Flaw Size and Position Measurement by Multiple Probe TOFD Method

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Abstract
Ultrasonic flaw detection and sizing are important issues for ensuring structural reliability of industrial plants. The Time-of-Flight Diffraction (TOFD) method is known as the most accurate flaw sizing method, though TOFD method is applicable only if the flaw exists on the perpendicular bisector of the ultrasonic probe pair. In this study, a new TOFD method which can measure the flaw tip position and depth simultaneously was introduced. This method uses the arrival times of flaw tip diffraction echo measured by many probe pairs. The flaw tip position and depth could be estimated accurately by nonlinear least square approach. Through this process, dilution of precision (DOP) parameter was introduced to evaluate measurement error. By using numerical calculation, the relationship between the DOP and the flaw tip position measurement accuracy was investigated.

Keywords: non destructive testing, ultrasonic testing, time of flight diffraction (TOFD), multiple probe, dilution of precision

1. Introduction
Ultrasonic flaw detection and sizing are important issues for ensuring structural reliability of industrial plants. The phased array technique has been used as one of the most effective tools for visualizing the flaws in structural components. However, in the case of flaw size and position measurement, only an A-scope signal is used for estimation usually. Therefore, in order to estimate flaw size accurately, high skill is required for examiner. On the other hand, the time-of-flight diffraction (TOFD) method is known as a one of the most accurate flaw size measurement method. However, TOFD method is applicable only if the flaw exists on the perpendicular bisector of the ultrasonic probe pair. In this study, new flaw sizing method by using many ultrasonic probes was introduced. Through this process, dilution of precision (DOP) parameter was introduced to evaluate measurement error of flaw tip position. By using numerical simulation, the relationship between the DOP and the flaw tip position measurement accuracy was investigated.

2. Theory of multiple probe TOFD method
2.1 Ordinary TOFD method
Figure 1 shows the schematic illustration of TOFD method. A pair of ultrasonic transducer is put on the specimen, one is a transmitter and the other is a receiver. Ultrasonic beam is widely spread in the specimen, and then several echoes reach to the receiver. The first echo which propagates the surface of the specimen corresponds to the lateral wave. If there is a flaw in the specimen, the flaw tip diffraction echo will be observed between lateral wave and back wall echo. The distance from surface of specimen to the flaw tip can be estimated by eq. (1) using the arrival time difference between lateral wave and flaw tip diffraction wave.
where \( t_d \) is the arrival time difference between lateral wave and diffraction echo, \( C_L \) is the velocity of longitudinal wave and \( S \) is the distance between transmitter and receiver. However, in order to estimate the flaw size accurately, the flaw must be exists on the perpendicular bisector of the probe pair. If there is a misalignment, the estimation error becomes larger.

\[
d = \sqrt{\frac{t_d^2 C_L^2 + t_d C_L S}{4}} \quad (1)
\]

2.2 Multiple probe TOFD method

Figure 2 shows a schematic illustration of the asymmetric TOFD method. If the ultrasonic beam is transmitted by transmitter \( i \) and receiver \( j \), the distance between the transmitter and the flaw tip \( \rho_i \) and distance between the flaw tip and the receiver \( \rho_j \) are described by following equation (2).

\[
\rho_i = \sqrt{(x_i - x)^2 + (y_i - y)^2}, \quad \rho_j = \sqrt{(x_j - x)^2 + (y_j - y)^2} \quad (2)
\]

where \((x_i, y_i)\) is the position of the transmitter, \((x_j, y_j)\) is the position of the receiver and \((x, y)\) is the position of the flaw tip. Then, the strict total beam path length \( \rho_{ij} \) is as follows.

\[
\rho_{ij} = \rho_i + \rho_j \quad (3)
\]

As shown in Fig. 2, the flaw tip exists on the ellipse line. The length of major axis corresponds to \( R_{ij} \) and foci correspond to the position of the transmitter and receiver.
However, in the case of the experiment, the observed beam path length $R_{ij}$ measured by arrival time of diffraction echo and ultrasonic velocity contains measurement error. The error is described as following equation (4).

$$R_{ij} - \rho_{ij} = n_{ij} \quad (4)$$

If the many waveforms are obtained by changing the positions of the transmitter and receiver, the ellipses corresponding number of waveform can be described. The flaw tip exists on all ellipses, hence the flaw tip position ($x, y$) can be estimated by solving the intersection point of the ellipses by the least square method. Because this is a nonlinear least square problem, the iterative calculation by Gauss-Newton method was utilized.

### 2.3 Dilution of precision (DOP)

The estimation error of the flaw tip position is strongly related to the position of the probes and the flaw tip. In the research field of global pointing system (GPS), the dilution of precision (DOP) is used to evaluate the position error of the GPS receiver. If the transmitter position and receiver position are expressed as follows;

$$\rho_i = [x_i, y_i]^T, \quad (i = 1, 2, ..., M) \quad (5)$$

$$\rho_j = [x_j, y_j]^T, \quad (j = 1, 2, ..., M) \quad (6)$$

where $M$ is a total transducer number. Then, the DOP value is defined as following equation.

$$h_{ij} = - \frac{1}{\rho_{0i}} (\rho_i - \rho_0)^T - \frac{1}{\rho_{0j}} (\rho_j - \rho_0)^T \quad (7)$$

$$H = [h_{i1}, h_{i2}, ..., h_{ij}]^T \quad (8)$$

$$M = (M_{ij}) = (H^T H)^{-1} \quad (9)$$

$$XDOP = \sqrt{M_{11}}, \quad YDOP = \sqrt{M_{22}} \quad (10)$$

As previously mentioned, the obtained beam path length $R_{ij}$ contains measurement error $n_{ij}$. If the range of error is $\sigma$, the estimation error of flaw tip position for $x$ direction and $y$ direction are described as following equation.

$$X_{error} = \sigma \times XDOP, \quad Y_{error} = \sigma \times YDOP \quad (11)$$

The DOP value is related only the transducers position and flaw tip position. Then, the measurement error of flaw tip position can be estimated if the transducer arrangement is
known. For example, Fig. 3 shows a numerical calculation model for XDOP and YDOP. Fig. 4 and Fig. 5 shows the XDOP and YDOP contour maps for 3 transducer arrangement and 5 transducer arrangement model respectively. For the Fig. 4 and Fig. 5 model, assumed combination of transmitters and receivers (i.e. number of the waveforms) are 9 \((3\times3)\) and 25 \((5\times5)\) respectively. The XDOP is better at the near field of the probe, though it becomes worse at far field of the probe. On the other hand, the YDOP is almost constant at the beneath area of the probe, though the value becomes worse at the side area. Moreover, the DOP value becomes better by increasing the number of the transducers.

![Figure 3 DOP calculation model](image1)

**Figure 3 DOP calculation model**

![Figure 4 Contour maps of XDOP and YDOP for 3 element model (model A)](image2)

**Figure 4 Contour maps of XDOP and YDOP for 3 element model (model A)**

![Figure 5 Contour maps of XDOP and YDOP for 5 element model (model B)](image3)

**Figure 5 Contour maps of XDOP and YDOP for 5 element model (model B)**

3. **Validation by numerical simulation**

3.1 **Simulation model**

In order to investigate the effectiveness of the multiple probe TOFD method, numerical simulation by the finite difference method (Wave2000, CyberLogic, Inc.) was used for simulating ultrasonic wave propagation. Figure 6 shows the simulation model for this study. The size and transducer arrangement are same to the DOP calculation model (Fig. 3) though a flaw was implemented in the center of the model. The gap in the flaw of is vacuum-field and
do not propagate any ultrasonic waves. The infinite boundary conditions were set on the left and right sides. Since the calculation assumes type 304 stainless steel, the acoustic speed of the longitudinal and shear waves were set as 5790 m/s and 3180 m/s respectively. This model assumed a homogeneous isotropic elastic body.

![Ultrasonic simulation model with slit](image)

Five transducers (1 mm width, 5 mm pitch) were put on the surface of the specimen. For the incident wave, 2 MHz longitudinal Gaussian sine pulse beams defined by the following equation were generated by each oscillator as displacement for simulation,

\[
P(t) = A \exp\left\{-\frac{(t-d/2)}{a^2}\right\}\sin(2\pi f t)
\]

where \(A\) is the amplitude, \(t\) is the time scale, \(d\) is the duration, \(a\) is the time constant and \(f\) is the center frequency. In this simulation, \(A\) was set as 50, \(d\) was set as 2.0 \(\mu\)s, \(a\) was set as 0.3 \(\mu\)s and \(f\) was set as 2.0 MHz. The waveform and its frequency component are shown in Fig. 7. Though the center frequency of the incident wave is 2 MHz, higher frequency components up to 4 MHz also exist. The wavelength of the shear wave at 4 MHz is 800 \(\mu\)m, the finite difference grid element size was set as 40 \(\mu\)m for resolving 800 \(\mu\)m by 20 points to provide a good approximation. The time step for simulation was set as 5.75 ns to avoid instability. The displacements of each oscillator were recorded as the ultrasonic waveforms. The 25 (5×5) ultrasonic waveforms were obtained for the multiple probe TOFD method.

![Waveform and its frequency component of incident wave](image)

### 3.2 Flaw size estimation by multiple probe TOFD method

Figure 8 shows an example of signals obtained by numerical simulation. The "L", "B1", "B2" and "R" correspond to the lateral wave that propagates along the surface of the specimen, the first and second back wall echoes and Rayleigh wave, respectively. Through the echo from flaw appear between the lateral wave and the first back wall echo, the amplitude is usually
The calculation of multiple probe TOFD method was conducted by using the arrival time of the maximum peak of the diffraction echoes. The flaw tip position estimation results for the 3 transducer model (model A, Fig. 4) and for the 5 transducer model (model B, Fig. 5) were both (50.0 mm, 30.3 mm). At the flaw tip position, the XDOP and YDOP for model A and B were (1.8, 0.17) and (0.62, 0.10) respectively. Then the estimation error for model B must be less than model A, though there is no difference of estimation error. This is because this result is based on the numerical simulation hence the accidental error for diffraction echo arrival time reading is scarce. The error of 0.3 mm for flaw tip depth estimation was considered due to the systematic error of this simulation.

In order to evaluate the relationship between the DOP and the estimation error, the Gaussian white noise was added to the observed beam path length $R_{ij}$ artificially. The multi probe TOFD method was conducted 1024 times for model A and B then the standard deviations of the flaw tip position estimation results were calculated respectively. Table 1 shows the relationship of the DOP value and standard deviation of estimation error for $x$ direction ($\sigma_x$) and $y$ direction ($\sigma_y$). The standard deviation of the noise $\sigma_R$ was set as 1.0 mm then the $\sigma_x$ and $\sigma_y$ are close to the multiplication of the $\sigma_R$ and each DOP. In the case of the actual experiment, the DOP value is effective indicator to estimate the measurement error.

Table 1 Relationship between the standard deviation for estimation error of diffraction echo arrival time and flaw tip position

<table>
<thead>
<tr>
<th></th>
<th>DOP at (50, 30)</th>
<th>$\sigma_R$ [mm]</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
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</thead>
<tbody>
<tr>
<td>3 transducers model</td>
<td>XDOP:1.8</td>
<td>1.0</td>
<td>1.8</td>
<td>0.18</td>
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<tr>
<td></td>
<td>YDOP:0.17</td>
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<td></td>
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<tr>
<td>5 transducers model</td>
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<td>0.64</td>
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<tr>
<td></td>
<td>YDOP:0.10</td>
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4. Conclusion
In this study, the flaw size and position measurement method by utilizing multiple probes was suggested. Through this process, the dilution of precision (DOP) parameter was introduced to evaluate measurement error of the flaw tip position. The flaw tip position was measured by
the suggested method. Moreover, the relationship between the DOP and the flaw tip position measurement accuracy was investigated.

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