ULTRASONIC SIZING OF VOIDS USING AREA FUNCTIONS

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INTRODUCTION

We present a simple technique for determining the size of voids by the inversion of backscattered ultrasonic signals using the area function formula. The formulation of this method is based on the Born approximation, which is a weak scattering approximation, but the method works well for voids. The area function has been widely used as a method for determining the position of the flaw centroid to assist implementation of some inversion algorithms. The method has been reported in [6]. Here, we report some further studies, and more experimental results in detail.

AREA FUNCTION

Fig. 1 shows a simple backscattering geometry, where $R_l(t)$ is the backscattered longitudinal-to-longitudinal impulse response from the flaw, and $S(t)$ corresponds to the cross-sectional area of the flaw intersected by a wave plane defined by the time, t, or by the position, z. Note that in the backscattering geometry, t and z have a simple relation,

$$z = \frac{ct}{2} \tag{1}$$

where c is the longitudinal wave velocity.

According to the time domain Born approximation, the backscattered impulse response, $R_l(t)$, from a flaw has a simple relationship to the cross-sectional area, $S(t)$, of the flaw [1]

$$R_l(t) = \frac{m}{c^2}\frac{d^2S(t)}{dt^2} \tag{2}$$

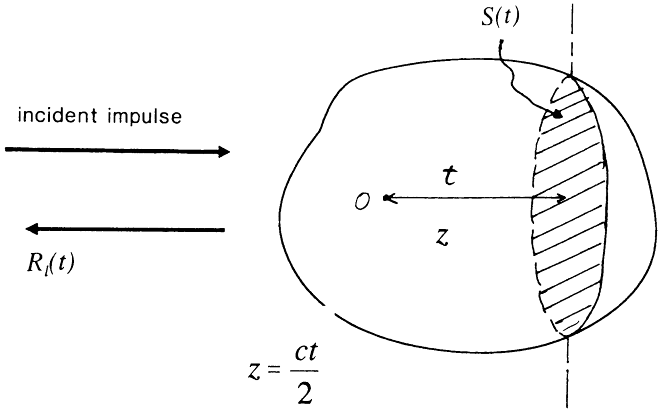

Fig. 1 Backscattering geometry

where m is a constant dependent on the flaw and the host material properties, c is the longitudinal wave velocity in the host material. Thus, the cross-sectional area of the flaw can be reconstructed by double integration of the backscattered impulse response from the flaw. To distinguish this reconstructed cross-sectional area from the true cross-sectional area, we define the reconstructed cross-sectional area as the area function, $AF(t)$, of the flaw

$$AF(t) = \frac{c^2}{m} \iint R_1(t)\, d^2 t \tag{3}$$

By the Fourier integral theory, Eq(3) can be expressed in the frequency domain as

$$AF(t) = \frac{c^2}{m} \frac{1}{2\pi} \int_0^{\infty} \frac{1}{f^2} e^{i2\pi ft} A_1 df \tag{4}$$

where f represents frequency, and A_1 is the Fourier transform of $R_1(t)$.

SPHERICAL VOID AND RADIUS ESTIMATION

The calculated area function, $AF(t)$, and the true cross-sectional area, $S(t)$, for a 200μm radius spherical void in titanium are shown in Fig. 2. The input backscattered amplitude, A_1, was simulated using the series solutions of Ying and Truell [2], and was in the frequency range of $0 \le ka \le 6.5$, where k is the longitudinal wavenumber and a represents the radius of the void. Both $AF(t)$ and $S(t)$ are normalized so that their maxima are one. It is seen that the early part of $AF(t)$ agrees very well with $S(t)$, while the their later parts obviously disagree. It is not a surprise, when one considers that the area function formula is derived from a weak scattering

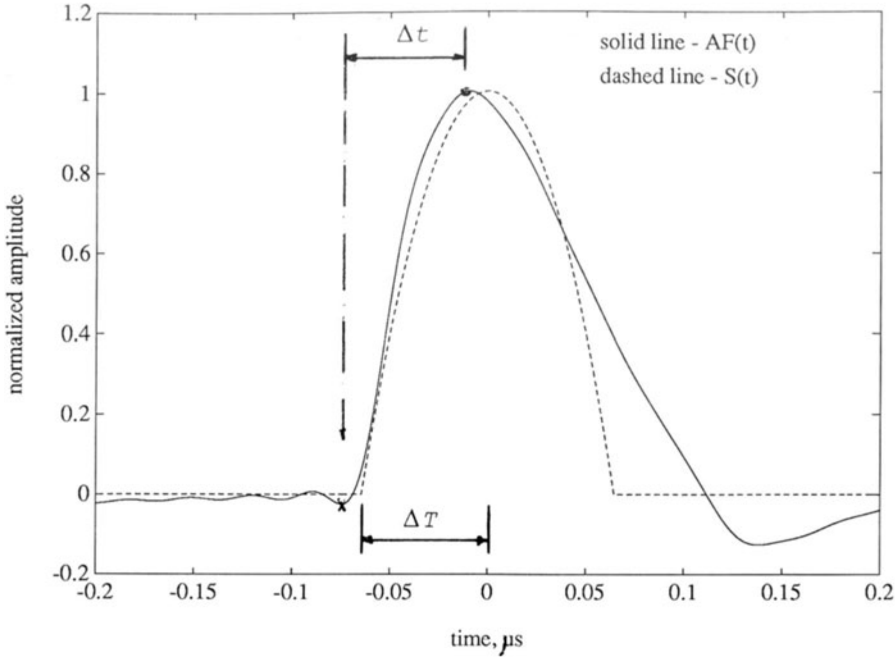

Fig. 2 *AF(t)* and *S(t)* for a 200 μm radius void

approximation, and that a void is a strong scatterer. The research by Chen [3] gives a more precise explanation. He found that for a host material having a Poisson ratio 1/3, which is true for most structural materials, the early portion of the backscattered signal from a void is expected to agree with the Born prediction.

The early portion of the area function for a spherical void can therefore be used to extract the radius of the void. Fig. 2 shows that the maximum value of *AF(t)* occurs a little before the maximum value of *S(t)*, where the wave plane passes through the centre of the void. The minimum value of *AF(t)* occurs a little before *S(t)* starts rising from zero, where the wave plane starts touching the void. The time difference, Δt, between the values where *AF(t)* starts from its minimum and reaches its maximum can therefore be considered as corresponding to the time difference, ΔT, between the times at which the wave plane starts touching the void and passes through the centre of the void. Given the relationship between the position z and the time t in the backscattering geometry as shown in Eq(2), the radius of the void can be obtained by measuring the Δt, that is

$$a = \frac{c\Delta t}{2} \qquad (5)$$

The radius estimated using the Δt given in Fig. 2 is 204 μm, which is just 2% over the true radius of 200 μm.

BANDWIDTH EFFECTS

In practice, the bandwidth of a transducer is usually not as wide as that used in the calculation of the data given in Fig. 2 ($0 \le ka \le 6.5$, where k is the longitudinal wave number.). Fig. 3 shows the shape change of the area function with varying bandwidth of the input A_l, in the range of $0 \le ka \le 6.5$ to $0.65 \le ka \le 4.6$. It is shown that while varying the bandwidth of the input data distorts the shape of *AF(t)*, the times at which the maximum and minimum values (points A and B) occur remain remarkably stable. We have not yet found a physical explanation for this phenomenon. However, this observation is the basis for the practical applicability of the area function sizing method.

The bandwidth requirements of this method were discussed in detail in [4]. The method was found to require a bandwidth of $1 \le ka \le 2.5$, in order to give radius estimates accurate to within 10% [4]. Fig. 4 shows the effect of limiting both the low and high frequency limits. The figure shows the normalized radius (defined as the ratio of the estimated radius to the true radius) against the central wavenumber (k_c) of a transducer multiplied by the flaw radius (a). Each curve is for a transducer of a different relative bandwidth, expressed in terms of the ratio of the maximum frequency of the transducer to the minimum frequency. For example, for a transducer with 8:1 relative bandwidth, the radius estimate will be accurate to within 20% for a 3:1 range of flaw sizes. If a transducer has a centre frequency of 7.5 MHz, a useful frequency range of 1.7 to 13.3 MHz, it would be capable of measuring void radii in titanium in the range of 200 to 600 µm. The exact range would of course depend on the detailed shape of the transducer spectrum and the signal-to-noise ratio. A good

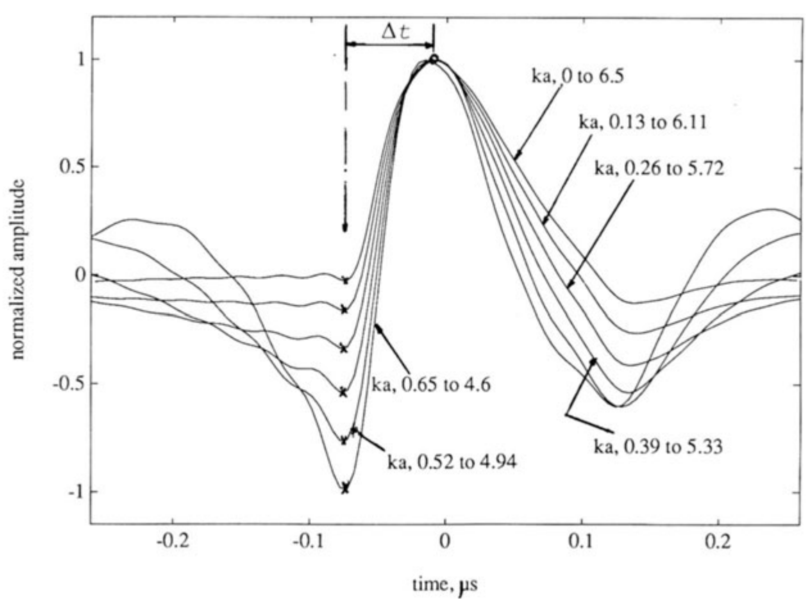

Fig. 3 *AF(t)*s with different bandwidth for input data

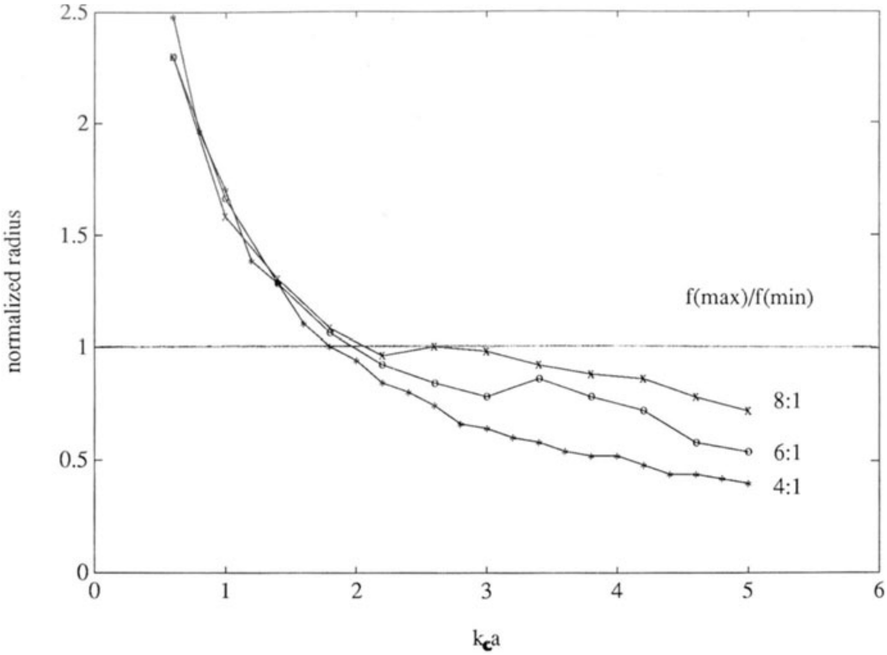

Fig. 4 Accuracy of the area function sizing method vs transducer centre frequency and bandwidth

broadband commercial transducer which has a large value of relative bandwidth can cover a wide range of flaw sizes.

Comparing Fig. 4 with a similar figure about the bandwidth requirements of the Born inversion published in [5], we found that the bandwidth requirements of this method is less severe. A transducer covers a wider range of flaw sizes using this method than using the Born inversion.

EXPERIMENTS

Three experiments were performed to test this sizing method, the results of which are shown here.

Water filled cylindrical hole

The sample was a titanium alloy block containing a 265μm radius cylindrical hole. The experiment was conducted in immersion mode. The transducer used in the experiments had a centre frequency about 7 MHz, with usable frequency range from 2 to 11 MHz ($0.54 \le ka \le 2.95$). Fig. 5(a) shows the captured time domain flaw signal (in the small window), and its spectrum is shown as Fig. 5(b). Fig. 5(c) represents the raw flaw frequency-domain response after deconvolution. The raw flaw response was then used to evaluate the area function which is shown in Fig. 5(d). The time difference, Δt, between the maximum point A and minimum point B was then measured and used to estimate the radius of the hole, employing Eq(5). The radius estimate was 260 μm, which was in excellent agreement with the true radius (2% over the true value).

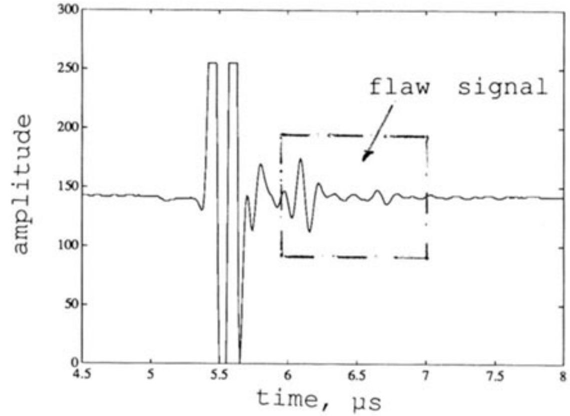

Fig. 5(a) Time domain flaw signal for the 265 µm radius hole

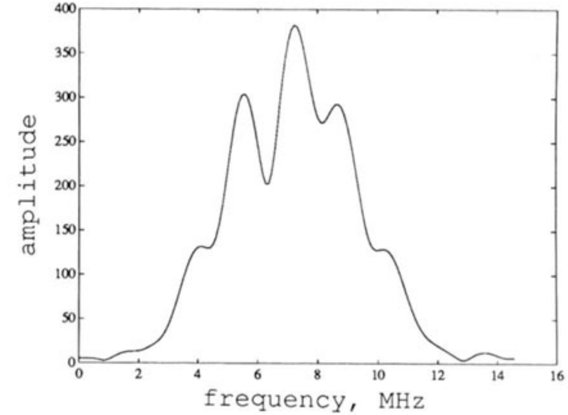

Fig. 5(b) Frequency spectrum of the flaw signal

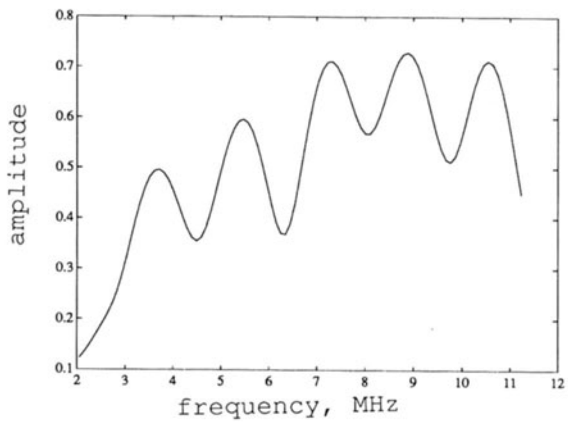

Fig. 5(c) Raw flaw spectrum after deconvolution

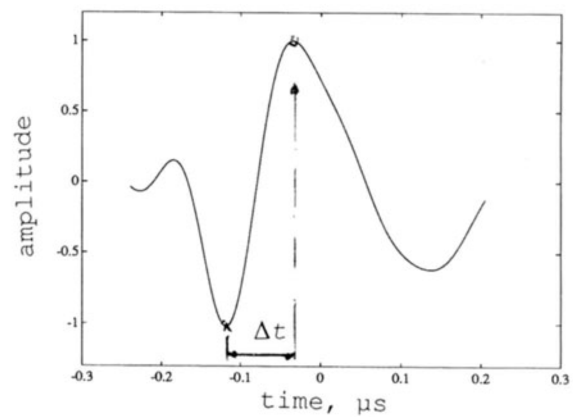

Fig. 5(d) *AF(t)* for the cylindrical hole

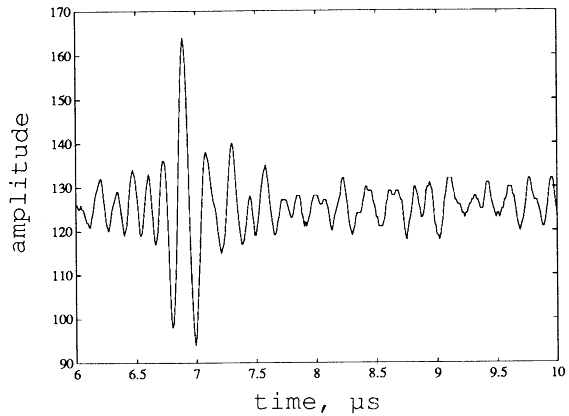

Fig. 6(a) Time domain flaw signal for the spherical void

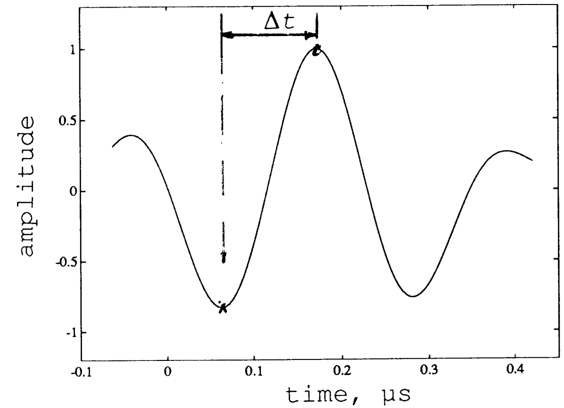

Fig. 6(b) The area function for the spherical void

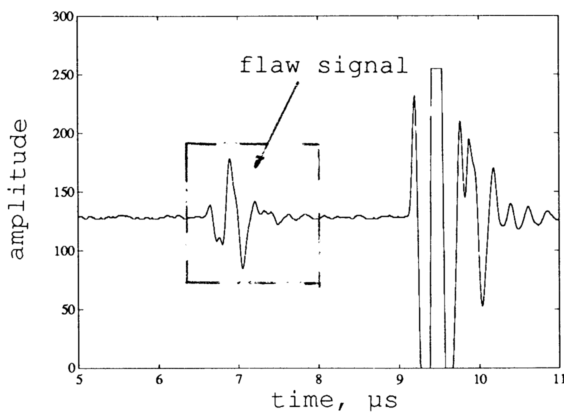

Fig. 7(a) Time domain flaw signal for the hole in aluminum

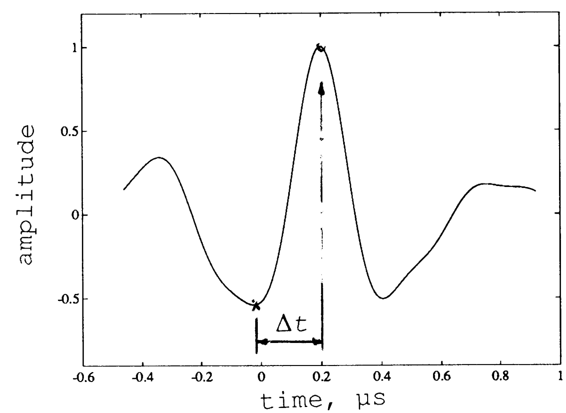

Fig. 7(b) The area function for the 725 μm radius hole

Spherical void

The sample was a maraging steel block containing a 300 µm radius spherical void. The sample was made by diffusion bonding. The experiment was conducted in contact mode. The transducer had usable frequency range of 1.5 to 6 MHz ($0.5 \leq ka \leq 2.0$). Fig. 6(a) shows the captured time domain flaw signal. After signal processing, the area function was obtained and is shown as Fig. 6(b). The time difference, Δt, between the maximum point A and minimum point B was then measured and used to estimate the radius of the void. The radius estimate was 336 µm, which was 12% over the true value.

Circular cylindrical cavity

The sample was an aluminum block containing a 725 µm radius cylindrical hole. Fig. 7(a) shows the time domain flaw signal. Fig. 7(b) shows the area function obtained after similar procedures. The radius estimate from the Δt was 696 µm (4% less than the true value). The scattering data in this experiment was in the frequency range of 1.17 to 4.6 MHz ($0.85 \leq ka \leq 3.3$).

CONCLUSION

We have shown numerically that the area function formula based on the Born approximation provides a simple inversion scheme which can be used to size voids. The experimental results have confirmed the validity and practicality of this method. Compared with most of other inverse sizing schemes, this method is simpler and has the advantage that it does not require the determination of the flaw centroid.

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