle fracture [2], brittle fracture often occurs suddenly without obvious precursor, so more attention should be paid to cracks.

Non-destructive testing methods for welded structures include radiographic testing, ultrasonic testing, magnetic particle testing, penetrant testing, strain gauge testing, etc. Wang Yigang and Ding Keqin use resistance strain gauges to detect the stress of crawler crane arms [4]; Kesheng OU, Xufeng LI proposed phased array ultrasonic testing to determine the external tension of surface cracks [5]; Yanfeng Li, Xiangdong Gao et al. proposed a magneto-optical imaging non-destructive testing system based on rotating magnetic field excitation to extract and detect the characteristics of weld defects [6]; Wang Qiang, Xiao Kun used ultrasonic phased array technology to analyze austenitic stainless steel welds Defects were detected [7]; Shi Yaowu used acoustic emission technology to apply to welding
production, and developed a welding crack acoustic emission monitor [8].

The above scholars use different methods to conduct non-destructive testing of steel welded structures, and can identify the size of the deformation or the location of the defect at the weld. However, the detection equipment used is large in size and high in cost, and it is difficult to perform on-line real-time detection of steel weld damage. Therefore, this paper proposes a non-destructive testing method based on piezoelectric ceramic excitation, develops a low-power online testing device, and conducts theoretical analysis and experimental research to verify the feasibility of the device.

2. Piezoelectric ceramic excited steel welding crack detection system

The composition of the steel welding area is affected by the welding environment, electrode material and welding process. For example, dust, nitrogen and oxygen in the air will enter the weld during welding, and the electrode coating will fall into the weld during the welding process, and the rapid cooling of the welding process will cause segregation [9], etc., all of which will cause the weld. Non-metallic inclusions appear, resulting in various welding defects. Because the chemical composition of the weld seam is not uniform, reflection and refraction will occur when the vibration wave propagates in the steel and encounters the weld seam. The expression of wave is:

\[ Y = A \cos(\omega t + \phi) \]  

(1)

From the analysis of the wave propagation path, compared with the ideal case where the weld composition is uniform, the actual propagation path of the wave in the uneven weld increases, resulting in an increase in the value of phase \( \psi \); from the energy perspective of the wave, the wave is passing through. When the weld is defective, the energy will be further attenuated, and the vibration amplitude \( A \) of the wave will decrease. Based on this theory, this paper artificially simulates weld defects, measures and compares the changes of waves after passing through a defect-free weld and a defective weld, and finds that the experimental results are consistent with the theory. According to the positive piezoelectric effect of PZT: it vibrate along the polarization direction, and alternating voltages are generated at both ends [10]. The schematic diagram of vibration wave propagation in steel is shown in Figure 1:

![Figure 1. Schematic diagram of wave propagation in steel](image)

The overall circuit block diagram of the device is shown in Figure 2. The excitation signal uses direct digital frequency synthesis technology [11] (DDS) to generate the original sinusoidal signal. After the signal is isolated from DC, it is amplified by a differential amplifier circuit, and then an active second-order bandpass filter circuit filters out power frequency interference and high-order harmonic. The signal excites the piezoelectric ceramic arranged on one side of the weld and receives the response signal of the piezoelectric ceramic on the other side. After the response signal is processed in the same way, it is converted into a direct current signal by an effective value conversion circuit, and then input to the ADC pin of the MCU after limiting the amplitude. The excitation and response signals are input to the phase difference detection circuit to obtain the phase difference, and then input to the input capture port of the MCU.
3. Construction of the experimental platform

3.1. Selection of steel and construction of structure
The carbon steel model selected for the experiment in this article is Q235B[12]. The actual welding situation in the project is more complicated. In addition to horizontal welding, there are welding conditions of various angles. Therefore, the platform in the experiment is divided into horizontal welding parts and right-angle welding parts according to the welding conditions, and divided into 5mm parts and 15mm according to the thickness of steel pieces. The attenuation of the wave propagating in the steel is related to the contact point between the steel and other supports before and after the experiment, that is, whether they are in the same position. In the experiment, the steel is fixed on the profile bracket to ensure that the position of the platform before and after the experiment is the same, thereby eliminating the error caused by the position change of the steel, as shown in Figure 3, the online NDT device for welding cracks developed in this paper is shown in Figure 4.

3.2. Selection of PZT
The literature [13] mentioned that there are several common types of PZT (PZT): PZT4D, PZT5A, PZT5H, PZT8, etc. Among them, PZT5A has the characteristics of high electromechanical coupling coefficient, high flexibility, high dielectric constant, etc. Its performance in driving and sensing has more advantages than other specifications of ceramic chips, and is mainly used in sensors, accelerometers, pressure gauges, anemometers, etc[13]. The effective electromechanical coupling coefficient (keff), resonance frequency, dynamic resistance, and quality factor are all important parameters of PZT. This article compares the three piezoelectric slices of the PZT5A series and selects one of them. The main parameters are shown in Table 1:

![Figure 2. Device overall circuit block diagram](image_url)

![Figure 3. Schematic diagram of power supply for steel welding crack detection system](image_url)

![Figure 4. Horizontal welding and right-angle welding used in the experiment](image_url)
Table 1. Main parameters of the three PZT of the PZT5A series (No. 1 is rectangular, No. 2, 3 are wafers)

| Serial number | Size(mm)     | Resonant frequency(HZ) | Dynamic resistance(ohm) | keff | Quality factor | Static capacitance(nf) |
|---------------|--------------|------------------------|--------------------------|------|----------------|------------------------|
| 1             | 60×30×0.2    | 59180                  | 6.93507                  | 0.177464 | 126.344        | 120.617                |
| 2             | 16×2         | 124274                 | 40.4691                  | 0.564531 | 64.8379        | 1.19975                |
| 3             | 25×2         | 77980                  | 25.5449                  | 0.599156 | 69.3204        | 2.69545                |

The experiment uses THS4001 chip to amplify and filter the DDS signal, and the processed sinusoidal signal has a peak-to-peak value of 10Vpp, which is used to excite PZT. Taking the first of the above three PZT as an example, its effective electromechanical coupling coefficient keff=0.177464, so the mechanical efficiency keff2 is about 0.0315, that is, 96.85% is consumed by itself. The dynamic resistance of PZT is 6.935Ω, according to the formula:

\[ P = \frac{U_m^2}{R} \]  \hspace{2cm} (2)
\[ U = \frac{U_m}{\sqrt{2}} \]  \hspace{2cm} (3)
\[ I = \frac{P}{U} \]  \hspace{2cm} (4)

Among them, Um is the peak value of the sinusoidal signal, Um=1/2Vpp, R is the dynamic resistance of the piezoelectric ceramic, P is the power consumption, calculated P=1.7456w, I=494mA, due to the mechanical efficiency of the first piezoelectric ceramic And the dynamic resistance is relatively large, the power consumption is relatively large, and the front stage of the op amp needs to provide a relatively large current, so the first piezoelectric ceramic does not meet the requirements. Similarly, after calculating the power P=0.21w and current I=59mA of the second piezoelectric ceramic under the same excitation; the power P=0.314w and current I=88mA of the third piezoelectric ceramic, which meet the requirements. Considering the actual situation, the size of PZT should be as small as possible when the performance is satisfied, so this experiment uses the second PZT.

3.3. Piezoelectric ceramic arrangement

The arrangement of PZT is divided into 3 groups. The first group: the two sides of the welding seam of the horizontal welding steel plate 1 with a thickness of 15mm are smoothed with sandpaper and wiped clean, and two pieces of PZT with leads are symmetrically pasted on both sides of the welding seam with AB glue, and air-dried naturally, As shown in Figure 5; the second group: paste two pairs of PZT on the steel plate 2 in the same way, as shown in Figure 6; the third group similarly, paste three pairs of PZT on the steel plate 3. As shown in Figure 7, all PZT are led from the positive and negative electrodes with DuPont wires.

Figure 5. The first group of test pieces
Figure 6. The second group of test pieces
4. Experiment and data analysis

4.1. Experiments with different sizes of cracks in welds
In this section, three groups of horizontal welding steels with PZT ceramics are arranged as follows: the first group uses a wire cutting machine to cut a groove with a width of 0.5mm and a depth of 5mm on the weld at the connection point of the two PZT. To simulate the crack, use the same sinusoidal signal to excite the piezoelectric ceramic on one side, and record the data of the signal received by the piezoelectric ceramic on the other side; then use a wire cutting machine to cut a groove with a width of 0.5mm and a depth of 7mm along the original position. Keep the other conditions unchanged, use the same sinusoidal signal to excite the PZT on one side, and record the data; then use the wire cutting machine to cut a groove with a width of 0.5mm and a depth of 9mm along the original position, keep the other conditions unchanged, and record the data; After continuous excitation for a period of time, the data is stable, and the experimental data is recorded as shown in Table 2:

| Groove size (mm) | Excitation signal frequency (KHZ) | Vpp of excitation signal (V) | Vpp of received signal (V) | Phase difference (us) |
|------------------|----------------------------------|-----------------------------|---------------------------|-----------------------|
| No groove        | 151                              | 10                          | 1.472                     | 2.20                  |
| Width 0.5 depth 5 | 151                              | 10                          | 1.127                     | 1.90                  |
| Width 0.5 depth 7 | 151                              | 10                          | 0.895                     | 1.87                  |
| Width 0.5 depth 9 | 151                              | 10                          | 0.544                     | 1.85                  |

4.2. Experiment on different positions of cracks in the weld
In the second set of experiments, sine signals were used to excite two PZT ceramics on one side of the weld. The two PZT ceramics were marked as group A1 and group B1. Then the data of these two groups of PZT ceramics were received and recorded, and the remaining conditions were maintained. After cutting, the two groups of PZT ceramics are recorded as group A2 and group B2. Record the two groups of PZT ceramics respectively. The third group of experiments and the second group of experiments are comparative experiments. Similarly, the three PZT ceramics on one side of the weld are excited by a sinusoidal signal. These three pairs of PZT ceramics are recorded as C1 group D1 group and E1 group, And then receive and record the data of these three groups of PZT ceramics, keeping the other conditions unchanged, cut a groove with a width of 0.5mm and a depth of 5mm near the PZT ceramic connection of the C1 group, and the three groups of PZT after cutting Ceramics are marked as C2 group, D2 group and E2 group. After the data is stable after continuous excitation for a period of time, the data of these three groups of PZT ceramics are recorded in Table 3 below:
Table 3. The data corresponding to the received signal at different positions of the crack in the weld

| Location of crack | Excitation signal frequency (KHZ) | Vpp of excitation signal (V) | Vpp of received signal (V) | Phase difference (us) |
|------------------|----------------------------------|-----------------------------|----------------------------|----------------------|
| Group A1         | 154                              | 10                          | 1.032                      | 2.52                 |
| Group A2         | 154                              | 10                          | 0.736                      | 2.33                 |
| Group B1         | 139                              | 10                          | 0.959                      | 2.81                 |
| Group B2         | 139                              | 10                          | 0.819                      | 2.78                 |
| Group C1         | 158                              | 10                          | 1.298                      | 3.00                 |
| Group C2         | 158                              | 10                          | 0.839                      | 2.71                 |
| Group D1         | 170                              | 10                          | 1.198                      | 2.00                 |
| Group D2         | 170                              | 10                          | 1.098                      | 1.95                 |
| Group E1         | 162                              | 10                          | 1.025                      | 3.05                 |
| Group E2         | 162                              | 10                          | 1.007                      | 3.03                 |

4.3 Data analysis
From the data in Table 2, it can be seen that when cracks appear in the welds of steel weldments, the energy of vibration waves will be significantly attenuated, and the attenuation is positively correlated with the depth of the cracks. Due to the existence of cracks in the steel welds, the wave As the actual distance of propagation increases, the phase difference between the transmitted wave and the received wave will increase; from the data in Table 3, it can be seen that the attenuation of wave energy is related to the position of the crack. The closer the crack is to a certain group of piezoelectric ceramics, the pressure of this group The greater the attenuation of the energy received by the ceramic, the less the energy attenuation the farther.

5. Conclusion
This paper analyzes the propagation mode of vibration wave in steel, explores the energy loss and phase change of vibration wave after passing through the welding seam, uses PZT to generate vibration wave and receive the energy of vibration wave, and design on-line non-destructive inspection of welding cracks system. This paper uses this system to conduct experiments on steels with different welded structures, and analyzes the influence of different degrees of crack damage in the welds on the experimental results. The results show that the energy loss of the sine wave generated by piezoelectric ceramic vibration increases with the crack expansion in the weld. At the same time, the existence of cracks causes the wave propagation path to be relatively longer, resulting in an increase in the time for the sine wave to propagate to the same location. Comprehensive analysis of the peak-to-peak value of the received signal and the phase difference between the sending and receiving signals can judge the damage degree of the weld and the position of the crack in the weld. The system designed in this paper has the advantages of small size, low cost, convenient layout, and good reliability, and can achieve good results of NDT.

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