LOCALIZATION AND SIZE ESTIMATION
OF CYLINDRICAL FLAWS

Akira Umeda and Namiteru Hida
National Research Laboratory of Metrology
Ministry of International Trade and Industry
1-4, 1-Chome, Umezono, Sakura, Niihari, Ibaraki, 305, Japan

INTRODUCTION

In recent years, a number of ultrasonic imaging systems for NDE have been developed. These systems are mainly composed of expensive high speed electrical circuits, expensive transducers with a number of elements, and signal processing equipment. However, if the processing of signals concerning flaws is based on phase information, the minimum number of transducer elements is only three in the pitch-catch method. This paper deals with a flaw measurement where only three ultrasonic transducers are used at most for localization and sizing of cylindrical flaws.

INSTRUMENTS

Figure 1 shows the block diagram of the instruments. The quartz oscillator with a pulse train output triggers two other oscillators, OSCa and OSCb. The output of the former is a single period sinusoidal burst wave (2MHz). It is amplified and becomes the driving signal of a transmitter. The output of the latter, \( N \) periods of sinusoidal burst wave (2MHz), is connected to a digitizer. The echo signal from a flaw and this signal are sampled and digitized simultaneously. The digitizer has the capability of sampling at a maximum speed of 100 MHz. The storage capacity of each channel is 2K bytes. The element in a linear array transducer (size 0.5" x 0.1", spacing 0.005") is used as a transmitter or receiver.

PRINCIPLE OF FLAW LOCALIZATION

Figure 2 shows a setup for flaw localization. If the minima of the time-of-flight (TOF) is given, the flaw depth, \( L_1 \), is derived as
follows:

\[ L_1 = \sqrt{(C_1 \Delta T_{\text{min}} / 2)^2 - D^2} \quad (1) \]

where \( C_1 \) is the velocity of the longitudinal wave in the host material, \( \Delta T_{\text{min}} \) is a minima of the TOF, and \( D \) means the spacing between two transducers. The TOF at each scanning position is determined using the cross correlation between the \( \alpha \) wave and the \( \beta \) wave in Figure 2. Since ultrasonic data are digitized and stored in the digitizer before they are transferred to a minicomputer, the TOF is the quantized time with units of the sampling time, \( T_s \), and is defined as the value which maximizes the cross correlation coefficient. The value of \( N \) is selected so that it can cancel the ringing effect of the transmitter and lead to an accurate computation of cross correlation. The minima of the TOF is derived from the application of experimental data to a parabola curve using the method of least squares as follows:

\[ \Delta T_{\text{min}} = [(4B_2B_0 - B_2B_1) / 4B_2]T_s \quad (2) \]

where \( B_2, B_1, \) and \( B_0 \) are the coefficient of the second order term, the coefficient of the first order term and the constant term, respectively.
PRINCIPLE OF FLAW SIZING

Sizing is performed with three transducers. One is a transmitter and the remaining two are receivers. The difference between the two ultrasonic path lengths, ABC and ADE in Figure 3 depends on scan length, $\xi$, flaw radius, $r$, flaw depth and spacing. If they are given and if the host material of a specimen is known, the path difference or the time corresponding to it can be calculated according to ultrasonic ray theory. Diagrams are also obtained, as shown in Figure 4. Plotting the relation between scan and path difference on the diagram permits flaw sizing, because flaw radii appear as parameters. The figure tells the necessary resolution in time or in distance to achieve the specified resolution in sizing. It is also known from this that there is an optimal point for sizing.
APPLICATION TO A SPECIMEN WITH A CURVED SURFACE

This method is applicable to a specimen with a curved surface. Figure 5 shows a setup and a co-ordinate system. Though the surface is assumed to be convex and circular, the principle is also applicable to the case where the surface is concave and circular.

When a transmitter is located at the point P which is an intersection of the surface and the line connecting the center of a cylindrical flaw with a center of the surface, the amplitude of the echo received by the transmitter becomes maximum. Using this phenomenon, the X-distance of the point P can be found. The length, PQ and QC can be measured using the pulse-echo method at point P. The angle, θ and the variation of a flaw from the center of the co-ordinate system, $E_R$ can be derived as follows:

\[
\theta = \tan^{-1}\left(\frac{|X_p|}{L_1 + R}\right) \quad (3)
\]

\[
E_R = |X_p| - (PQ + L_3 + r) \sin(\theta) \quad (4)
\]

According to the way already mentioned, the path difference, ABCDE–EFCHI, or the corresponding time can be calculated. Plotting the experimental data on the diagram like Figure 4 results in the estimation of a flaw radius.

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Figure 5. Setup for Localization and Sizing for a Specimen with a Curved Surface
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SIMULATION OF FLAW LOCALIZATION

A study was carried out to investigate the effect of experimental parameters on errors in flaw depth measurement. The parameters considered are the scanning start point, sampling time, increment of mechanical scanning, spacing between transducers, flaw radius and flaw depth. The error refers to the discrepancy of the estimated value from the assumed value. The propagating time is digitized by the $T_s$. As a result of truncation, a set of integers corresponding to the TOF at each scanning position is obtained and regarded as experimental data in the simulation.

THE RESULTS OF SIMULATION (One-side scanning)

The one-side scanning means that both the transmitter and the receiver are scanned on the same side of a flaw. The transducers move in the $+X$ direction. The results indicate that a sufficient number of scanning position makes the accuracy of estimation within 0.04% without any relation to the start point of scanning. This method is effective when scanning is limited because of surface roughness or irregular shape of a specimen, as is often the case with mechanical parts. The results also show that there are situations where accuracy of estimation is poor in spite of a sufficient number of data points. The scanning point corresponding to this is just above a flaw. This stems from the nature of the method of least squares and leads to the necessity of an appropriate number of data points. In this respect, the terminal point of scanning is obtainable from the derivative of the TOF with regards to the transfer distance of transducers, because the derivative becomes zero when the ultrasonic propagation path is minimum.

Symmetrical scanning

In case of one-side scanning, estimation shows some degree of fluctuation, particularly when the number of data points is not sufficient. Therefore, symmetrical scanning where a transducer is scanned from $-X_0$ to $+X_0$ is considered. The sign of error is always positive, because the minima of the TOF is derived from the apex of a parabola. The $Y$-distance of the apex of the parabola obtained using the method of least squares is greater than the minimum experimental value, because the method minimizes the error in average. As a result, it is demonstrated that the smaller the radius of a flaw is, the deeper the flaw is located; and the smaller the spacing is, then the smaller the error in estimation becomes.

ENHANCEMENT OF RESOLUTION IN SIZING

Asymmetrical spacing seems effective when three transducers are placed directly on a surface of a specimen. To support a specimen with a flat surface in water in such a manner that the surface is
tilted forward the scanning line also seems effective. However, if the repetition rate of the ultrasonic pulse is highly accurate and stable and if the ultrasonic wave can be sampled with the clock pulse whose frequency and phase can be changed with high accuracy and stability, the relocation of the digitized data in the computer memory results in sampling frequency higher than 100 MHz.

EXPERIMENTAL DATA

The specimen used was made of poly-methyl-meta-acrylate (PMMA) and a steel wire. Utilization of PMMA as host material is advantageous because of its optical transparency, independence of the capability of machine tools for simulated flaw manufacturing such as drilling and high cost effectiveness.

As for flaw localization, experimental data are ordered with regard to the relationship between an estimated flaw depth and the number of data points used for the method of least squares. Figure 6 shows the raw data. The abscissa gives each scanning position. The total number of scanning points in this case is about 2100. The ordinate gives the TOF. A discontinuity can be recognized on the left side of this diagram. This occurs because the main lobe of a transmitting probe did not hit a flaw. The continuity of plotted dots in the most part, however, indicates the validity of a polynomial approximation for the locus of the TOF.

Figure 7 illustrates the processed results. The abscissa of this diagram shows the total number of data points used for least square estimation. The ordinate indicates the estimated value of the flaw depth. The dotted line means the measurement with an optical projector. In the optical projector measurement, a specimen is

![Figure 6. Experimental Value of the TOF](image-url)
placed on a mechanical table with two degrees of freedom for transverse motion and one for focusing. The depth of a flaw is defined as the transfer distance of the mechanical table. The edge of both surfaces of the specimen and the flaws can be clearly recognized on the projector screen, which can rotate for adjustment.

The small black circles in Figure 7 mean that the 241st datum, in Figure 6, is the 1st datum in the data set for flaw depth estimation. The small white squares mean that the 300th datum in Figure 6 is the 1st datum in the data set for estimation. Therefore, when the total number of data points is 500, both probes are located on the same side of a flaw during the scanning. In this case, both results using ultrasonic measurement agree well with each other and they are independent of the start point of the scanning. The estimated value obtained by ultrasonics agrees well with the results obtained by optical measurements within an accuracy of 0.5%.

As for the deformation of echos from flaws, there seems to be some influence of the attenuation of the PMMA on the cross correlation coefficient. This is one of the reasons that there is a small difference between optical measurement and ultrasonic measurement.

Figure 8 shows the experimental results for flaw sizing. The line connecting the black squares indicates the theoretical results obtained, based on ray optics theory. The black circles mean the experimental values. It can be predicted from this figure that the size of this flaw is between 4mm and 5mm.

CONCLUSION

A method of measuring flaw depth with two probes of a longitudinal wave is described. A study on the relationship between the error in depth estimation and the experimental parameter was carried out. Theoretical and experimental results show that flaw depth can be estimated using two probes, even when they are not placed directly above a flaw. This method is effective in field ultrasonic flaw detection for a specimen with an irregular shape or a limited surface
for scanning. Although the cross section of the flaw is a circle in this report, this method of localization is applicable to convex internal flaws with smooth surfaces, as well.

As for flaw sizing, the validity of measurement based on the ray optics theory was demonstrated. The method described here is advantageous in that sizing is carried out using phase information, because measurements based on the amplitude of echo signals from flaws need calibration blocks and can not be used on a variety of materials. Ultrasonic measurement for flaws based on the TOF appears to have a wide application.

REFERENCES