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Ultrasonic flaw sizing—An overview

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Abstract
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Keywords
cracks, ultrasonic waves, QNDE

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Comments

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ULTRASONIC FLAW SIZING – AN OVERVIEW

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ABSTRACT. The time-of-flight diffraction (TOFD) technique is one of the most common sizing methods in practical use by industry today. This method was developed over 40 years ago and is based on the technology and state of knowledge present at that time. A combination of phased arrays and equivalent flaw sizing methods are proposed as the foundation for a new generation of sizing methods that go beyond TOFD sizing.

Keywords: Phased Array, Time-of-Flight Diffraction, dB Drop, Equivalent Flaw Sizing
PACS: 43.35

INTRODUCTION

Although many methods have been developed for sizing flaws with ultrasonic waves, few of those methods have been accepted and seen use in industry. In fact, today there are primarily only two sizing methods in common use. One of the oldest of these is the dB-drop method where a transducer is scanned over the flaw and the region over which the amplitude is not small (as defined by a drop in decibels of a certain amount) is taken as a measure of the flaw size [1]. The dB-drop method is simple to use and it is easy to train inspectors in its application. However, studies of its performance typically show very poor performance [2] and any defect smaller than the width of the interrogating beam of ultrasound is typically sized as that beam width. In spite of these severe limitations, dB-drop methods are still in use and in some cases specified in codes and recommended procedures. In the ‘70s, Silk at Harwell developed an alternative sizing method called the time-of-flight diffraction (TOFD) method [3]. The TOFD method relies on identifying the edges of a crack-like flaw from the ultrasonic waves diffracted from the crack tips. The TOFD method is typically applied in weld problems with a pair of transducers as shown in Fig. 1. By measuring the time of flight between the transducers from these crack tips and from a “lateral” wave that travels directly between the transducers, the length, L, of the crack can be determined. The TOFD method is also simple to use, fast, and can be effectively implemented with a modest amount of training. Studies have shown TOFD to be much more reliable than the dB-drop method [2] and the TOFD method also has been made a part of codes and recommended practices. Today, commercial systems are readily available for implementing the method. A key part of the TOFD method is identifying the

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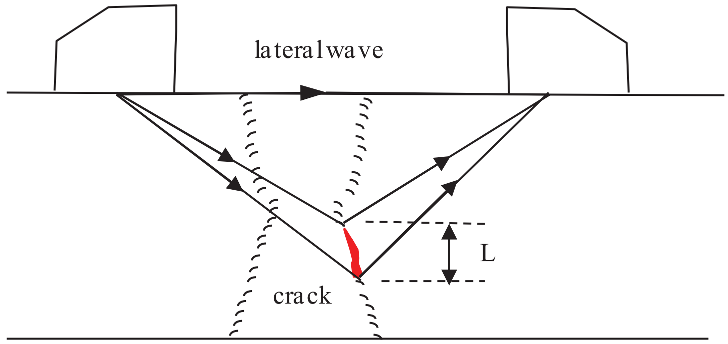

FIGURE 1. A typical inspection geometry for measuring the size of a crack in a weld with the TOFD method.

crack tip signals so that the appropriate time-of-flight measurements can be made. This can be challenging because the waves diffracted from the crack edges are typically much smaller than the waves specularly reflected from the crack surface. Thus, imaging approaches are used with the TOFD method to help identify the crack tip signals. Originally, D-scan images formed with single element transducers were used, but current systems often employ phased images generated with phased arrays instead.

In the TOFD method, the length of the crack, L, is obtained by assuming the crack is vertical, but this may not be the case, as shown in Fig.1. While this length can be used in fracture mechanics studies, a more complete description of the crack shape and orientation would be better. For surface-breaking cracks there is only one crack tip signal so that one must use this signal in conjunction with a back surface or corner trap signal to obtain an estimate of the crack length, again assuming a particular crack orientation. For volumetric flaws without sharp edges, such as pores, there are no edge signals present so that the TOFD method fails.

The TOFD is a mature, well-tested method but it is also a method rooted in the technology of the '70s and '80s. It would be useful to have a method that is 1) simple, 2) fast, 3) easy to learn and implement, 4) provides more detailed flaw size and orientation information, and 5) makes full use of modern ultrasonic technology such as phased arrays. Thus, we can ask the question: Is there a method that has all five of these attributes and can go a step beyond TOFD to provide a new, practical sizing tool for NDE?

EQUIVALENT SIZING OF ISOLATED CRACKS WITH ARRAYS

The answer to this question we believe is yes if one combines equivalent flaw sizing methods with phased array measurements. Equivalent flaw sizing is a technique developed in the '80s as an outgrowth of studies of the Born and Kirchhoff approximations [4], [5]. For an isolated crack, the case considered by the traditional TOFD method (Fig. 1), equivalent flaw sizing converts measurements made of the time interval, Δt, between crack flashpoints at different incident wave directions to measures of the equivalent radius, r_e, of a degenerate ellipsoid (ellipse). The conversion is simple because we have $r_e = c\Delta t / 4$, where c is the wave speed. Figure 2 illustrates this process for a pulse-echo setup. By combining these equivalent radii measurements with a linear least squares, eigenvalue approach, one can obtain estimates of the size and orientation of an equivalent flat elliptical crack that best matches the data [4]. This is possible since we can relate the equivalent radius to the geometry of the ellipse through

$$r_e^2 = a_1^2 \left(\mathbf{e}\cdot\mathbf{u}_1\right)^2 + a_2^2 \left(\mathbf{e}\cdot\mathbf{u}_2\right)^2 + a_3^2 \left(\mathbf{e}\cdot\mathbf{u}_3\right)^2 \tag{1}$$

with $a_3 = 0$. The outputs of the method are estimates of the two semi-major axes of the ellipse $\left(a_1, a_2\right)$ and the three unit vectors $\left(\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3\right)$ that define the direction of the axes and normal of the ellipse (see Fig.2). The companion paper by Engle et al. [6] in this Proceedings describes more explicitly the steps in the linear least squares/eigenvalue sizing approach so we will not give those details here. Equivalent flaw sizing can be implemented with a phased array, as shown in Fig. 3, since the beam of the array can be steered in

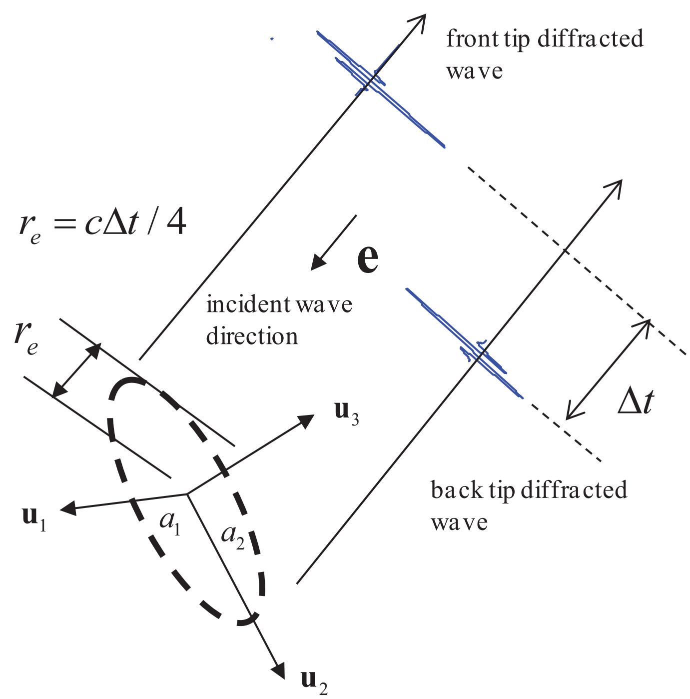

FIGURE 2. Geometry of an elliptical crack and the relationship between the effective radius, r_e, and the time, Δt, between crack tip flashpoints.

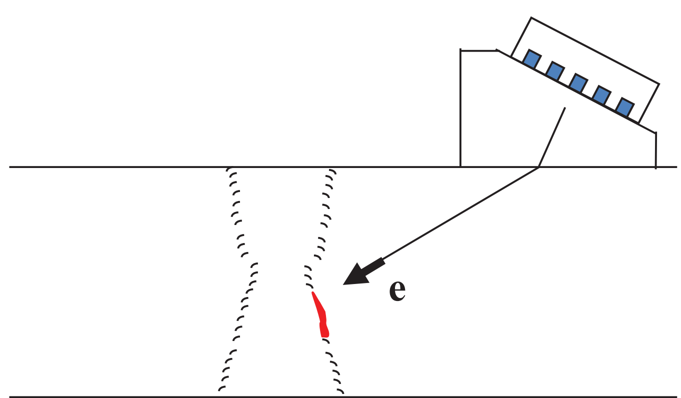

FIGURE 3. Implementation of an equivalent flaw sizing approach with a phased array.

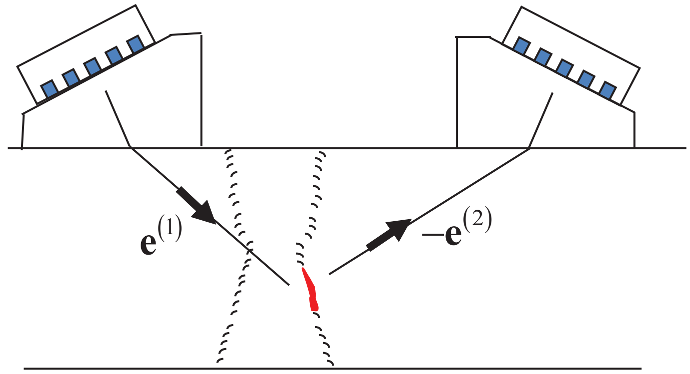

FIGURE 4. Implementation of the equivalent sizing of an isolated crack with pair of phased array transducers.

different directions and the transducer itself can be moved to generate a set of different look angles corresponding to different incident unit vectors, $\mathbf{e}$. Originally, this equivalent flaw sizing method was implemented with the multi-viewing transducer system of D. O. Thompson, which was a sparse array of single element transducers in a precision mechanical motion framework [7]. The use of the electronic steering of phased arrays significantly reduces the requirement for mechanical motion of the array and makes this sizing method more practical. Also, in its original form this flaw sizing method used a model-based approach where the system function and beam characteristics of the measurement system were removed from the measured voltage data through deconvolution [4]. However, here we propose to calculate the times, Δt, directly from the measured crack tip signals, thus removing a significant signal processing and modeling step. This makes the equivalent flaw sizing method more "industry friendly" in terms of data acquisition and processing. One processing step we do make, however, is to correct for the finite bandwidth effects of real ultrasonic measurement systems. This can improve the results since the relationship between Δt and the r_e given by Eq. (1) is based on an ideal, infinite bandwidth response of the crack. A real finite bandwidth system introduces a systematic error in the Δt measurements that can be easily corrected for with a pre-calculated error calibration curve [4]. In a companion paper in this Proceedings [6], B. Engle used such an error correction curve and successfully sized a 2.5 *mm* x 0.6 *mm* artificial crack in titanium using 12 different look angles obtained with the motion and beam steering of a linear array.

Note that unlike the TOFD method the equivalent flaw sizing method can be implemented in a pulse-echo setup, as shown in Fig. 3. However, one can also use a pair of phased arrays in a pitch-catch arrangement similar to that of the TOFD method (Fig.4). The only change to the method is to write the equivalent radius in a pitch-catch setup as

$$r_e^2 = a_1^2\left(\mathbf{e}_q \cdot \mathbf{u}_1\right)^2 + a_2^2\left(\mathbf{e}_q \cdot \mathbf{u}_2\right)^2 + a_3^2\left(\mathbf{e}_q \cdot \mathbf{u}_3\right)^2 \tag{2}$$

where (see Fig. 4)

$$\mathbf{e}_q = \frac{\mathbf{e}^{(1)} + \mathbf{e}^{(2)}}{\left|\mathbf{e}^{(1)} + \mathbf{e}^{(2)}\right|} \tag{3}$$

All the other steps in the method remain unchanged.

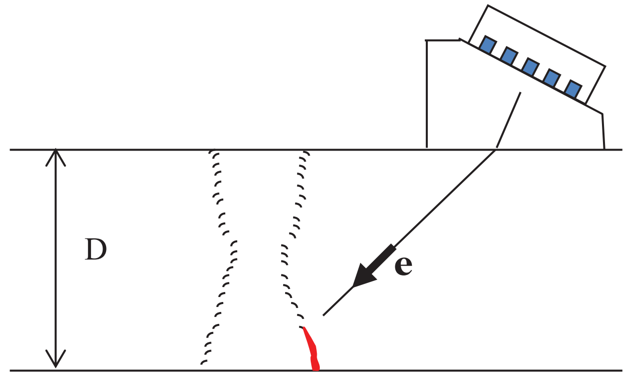

FIGURE 5. Geometry for sizing a surface breaking crack with a phased array.

EQUIVALENT SIZING OF SURFACE-BREAKING CRACKS WITH ARRAYS

It is also possible to implement an equivalent flaw sizing method for surface-breaking cracks, as shown in Fig. 5, since one can adapt the time-of-flight equivalent flaw sizing approach of Song and Schmerr [8] to this problem. One difference between the surface-breaking crack and isolated crack problem is that there is only one crack tip signal that can be seen at M different look angles $\mathbf{e}_m \left(m=1,2...M\right)$ for the surface-breaking case. One can measure the time-of-flights, t_m, between the transducer and this crack tip at these different look angles for an elliptical crack whose center is located at a point $\left(x_c, y_c, D\right)$, as shown in Fig. 6, where the distance, D, to the back surface is assumed to be known. One can then reduce this problem to one of determining the unknown center locations, $\left(x_c, y_c\right)$, crack semi-major axes, $\left(a_1, a_2, a_3\right)$, and unit vector directions $\left(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3\right)$, where $\mathbf{e}_3$ is again normal to the flat elliptical crack. To find these unknowns, we form up a function

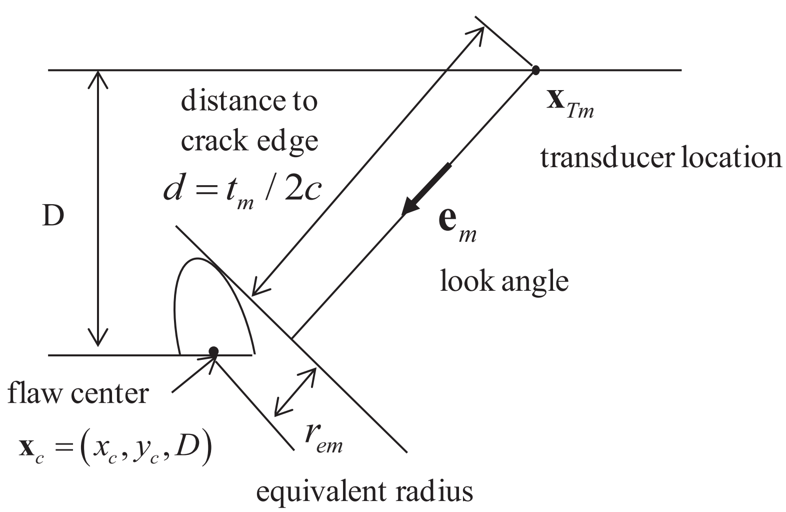

FIGURE 6. Parameters for sizing a surface breaking crack.

$$F_m = \left(\mathbf{x}_{Tm} \cdot \mathbf{e}_m + t_m / 2c\right)^2 - 2\left(\mathbf{x}_{Tm} \cdot \mathbf{e}_m + t_m / 2c\right)\left(\mathbf{x}_c \cdot \mathbf{e}_m\right) + \left(\mathbf{x}_c \cdot \mathbf{e}_m\right)^2$$
$$-C_{11}e_{1m}e_{1m} - C_{22}e_{2m}e_{2m} - C_{33}e_{3m}e_{3m} - C_{12}e_{1m}e_{2m} - C_{13}e_{1m}e_{3m} - C_{23}e_{2m}e_{3m} \quad (4)$$

where the sum of the **C** matrix terms in Eq. (4) just represent the square of the equivalent radius, i.e.

$$r_{em}^2 = C_{11}e_{1m}e_{1m} + C_{22}e_{2m}e_{2m} + C_{33}e_{3m}e_{3m} + C_{12}e_{1m}e_{2m} + C_{13}e_{1m}e_{3m} + C_{23}e_{2m}e_{3m} \quad (5)$$

and $\mathbf{x}_{Tm}$ is the location of the transducer for the *m*th measurement, and $\mathbf{x}_c = \left(x_c, y_c, D\right)$ (see Fig. 6). From Eqs. (4) and (5) and the geometry of Fig. 6 it is easy to see that ideally $F_m = 0$. Thus, if one forms up the error function

$$E\left(\mathbf{C}, \mathbf{x}_c\right) = \sum_{m=1}^{M} F_m^2 \quad (6)$$

with *M* measurements of *E*, we can use a non-linear least squares routine to minimize *E* and determine best fit values for the matrix **C** and vector $\mathbf{x}_c$. As in the isolated crack case we then obtain the eigenvalues and eigenvectors of the matrix **C**. These eigenvalues are just $\left(a_1, a_2, a_3 \cong 0\right)$ and the corresponding eigenvectors are the unit vectors $\left(\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3\right)$. For the isolated crack problem one needs to solve only a linear least squares problem for the matrix **C**, while here we have a non-linear least squares problem since *F* is non-linear in the unknown $\left(x_c, y_c\right)$ parameters. However, this is only a quadratic nonlinearity so that the solution is still well-behaved and the problem can be solved with common nonlinear least squares solution routines.

We have illustrated this procedure with noisy synthetic data for the problem shown in Fig. 7. In this case we assumed a flat elliptical crack with dimensions $a_z = 5mm, a_y = 3mm$ was located at a depth z = 25 mm with its normal oriented along the x-axis. The phased array, located at $\mathbf{x}_T = \left(-25, 0, 0\right) mm$, was steered at four angles $\theta = 30^o, 35^o, 40^o, 45^o$ and oriented at the four angles $\phi = -10^o, 0^o, 10^o, 20^o$. The array was then moved to the other side of the weld ($\mathbf{x}_T = \left(25, 0, 0\right) mm$) and steered at the same four

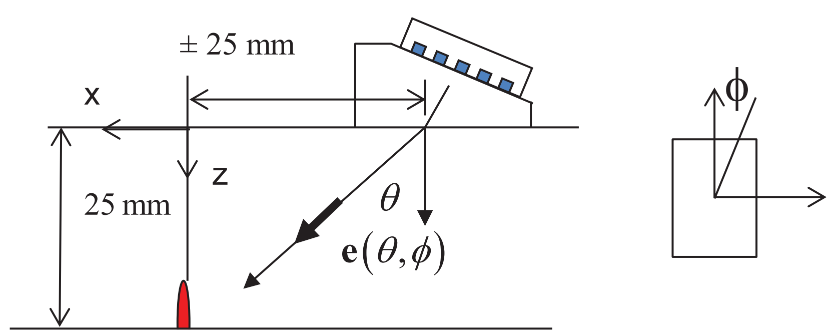

FIGURE 7. Example geometry for sizing a surface-breaking crack.

θ-angles with $\phi = 180^o$. This latter case was included since for sizing surface-breaking cracks it is important to have look angles that see the crack from both sides of the x-axis so that the crack center location can be adequately constrained. A small amount (several percent) of noise was added to these 20 time-of-flight values to simulate some uncertainty in the measurements. The results obtained were $a_y = 2.95\, mm, a_z = 5.02\, mm$, with center at $x_c = 0.0064\, mm, y_c = -0.182\, mm, z_c = 25 \quad mm$ (exact values were $\mathbf{x}_c = (0,0,25)$ mm, respectively), and crack orientations for the x, y, and z-axes of the ellipse, respectively, given by $\mathbf{e}_x = (1.00, 0.00, 0.00)$, $\mathbf{e}_y = (0.00, 0.99, 0.11)$, $\mathbf{e}_z = (0.00, -0.11, 0.99)$, in comparison with the exact values of $\mathbf{e}_x = (1,0,0)$, $\mathbf{e}_y = (0,1,0)$, $\mathbf{e}_z = (0,0,1)$. These results illustrate the viability of the method but in practice one might use more data from both sides of the crack since the absolute time-of-flight measurements needed here are more susceptible to uncertainties than the small time differences needed in the isolated crack case.

SUMMARY AND CONCLUSIONS

We have presented sizing methods for both isolated and surface-breaking cracks that are logical extensions of the TOFD method. These new methods are ideally suited for implementation with phased array transducers and they provide more complete sizing information than the TOFD method. In addition, the methods are simple to learn, fast to execute, and require very modest amounts of data. A method similar to the surface-breaking crack technique can also be used to size non-crack-like volumetric flaws, where a full best-fit equivalent ellipsoid shape, orientation, and center location is found [4]. However, in this case one needs a more complete set of look-angles that require the use of back surface reflections [8] to fully constrain the location of the center of the equivalent ellipsoid.

Experiments done with linear arrays [7] show the viability of sizing small isolated cracks with these methods. The use of 2-D arrays could make the methods even more versatile since beam steering could then be done in two directions, thus reducing the need for moving the array(s). Sizing surface-breaking cracks is more challenging since the absolute time-of-flight measurements required in this case are more susceptible to errors in the position of the array and the material wave speeds. However, the preliminary numerical results in this case are promising and will be followed with comparable experiments.

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REFERENCES

1. www.aws.org/w/a/itrends/2005/01/021/index.html
2. www.twi.co.uk/technical-knowledge/published-papers/structural-integrity-with-time-of-flight-diffraction-tofd-ultrasonic-inspection-july-2005/
3. J. P. Charlesworth, and J. A. G. Temple, “Engineering Applications of Time-of-Flight Diffraction,” (2nd Ed.) Research Studies Press, Baldock, England, (2001).
4. L. W. Schmerr, “Fundamentals of Ultrasonic Nondestructive Evaluation – A Modeling Approach,” Plenum Press, New York, N.Y., (1998).
5. C. P Chiou and L. W. Schmerr, “New approaches to model-based ultrasonic flaw sizing,” J. Acoust. Soc. Am., 92, 435-444, (1992).
6. B. J. Engle, L. W. Schmerr, and A. Sedov, “Equivalent flaw time-of-flight diffraction sizing with ultrasonic phased arrays,” Review of Progress in Quantitative Nondestructive Evaluation”, Eds. D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 32 (in publication), 2013.
7. D. O. Thompson, S. Wormley, and D. Hsu, “Apparatus and technique for reconstruction of flaws using model-based elastic inverse ultrasonic scattering,” Rev. Sci. Instrum. , 57, 3089-3098, (1986).
8. S.-.J. Song, and L. W. Schmerr, “An ultrasonic time-of-flight equivalent flaw sizing method,” Research in NDE, 4, 1-18, (1992).