A note on the smallest defect that can be detected using ultrasonics

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In spite of the extensive experience gained in the use of ultrasonics as a non-destructive test for steel products, doubts still remain as to the sensitivity limits of this form of test. Sensitivity is understood as the dimension of the smallest defect that can be detected. It is not possible to give a final, precise answer which will be generally valid, because of the often complex influence of many metallographic and physical factors, but it is possible to demonstrate that there is no theoretical limit to sensitivity in ultrasonic tests. Data are provided from practical experience and the results of laboratory tests – all supported by well-established theoretical principles – which demonstrate that it is possible to detect by means of ultrasonics, flaws in steel which are much smaller than the wavelength used. A method for estimating sensitivity is suggested.

Keywords: ultrasonic testing, flaw detection, sensitivity, acoustic impedance, diffusion (waves) + ultrasonics.

One often hears the question which forms the subject of this article answered in a confused manner, often involving conceptual errors. In fact, there is a tendency to associate the limit of sensitivity of ultrasonic instruments with the wavelength used, and one talks of sensitivity as if one were dealing with the resolving power.

This subject was dealt with by the present authors, in its basic aspects, many years ago in a general article on the interpretation of non-destructive ultrasonic examinations[1]; the topic has now been taken up again, and the conclusions drawn at that time confirmed on the basis of a larger body of evidence and a more extensive development of the experimental aspect. It will be seen that it is not possible to give an unambiguous answer which will be valid for every case. Moreover, the only objective here is to supply the material to demonstrate, on the basis of the theoretical principles and experimental results, that the defects that can be detected using normal commercial instruments may be much smaller than the wavelength of the ultrasonic waves used.

It is considered that this paper, although modest in scope, may be of some use both in removing the last misunderstandings and, in the educational field, in the training of the new generation of NDT operators.

Theoretical aspect

Ultrasonics, like light, belong to the class of vibratory phenomena that are propagated by means of waves. A characteristic of this type of propagation is the phenomenon of diffraction, which occurs most evidently when the dimensions of an obstacle which is immersed in the medium in which the wave is being propagated are very close to or less than the wavelength. The incident wave may pass by the obstacle, thus invalidating the concept of shadow in geometrical acoustics, and one cannot talk of reflection in the classical sense; it is replaced by scattering.

If one considers an obstacle consisting of a sphere with a smooth surface, then as the diameter of the sphere is ideally made to decrease so that the ratio d/λ (d = diameter of sphere; λ = wavelength) gradually decreases, the following phenomena predicted by the theory occur[2]:

- While the diameter of the sphere is large with respect to the wavelength, geometrical acoustics are valid. The reflected energy (*ie*, that returned by the obstacle) has a single maximum of intensity which is in the opposite direction to the direction of propagation of the incident wave. Behind the obstacle there is a shadow, *ie*, the absence of a vibrational field. The wavelength does not play any practical role.
- When the diameter of the sphere decreases and approaches the dimensions of the wavelength, scattering begins to have increasing importance. The intensity of the energy reflected by the obstacle assumes an extremely complex distribution in various directions, with one or more maxima which may not coincide with the direction opposed to that from which the wave arrives; in fact, under certain critical dimensional circumstances, there may be a minimum in this direction. The manifestation of a shadow is also complex, and it may merely be absent. In this phase, when two spheres are placed close to each other at a separation of less than one wavelength, they can no longer be 'seen' separately. This theoretical conclusion, which is confirmed by experience, is the origin of the definition of resolving power: it is the minimum distance two objects can be placed away from each other in order to be seen separately and distinctly. The resolving power depends essentially on the wavelength.

- When the diameter of the sphere decreases still further until it becomes a small fraction of the wavelength, it is no longer meaningful to talk of an obstacle in the form of a sphere – because, for example, a tetrahedron or a cube of the same dimensions behaves in the same way – and it is no longer possible to receive information from the scattered energy which will indicate the form of the obstacle. However, the obstacle, whatever its form and however small it may be, always scatters energy in all directions and hence also in the direction opposite to that from which the incident wave arrives. Certainly, the intensity of the backscattered energy may be extremely small compared with the incident energy: a simple calculation using the theoretical formulae contained in Reference 2 gives, for example, −120 dB at a distance of 100 mm for a spherical obstacle of diameter 0.05 mm struck by a 2 MHz ultrasonic wave.

Experimental

That then is the theory. How do things turn out in practice? The transfer into practical terms involves the combination of at least four factors:

- the effect of the acoustic impedance of the obstacle as compared with the acoustic impedance of the medium in which the obstacle is immersed
- the attenuation which the intensity of the wave, whether incident or scattered, inevitably undergoes
- the masking disturbance due to the presence of scattering elements throughout the medium
- the availability of a sufficiently sensitive detecting device, capable of responding to extremely weak levels of back-scattered intensity.

A discussion of these four subjects would not only take a long time, but also it would not lead to any easy practical conclusion owing to the difficulty of having at one's disposal most of the quantitative parameters, some of which also vary considerably from case to case – transparency, grain disturbance *etc.* It is preferable to consider as a whole and to rely on direct experience.

A test block was constructed, with flat-bottomed holes which had their axes parallel to the direction of propagation of the ultrasonic waves, and with diameters d = 1.5, 1.2, 1.0, 0.8, 0.5 mm. The distance of the bottom of the holes from the test surface was 135 mm, except for the bottom of the 0.5 mm diameter hole, which was 140 mm from the surface. The block had an overall height of 150 mm and was made of normalized Ni-Cr-Mo steel of hardness 260 Hd. The attenuation was moderate (about 16 db/m), but the grain disturbance almost non-existant. A normal Krautkramer USIP 11 instrument of nominal frequencies 4 and 2 MHz (effective frequencies 3.8 and 1.98 MHz, respectively) was used with B4S and B2S probes. The propagation velocity in the block was 5995 m/s and the corresponding wavelengths were 1.57 and 3.03 mm, respectively.

The results are shown in Figure 1. The abscissa axis shows the ratio of the diameter of the hole to the wavelength (d/λ), and the ordinate axis represents the response of the instrument as the intensity level expressed in decibels (reference amplitude A_0 = 70 mm, measured on the CRT screen). The points on the graph relating to the higher frequency were plotted by correcting the intensity level by 11 dB to allow comparison of the results from two different probes operating at different frequencies, and

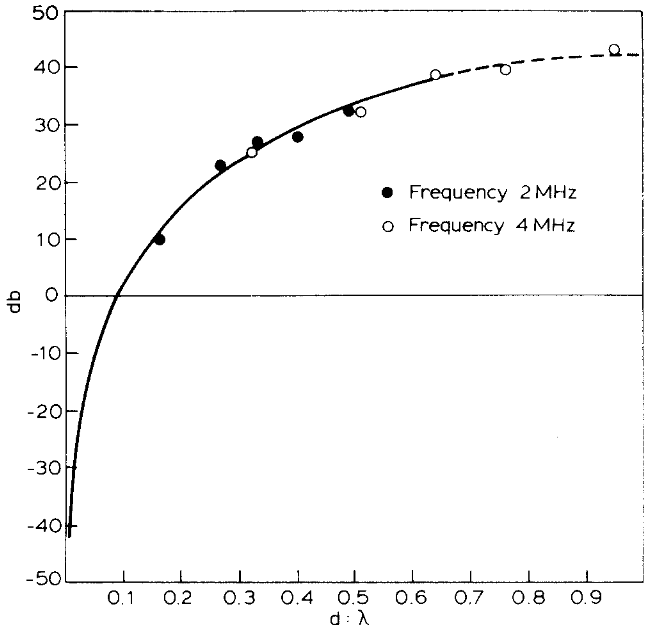

Fig. 1 Signal intensity level (in dB) plotted against the ratio of the diameter of the simulated defect *d* to the ultrasonic beam wavelength (τ)

hence having different sensitivities. From Figure 1 it can be seen that, by in fact operating on an artificial defect with a diameter d = 0.5 mm (equal to 16% of the wavelength), we obtained an echo height of 70 mm + 10 decibels, which immediately suggests an even lower possible practical detection limit.

In Figure 1, the alignment of the experimental points is very good, and the associated curve can be closely fitted to the equation:

$$\text{db} = -50/3\ [(d/\lambda)^2 - (d/\lambda)] + 42 \log_{10}(d/\lambda) + 127/3$$

which was obtained empirically by successive fittings; this curve is drawn in the graph.

It should be noted that the above equation was obtained not in an attempt to find the physical meaning of the law which contains the results obtained, but only to allow a rational extrapolation to the lower values of the ratio d/λ. Moreover, the authors would point out that the extrapolation is legitimate in so far as they were dealing with complete scattering conditions, and not the case of the wave interference which characterizes the $d/\lambda \cong 1$ region (broken line), where irregularities may occur with a loss of the unique character of the curve.

For the test block used, and under the experimental conditions in question, a 2 mm high indication could be easily read off the CRT screen; its expression in terms of intensity level was:

$$20 \log_{10} 2/70 = -30.8 \text{ decibels}$$

From the graph (or preferably from the equation of the curve), the corresponding value of d/λ = 0.018 (1.8% of λ!) was obtained; hence, it was deduced that the limit defect (limit of sensitivity), with a frequency of 2 MHz, was 0.05 mm.

Conclusions

The authors consider they have demonstrated that the wavelength is not a limiting constraint on the sensitivity of an ultrasonic examination. None of this is new, either from the theoretical or the experimental point of view. Quite apart from the fact that when operating, in optics, under ultramicroscopy conditions, it is possible to see bodies having dimensions less than $\lambda/20$, in ultra-acoustics itself there are many examples of the detection of objects which are much smaller than one wavelength[1,3,4]

Quite recently the authors ascertained the detectability of flaws (inclusions) of a few tenths of a millimetre in diameter.[5] It should be pointed out, incidentally, that destructive verifications of these tests are extremely difficult and expensive. In fact, it is extremely difficult to detect small, individual defects by the destructive method, even though they are certainly present.

It is evident that the sensitivity of an ultrasonic examination is characteristic of the individual, specific test. If an evaluation is required, a test block could be constructed – similar to that described earlier – which would be representative of the metal under examination and have a thickness (distance from the artificial defects to the test surface) equal to the thickness in question. A graph could then be plotted and the investigator could read off the ratio d/λ corresponding to the level of intensity, as calculated from the minimum height of the indication which can be read on the CRT screen, in the presence of the background interference caused by the grain and other diffusing elements.

It will be realised that the procedure suggested here takes into account all the considerations stated at the beginning of the earlier 'Experimental' section except for the first – acoustic impedance – which depends on the nature of the obstacle, which is itself extremely difficult to know either beforehand or in retrospect. However, bearing in mind that vacuum, air and every gas have acoustic impedances practically equal to zero, it is cavities and cracks, the flaws which are of greatest interest, that are liable to give the maximum scattered energy. Although a reduction in sensitivity is to be expected as a result of the acoustic impedance of the defect, this certainly does not occur in the case of the more important defects which are dealt with here.

References

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