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Testing Echo Amplitude Changes in relation to an Ultrasonic Beam Angle of Incidence at an Infinite Reflector

Abstract: The article presents test results related to the detectability of flat discontinuities depending on their orientation in relation to the axis of an ultrasonic wave beam. The flat discontinuity used in the tests was the skew surface of a DGS standard, being an infinite reflector for an ultrasonic wave. The tests were performed using a Phased Array transducer and a defectoscope with a Phased Array imaging package enabling the determination of echo amplitude for various beam insertion angle values. As a result, it was possible to obtain the characteristics of a decibel echo drop depending on the beam angle of incidence on the reflector in a range from the optimum to a disadvantageous value. The article also contains the analysis of the effect of a determined characteristic on the detectability of flat discontinuities in conventional ultrasonic tests as well as discusses manners of making it possible to increase the detectability of flat discontinuities.. The article is directed primarily to NDT personnel, in particular to those performing ultrasonic tests of welded joints.

Keywords: non-destructive testing, ultrasonic testing, echo amplitude changes,

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Introduction

Ultrasonic testing (UT) is a non-destructive method commonly used for volumetric control of materials and products, including welded joints. Factors supporting the use of this method include the low costs of the tests and of the testing equipment, the possibility of controlling quality in spite of the lack of access from the other side of a joint as well as the possibility of performing tests during production without the necessity of evacuating personnel from the test zone. In addition to economic and organisation-related factors, ultrasonic tests, if compared with their alternative, i.e. X-ray radiography, offer significantly higher detectability of flat discontinuities such as cracks or incomplete fusions [1, 2]. The detection of such discontinuities is of key importance for the safe operation of welded structures. Undetected imperfections can result in the failure or even in the total destruction of an entire element, particularly if the element is exposed to dynamic and changing loads or low temperature.

However, detecting such discontinuities in ultrasonic tests using the commonly applied echo method requires that an ultrasonic beam

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insertion angle should ensure that the beam optimally strikes the flat discontinuity (i.e. at angle γ possibly close to zero in relation to the normal to the surface of a flat discontinuity). Only such a case enables the most effective reflection of the beam from the discontinuity and its return to the head (receiving the beam and creating a corresponding indication on a defectoscope display). When the ultrasonic beam strikes the discontinuity at an angle significantly different from the optimum angle, the beam gets reflected in another direction, and it is not possible to obtain the beam echo on a defectoscope. For this reason, the most important factor affecting the detectability of flat discontinuities is their orientation in relation to the ultrasonic beam propagation direction. The detectability of positively oriented discontinuities is very high. In turn, when the surface of a flat discontinuity is parallel in relation to the ultrasonic beam propagation direction, it is not possible to detect the discontinuity for a given position of the head.

Hence the conclusion that the mutual orientation of the surface of a flat discontinuity and the direction of an ultrasonic beam propagation direction are decisive for the detectability of flat discontinuities. Sadly, scientific publications fail to provide comprehensive information about the quantitative correlations of these factors being of key importance for a successful ultrasonic test. The issue was addressed in the publication [1], presenting tests confirming the significant influence of a discontinuity orientation on the amplitude of its echo for three various angles at which the beam strikes a discontinuity. This inspired an attempt to quantitatively determine an echo amplitude drop from an infinite reflector in relation to angle γ, at which the beam strikes the discontinuity.

Testing Methodology

The tests involved the use of an Olympus Epoch 1000i ultrasonic defectoscope with a Phased Array imaging package. The defectoscope was equipped with a 16-element 5L16-A10P head having a frequency of 5MHz and an active aperture of 9.6 mm. The tests also involved the use of a SA10P-N55S wedge. A specimen used in the tests was a DGS Eksplast 7xΦ2x10-45° standard. The test rig equipment is presented in Figure 1.

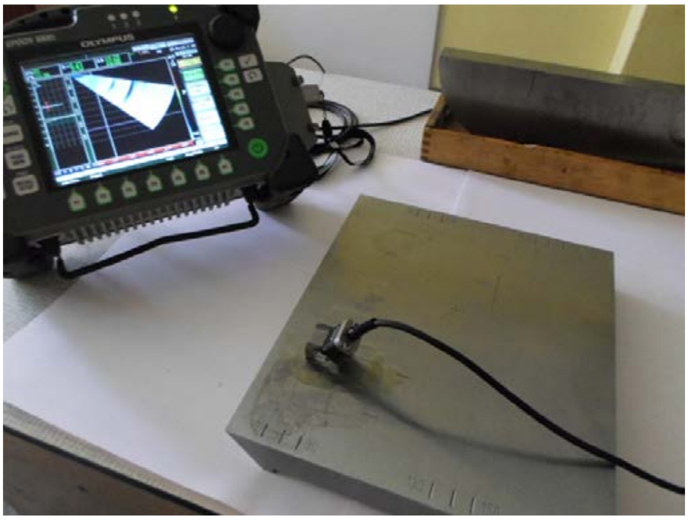

Fig. 1. Test rig equipment: the Olympus Epoch 1000i defectoscope, the 5L16-A10P ultrasonic head with the SA10P-N55S wedge; the DGS Eksplast 7xΦ2x10-45° standard

An infinite reflector used in the tests was the lateral surface of the DGS standard positioned at an angle of 45° in relation to the test surface. The essence of the tests consisted in recording amplification V, at which echo from the infinite reflector amounted to 80% FSH (full screen height). Using a defectoscope with the Phased Array imaging package (UT-PA: Ultrasonic Testing Phased Array) and the Phased Array transducer, it was possible to record amplification V for each of beam insertion angles α in the range of 40-70°, changing an angle by 1°. It enabled the recording of echo amplitude changes in relation to the angle at which the beam struck the infinite reflector. As can be easily seen, the beam strikes the reflector in the optimum manner (i.e. the incidence angle γ defined as the angle between the beam, and the normal to the reflector surface amounts to 0° (Fig. 3b)) when the beam insertion angle α amounts to 45°. The measurements of amplification V were performed for three positions of head 1, 2 and 3 presented in diagrams (Fig. 2 a, b, c).

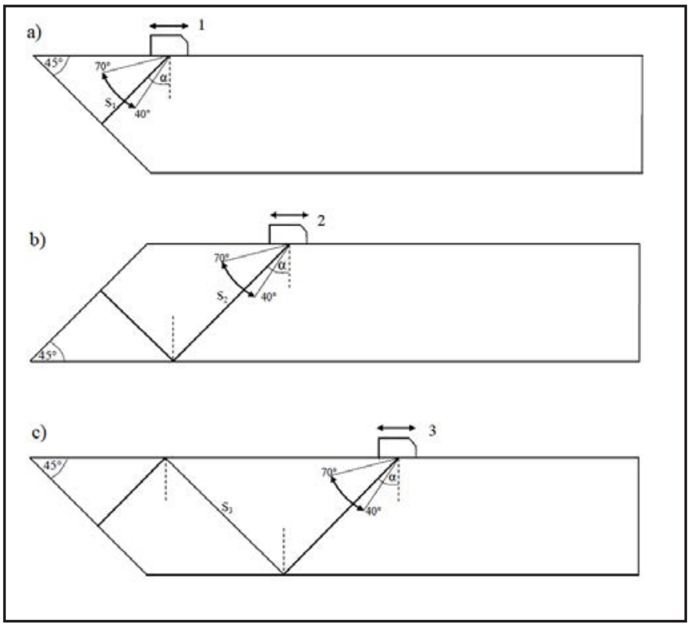

Fig. 2. Positioning of head no. 1, 2 and 3 when recording amplification V for three values of beam path amounting to S_1=40 mm, S_2=90 mm and S_3=160 mm respectively

For position no. 1 the beams strikes the skew surface of the standard directly from the first pitch of the head. As the infinite reflector does not limit the beam-struck area to one specific point (as is the case with, e.g., small-area flat-bottomed reflectors), while changing the beam insertion angle the head was moved towards the skew surface of the standard in order to compensate the changes of beam path lengths in the material (resulting from beam insertion angle changes). In this way, the path of the beam in the material always amounted to approximately S_1= 40 mm for head position no. 1 and for each successive head position (e.g. 1-40°, 1-45°, 1-50°, Fig. 3 a, b and c respectively). As a result, it was possible to measure echo amplitude changes in relation to one parameter, i.e. the angle γ at which the beam struck the reflector (Fig. 3). Otherwise, in cases of various values of wavelength in the material for successive beam insertion angles α, the results would also depend on various losses resulting from material damping and beam divergence. The same approach was adopted for head position no. 2 and no. 3. Then, the path of the beam in the material amounted to S_2=90 mm and S_3=160 mm respectively (Fig. 2 a, b). The calibration of zero and of sensitivity was performed on radius R100 of standard no. 1. The test involved the use of a beam without focusing.

Test Results and Analysis

The test results are presented as diagrams of amplification V for 80% FSH in relation to the beam insertion angle α. Figure 4 presents the results for head position no. 1 and the beam path S_1=40 mm. The greatest amplitude of echo from the infinite reflector was obtained for the beam insertion angle α=45°, i.e. when the angle at which the beam strikes the reflector (γ) is optimum and amounts to 0°. In such a situation, the beam is reflected from the reflector surface in such a manner that the axis of the striking beam coincides with the axis of the reflected beam returning to the head (Fig. 3b). Each successive change of the beam insertion angle α by 1° causes the gradual reduction of the amplitude of the echo from the reflector, which in turn, significantly decreases echo detectability. A similar amplitude drop can be observed for head position no. 2, i.e. from the second half of the first pitch of the head (Fig. 5). Due to the longer beam path in the material of S_2=90 mm, the whole curve is shifted towards greater amplifications V. However, in this case it was possible to observe greatest echo amplitude for the

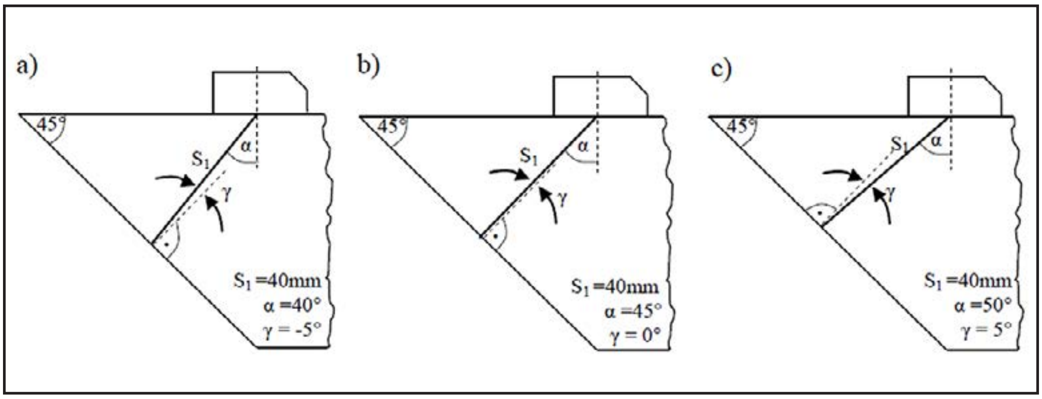

Fig. 3. Head position no. 1 for the beam path of S1=40 mm and the beam insertion angle of α=40°, α=45°, α=50°

optimum beams insertion angle α of 45°. This characteristic is also confirmed for head position no. 3 and the beam path of S3=160 mm (Fig. 6). The curve is shifted towards greater amplifications, with the amplitude reaching its maximum for the beam insertion angle of α=45°.

In order to facilitate the comparison of the results obtained, Figure 7 presents three curves for head positions no. 1, 2 and 3. It is possible to observe significant similarity as regards the echo amplitude drop characteristics for all three beam path values.

The results are also presented in the form of a diagram where amplitude maxima meet at one point (Fig. 8). The x-axis presents the angle γ (at which the beams strikes the reflector surface) for the assumption that the angle amounts to 0° for the beam insertion angle α=45°.

In turn, the y-axis presents the difference of amplification $\Delta V = V - V_{Xmin}$ defined as the difference between amplification V for 80% FSH and the minimum amplification obtained for a given beam path length, i.e. V_{1min}= 11.5 dB, V_{2min}= 15.7 dB and V_{3min}=22.8 dB (minimum amplification V is tantamount to the maximum amplitude of echo from the reflector). As a result, the diagram makes it possible to directly read out a decrease in echo amplitude for any angle γ, i.e. the angle at which the beam strikes the infinite reflector. For instance, a change in the angle at which the beam strikes the infinite reflector from γ=0° to γ=5° entails an echo amplitude drop of approximately 20 dB (values

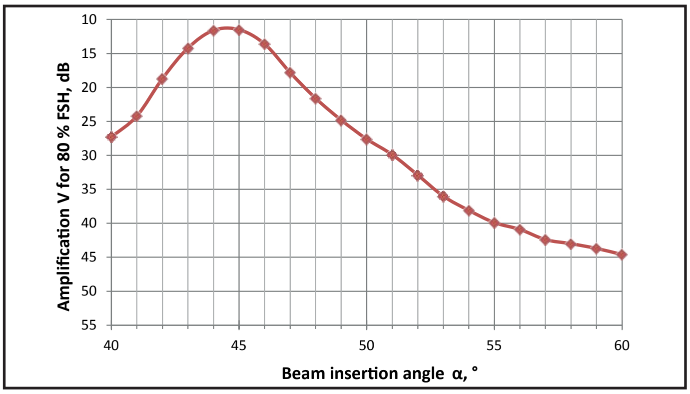

Fig. 4. Diagram of amplification V in relation to the beam insertion angle α for head position no. 1 and the beam path in the material of S1=40 mm

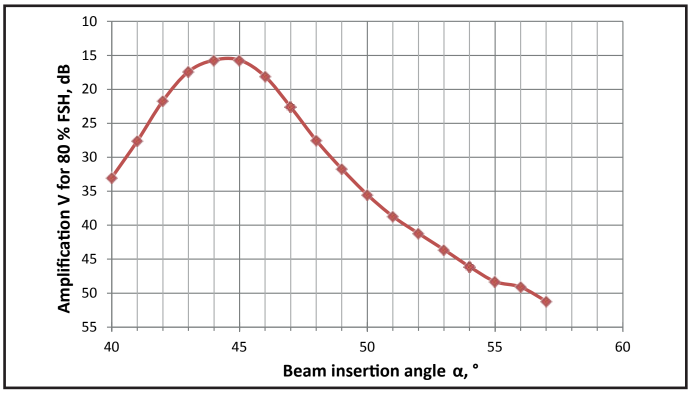

Fig. 5. Diagram of amplification V in relation to the beam insertion angle α for head position no. 2 and the beam path in the material of S2=90 mm

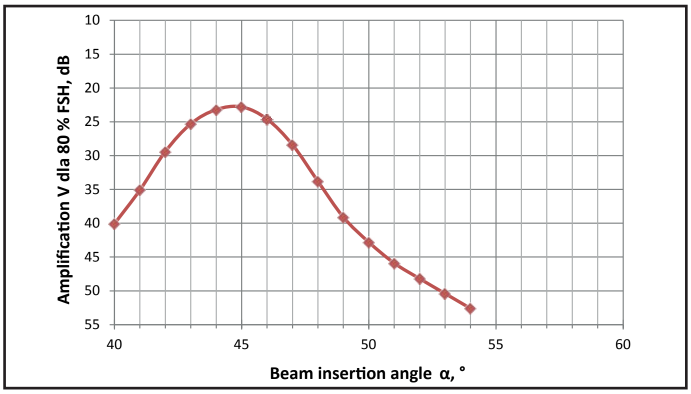

Fig. 6. Diagram of amplification V in relation to the beam insertion angle α for head position no. 3 and the beam path in the material of S3=160 mm

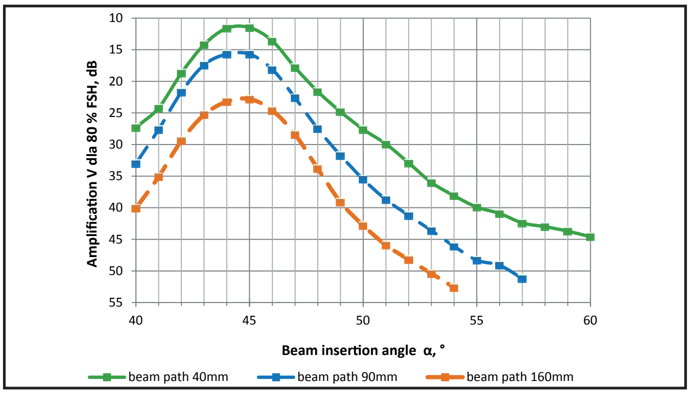

Fig. 7. Diagrams of amplification V in relation to the beam insertion angles α for head positions no. 1, 2 and 3

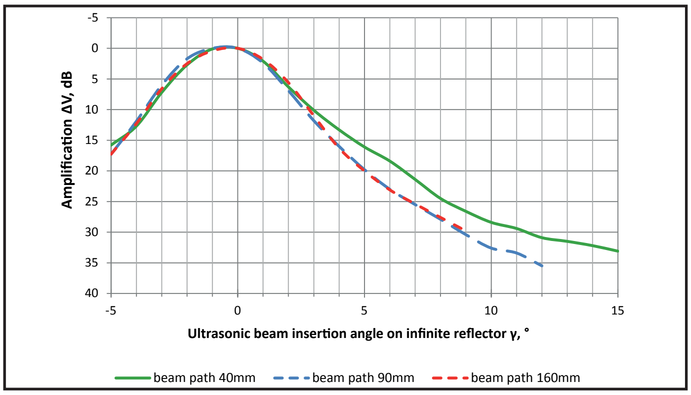

Fig. 8. Diagram of amplification ΔV difference in the function of angle γ for three different head positions, i.e. no. 1, 2 and 3

were read out of curves for the beam path of S_1= 90 mm and S_3= 160 mm). The curve for the beam path of S_1= 40 mm reveals a slightly lower drop of approximately 16 dB). In turn, a change in the angle at which the beam strikes the infinite reflector from γ=0° to γ=10° leads to an echo amplitude drop of approximately 30 dB. It is easy to observe a considerable influence of flat discontinuity orientation in relation to ultrasonic beam orientation. Even a slightly mismatched angle γ can lead to such a significant echo amplitude drop that it may result in the lack of indication on a defectoscope screen or in an indication not exceeding the acceptance level.

It should be noted that the diagrams provided present the echo amplitude drop characteristic for the head having a frequency of 5 MHz, i.e. the value close to the upper limit of the frequency commonly used in ultrasonic tests of welded joints, usually amounting to 2÷5 MHz (less frequently to 1÷10 MHz). It should be expected that this characteristic will largely depend on the frequency of the head. This is due to the fact that the lower the head frequency, the greater the beam divergence angle (determining the detectability of inconveniently oriented discontinuities). Therefore, it can be presumed that for heads of frequencies lower than that used in the test, an echo amplitude drop will be lower for an increasing angle γ.

It is worth noticing the repeatable characteristic of the curve of amplification ΔV for the beam paths of S_2=90 mm and S_3=160 mm (Fig. 8). The results obtained for these paths do not differ by more than 1 dB. This can be ascribed to the fact that in both cases the reflector is located outside the field close to the head. A slightly different situation can be observed for the beam path of S_1=40 mm. In this case, for the angle γ in the range of -5°÷2° the characteristic of the curve of amplification ΔV coincides with the remaining curves. However, for $\gamma \geq 3°$, the curve reveals a lower amplification drop for an increasing value of the angle γ if compared with other curves. The differences between the curves mentioned above do not exceed 5 dB. Therefore, it is possible to observe a slower echo amplitude drop for the reflector located close to the head (S_1=40 mm). However, confirming this characteristic requires further research.

All the characteristics obtained for echo amplitude drop are not symmetric in relation to the straight line α=45° or γ=0° (Figures 7 and 8 respectively). They show the maximum amplitude point slightly shifted towards the smaller beam insertion angle α (Fig. 7) and towards negative values δ (Fig. 8). The situation indicates that the optimum value of the beam insertion angle is not α=45°, but α=44.5°. This also justifies very close values of amplification V for the beam insertion angles α of 44° and 45°. For such an adopted optimum value of the beam insertion angle α=44.5°, the characteristics of echo amplitude drop would be symmetric for the negative and positive values of the angle γ. Assuming that the DGS standard was made ideally consistent with its nominal angle of 45°, the fact presented in the previous sentence can be ascribed to the difference between the assumed and the real beam insertion angle of 0.5°. Therefore, it can be supposed that the slight shift of the characteristics to the left is due to the inaccuracy of the real beam insertion angle measurement and that the characteristics should be symmetric in relation to the straight lines α=45° and γ=0°.

The analysis of the test results leads to the conclusion that the mismatch of the angle γ (at which the beam strikes the infinite reflector) not exceeding 2° causes a relatively small echo amplitude drop amounting to not more than 4 dB. For most indications, such a decrease in amplitude should not cause a drop below the acceptance level. However, a further increase in the mismatch of the angle γ by a further 2°, both for its positive and negative values, causes a significantly faster echo amplitude drop amounting to a further 10 dB. For this reason, the mismatch of the angle γ greater than 4° and the resultant echo amplitude drop of 14 dB can create a situation in which a flat discontinuity will become accepted (indication will not exceed the acceptance level). Such a situation might take place in spite of the fact that if the optimum beam insertion angle was used, such a flat discontinuity would be unacceptable, and its decibel exceeding over the acceptance level would be very high. This can lead to situations where potentially dangerous flat discontinuities such as cracks, incomplete fusions or lacks of penetration will not be detected.

Summary

The obtained results demonstrate that the convenient orientation of flat discontinuities is of key importance for their detectability in ultrasonic tests. Even a small mismatch of the angle at which the beams strikes the discontinuity can result in the omission of hazardous imperfections. For instance, the use of each of beam insertion angles applied in conventional ultrasonic tests, i.e. α=70°, α=60° and α=45°, fails to ensure the obtainment of the sufficiently convenient value of angle γ for all possible orientations of flat discontinuities positioned askew in relation to the test surface (flat discontinuities oriented perpendicularly to the test surface are usually detected when using the tandem technique, whereas flat discontinuities parallel to the test surface are detected using a normal double head moved over a previously treated weld face or root). However, usually only one beam insertion angle is used (only in some cases two angles are used, i.e. for quality level B – always for a joint thickness exceeding 25 mm and for a thickness in the range of 15-25 mm – when the head frequency is higher than 3 MHz [5]). It is possible to slightly increase the detectability of inconveniently oriented discontinuities during conventional ultrasonic tests by using a head characterised by a lower frequency or a smaller transducer diameter. Such a head has a greater beam divergence angle, yet the beam fragments of the greatest and smallest angle are located far from the beam axis, therefore the distribution of acoustic pressure is the smallest there. At the same time, such a solution is disadvantageous due to a decreased resolution and an excessively increased beam width.

The obtainment of the optimum angle at which the beams strikes the reflector for each flat discontinuity orientation would require the use of many – preferably between ten and twenty – beam insertion angles. However, in conventional ultrasonic tests such a solution is impossible due to the very few beam insertion angles available and due to the laboriousness of this solution requiring the performance of many searches for the same joint. For this reason, the most convenient solution would be the use of ultrasonic tests employing Phased Array transducers (PAUT). Such a method enables testing the volume of a joint using many beam insertion angles combined with the meandering movement of the head. In this manner it is possible to scan any fragment of the volume for each defined beam insertion angle (S-scan raster) [4]. The available S-scan makes it possible to simultaneously observe the echo amplitude for each of the beam insertion angles applied, thus enabling the optimum selection of the angle for which the amplitude value would be the highest. Regardless of the orientation and position of a skew flat discontinuity, such a solution enables the obtainment of the maximum amplitude for the beam striking the discontinuity at the optimum angle of γ=0° (as was the case in the tests for the beam insertion angle of α=45°). Such a testing manner, ensuring a very high likelihood of detecting discontinuities, is recommended in PN-EN ISO 13588 as regards testing level C for semi and fully automated ultrasonic testing using the Phased Array technology.

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