Time-of-flight diffraction technique for Pressure Equipment

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\textbf{Abstract.} This paper mainly introduced the application of TOFD technique in pressure equipment, and systematically discussed the principle of TOFD technique. The development of TOFD technique and the influence of TOFD technique on the attenuation of acoustic beam in austenitic stainless steel were introduced. In addition, the reasons and solutions of the blind area on the surface of TOFD technique were explained, and the application of TOFD technique in pressure parts was prospected.

1. Introduction
Supercritical and ultra supercritical units have been put into operation successively, which has effectively alleviated the domestic power shortage. The safety and stability of pressure equipment in thermal power plant units are related to personal and property safety. The weakest part of pressure equipment is butt weld, especially the main steam pipeline pressure of supercritical and ultra supercritical units has reached 25MPa, and the temperature has reached 600°C. Because of the high pressure and temperature, the quality of butt weld in pipeline is needed. So the quality inspection of butt weld in pressure equipment is particularly important. The nondestructive testing of medium and thick components is mainly ultrasonic testing, but the conventional ultrasonic testing technology for large wall thickness components has a low detection rate due to the influence of sound beam attenuation, and the defect are easy to be missed. TOFD technique is widely used in the nondestructive testing of butt welds of large wall thickness components of pressure equipment due to its recordable, high detection rate, accurate defect positioning and high sensitivity.

2. The development of TOFD technique
TOFD technique was first proposed by Dr. Mauric silk, national NDT center of the UK in 1970s. It was an ultrasonic technology that could accurately locate and quantify defects. TOFD technique was widely used in petrochemical industry and other industrial fields. Later, in order to standardize the application of TOFD technique, Britain, European Union, the United States and Japan issued TOFD testing standards suitable for their own countries. BS7706-1993, ENV583-6-2000, CEN/TS-14715-2004, ASTM E2373-2004 and NDIS 2423-2001 are the current method standards, and ASME CC 2235-9 is the acceptance standard.

In 1990s, China began to introduce TOFD technique. In 2007, AQSIQ issued a document stipulating that "For pressure vessels with a wall thickness of more than 60mm, TOFD technique method can be used instead of X-ray for nondestructive testing", and then a large number of manufacturing sites began to apply TOFD technique. In 2010, the National Energy Administration issued the first TOFD technique specification Nb/T 47013.10-2010 nondestructive testing of pressure
equipment Part 10: diffraction time difference ultrasonic testing.

3. Principle of TOFD technique
TOFD technique (ultrasonic diffraction time difference method) uses Huygens principle to detect defects\cite{1-4}. The reflection and diffraction occur when the ultrasonic meets the defect. When the defect size is smaller than the ultrasonic wave length, the diffraction occur. When the defect size is larger than the ultrasonic wave length, the reflection occur. TOFD technique has a high sensitivity because it has little relationship with amplitude and defect angle. In the detection process, the mode of two probes, one sending and one receiving, is adopted. The probes have the same frequency, angle and chip size, and the probes are scanned across both sides of the weld in non parallel and parallel. When the moving direction of the probe is consistent with the propagation direction of the acoustic beam, it is called parallel scanning. When the moving direction of the probe is perpendicular to the propagation direction of the acoustic beam, it is called non parallel scanning. The non parallel scanning can be used as the initial detection during TOFD technique, and the defect can be initially located, but the defect cannot be located away from the center of the weld. The parallel scanning can accurately locate the defect away from the center of the weld. When the transmitted longitudinal wave meets the defect, diffraction wave is generated at the upper and lower points of the defect. When the instrument receives the A-scan signal, D-scan image is generated synchronously. In the image, defect wave appears between the lateral wave and the back wall reflection, as shown in Figure 1.

![Figure 1 TOFD technique principle](image)

3.1. TOFD map analysis
TOFD scanning image is mainly divided into A-scan image, B-scan image and D-scan image. TOFD map is formed by receiving A-scan signal. The gray scale is related to the amplitude of A-scan signal. Therefore, a TOFD map is composed of a series of A-scan signals transformed into gray-scale images. The TOFD pattern defects are mainly divided into surface open type defects and buried type defects, among which the buried defects are mainly porosity, cracks, incomplete penetration, strip slag inclusion and groove incomplete fusion, etc. As shown in Figure 2. The porosity is a point defect. The porosity defect is very small and has no height, there is no obvious diffraction signal from the upper and lower points in the defect map, and the signal is arc-shaped. There is a straight signal in the length direction of the slag, which is intermittent, and the head and tail are arc-shaped. For the X-groove structure, the incomplete penetration defect map often appears in the middle position, and the defect map is relatively straight but not parallel to each other, similar to the saw. For V-groove structure, incomplete penetration often occurs at the bottom wave position. The incomplete penetration bottom wave is continuous, which is different from the opening defect on the bottom surface and the diffraction signal of the lower end point can be found. The incomplete fusion is divided into groove incomplete fusion and interlayer incomplete fusion, and its pattern is similar to incomplete penetration.
The upper and lower end points cannot be effectively identified due to its low height, which is characterized by uneven blackness and a certain length of black. The upper and lower points of the crack image are irregular, the signal is discontinuous, there are many small end angles at the signal end, and the crack is the most dangerous, so attention should be paid to the crack.

![Figure 2 TOFD technique map](image)

**Figure 2** TOFD technique map

### 3.2. TOFD blind area

TOFD technique receives the diffraction wave of defects, and the defect location does not depend on the amplitude, so the detection rate of small defects is high. However, TOFD detection also has limitations. There are blind areas in TOFD detection, mainly from the upper surface blind area, the lower surface blind area and the axis deviation blind area. The main reason for the blind area of TOFD upper and lower surfaces is the pulse width of through wave and bottom echo. Within the transmission time range of the width, it is impossible to distinguish between through wave, bottom echo signal and defect wave signal. This blind area cannot be eliminated but can be minimized. Generally, short pulse width, increasing probe frequency and reducing PCS distance are used to reduce the upper surface blind area. Axis deviation blind area is due to the fact that the diffraction signal on the ellipse track has the same propagation time with the echo on the bottom surface, and the diffraction signal outside the ellipse track is covered by the echo on the bottom surface and cannot be displayed. In the actual inspection, there is a large blind area near the weld fusion line. The larger the width of the weld on the lower surface, the larger the axis deviation from the blind area. Generally, scanning with a certain distance offset to the blind area direction is used to reduce the axis deviates from the blind area. In order to effectively detect the defects in the blind area, TOFD + MT, TOFD + UT and TOFD + PA detection methods are usually used. Among them, TOFD + PA is the best method to detect the defects in the 12.7mm plate thickness, with a detection rate of 75%, as shown in Table 1. In addition, by using TOFDR + TOFDW, the time window is adjusted between the primary reflection wave on the bottom and the secondary reflection wave on the bottom, so that the multiple reflections can improve the acoustic path difference between the near surface defect signal and the adjacent wave, and improve the resolution[5]. The research shows that this method can identify defects in the depth range of 1mm. In addition to reducing the surface blind area in terms of technology, the surface blind area is also reduced by processing the defect signal. The research showed that the autoregressive spectrum extrapolation method was used to establish the autoregressive model for the frequency-domain data of the surface defect signal and the through wave mixed signal, it could expand the data outside the effective frequency band, separate the superimposed signal, improve the vertical resolution, and reduce the blind area to 2.6mm[6]. The research showed that the defect in the depth range of 1-6mm
could be detected effectively by optimizing the positioning formula through the waveform conversion theory[7].

Table 1 Detection rate of three methods[%]

| Test method | Defect detection rate of test block with different thickness |
|-------------|----------------------------------------------------------|
|             | 12.7mm | 19mm | 32mm |
| TOFD + PA   | 75     | 100  | 100  |
| TOFD + UT   | 75     | 80   | 90   |
| TOFD + MT   | 50     | 75   | 80   |

3.3. TOFD austenitic stainless steel inspection

During the welding process of austenitic stainless steel, it is easy to form columnar crystal when it is heated and grown up, and there is no phase transformation in the process of condensation. Therefore, the austenite grain is coarse at room temperature. In addition, there are inhomogeneity and anisotropy in the weld of austenitic stainless steel. When ultrasonic wave propagates in austenite stainless steel grain, it is easy to produce beam deflection, beam distortion, ultrasonic attenuation, grain scattering and structure noise. Structural noise reduces the signal-to-noise ratio of TOFD technique, which makes it difficult to identify defects. Generally, the wide-band narrow pulse probe is used, and the frequency of the probe should not be too high. The scanning is carried out from the root of the weld, because the angle between the propagation angle of the sound beam and the production direction of the columnar crystal is small, it can reduce the ultrasonic attenuation to a certain extent. In addition, signal-to-noise ratio can be improved by signal processing. Research showed that the improved nonlinear wavelet threshold denoising method could effectively improve the signal-to-noise ratio. The research showed that the defect signal was decomposed by three-layer wavelet packet to obtain multiple decomposition signals, and the main decomposition signals were reconstructed into gray-scale image, the quality of the new gray-scale image was significantly improved, and the signal-to-noise ratio was improved[8]. Through the synthetic aperture focusing technology, the feature that the defect correlation and similarity were higher than the structure noise was used to suppress the structure noise amplitude, and it could improve the signal-to-noise ratio of the defect signal[9].

3.4. Process parameter selection of TOFD probe

When TOFD detects the workpiece, the thickness of the workpiece should be considered when selecting the probe angle. Because the larger the probe angle, the longer the detection range and the greater the acoustic reflection attenuation, it is not suitable to select the large angle probe for the parts with large wall thickness. Secondly, under the premise of ensuring the energy and penetration, the probe with larger angle should be selected as far as possible, which is conducive to the detection of cracks. In addition, by increasing the probe frequency, the time interval between the through wave and the bottom wave contains more signal periods, and the depth resolution is higher. In the actual detection process, it is generally up to 20 periods. However, the increase of probe frequency will also increase the attenuation and noise signal, and it can reduce the signal-to-noise ratio, it also can reduce the sound beam diffusion angle, so the probe frequency should not be too large. The small chip size is beneficial to the good contact with the workpiece, the near-field area is reduced. But the sound beam energy is low, so the large chip size is needed to detect the thick wall workpiece.

To sum up, for thin workpiece detection, high resolution requirements and low penetration requirements can be selected, and probes with large angle, high frequency and small size chips can be selected. With the increase of workpiece thickness, resolution requirements gradually decrease and penetration requirements gradually increase, so probes with small angle, low frequency and large chip size can be selected. Recommended process parameters of 12-200mm thick components detected by TOFD are shown in Table 2.

Table 2 Recommended selection and setting of probe for flat butt joint

| Thickness t(mm) | Pattition Depth t(mm) | Frequency f(MHz) | Angle a(°) | Diameter d(mm) |
|-----------------|-----------------------|------------------|------------|----------------|
In addition, the sound beam simulation experiment can be carried out through the sound beam simulation software. CIVA software is a professional platform for NDT industry developed by French Atomic Energy Commission. It is composed of simulation, imaging and analysis modules, which are mainly used in data analysis, performance verification, probe design and training. It can simulate ECT, UT and RT technologies, and provide accurate defect simulation results with short calculation time to meet the needs of industrial complex components inspection. The CIVA software can simulate instantaneous ultrasonic field at a certain position of workpiece under the different probe frequency, angle, chip size, as shown in Figure 3.

| Frequency Range | Step 1 | Step 2 | Step 3 |
|-----------------|-------|-------|-------|
| 12-15           | 0-t   | 15-7  | 70-60 | 2-4   |
| 15-35           | 0-t   | 10-5  | 70-60 | 2-6   |
| 36-50           | 0-t   | 5-3   | 70-60 | 3-6   |
| 50-100          | 0-2t/5| 7.5-5 | 70-60 | 3-6   |
|                 | 2t/5-t| 5-3   | 60-45 | 6-12  |
| 100-200         | 0-1/5 | 7.5-5 | 70-60 | 3-6   |
|                 | 1/5-3t/5| 5-3  | 60-45 | 6-12  |
|                 | 3t/5-t| 5-2   | 60-45 | 6-20  |

Figure 3 Diffraction sound field simulation diagram

4. Summary
NDT technology mainly includes penetrant testing, magnetic particle testing, conventional ultrasonic testing and radiographic testing. Through penetration and magnetic particle testing, only defects on the surface and near the surface can be found, and the buried defects cannot be limited tested. The large tube voltage and exposure time are required for the large wall thickness parts in radiographic testing, which is easy to cause the film to be blurred. When the direction of the ray is parallel to the angle of the groove, the incomplete fusion defects of the slope is missed. Besides, radiation is harmful to human body; Although conventional ultrasonic testing technology can effectively detect buried defects, its qualitative and quantitative defect depends on the magnitude of wave amplitude, which is easy to cause the omission of small defects. The application of TOFD technique in large wall thickness parts has obvious advantages, such as easy operation, high sensitivity and high detection rate, but it also has some limitations, such as the problem of blind area on the surface and the problem of low signal-to-noise ratio for structural parts with coarse grains. However, with the development of related software and hardware, the blind area of TOFD technique and the problem of low signal-to-noise of coarse grain structure have been controlled within the allowable error range. Through phased array,
creeping wave and other detection means, the effective NDT of weld components can be realized.

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