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THE INFLUENCE OF SENSITIVITY FIELD OF DUAL TRANSDUCER PROBES ON ACCURACY OF DISCONTINUITY SIZING AND EVALUATION IN TERMS OF TESTING OF FORGINGS ACCORDING TO EN 10228-3

The article presents results of research on the impact of sensitivity distribution of double transducer probes, which are often used in non-destructive ultrasonic testing of components such as forgings. Distribution of sensitivity measured in two orientations, parallel and perpendicular to the plane of separation of a double transducer probe has been tested and analyzed. A significant influence of orientation of a probe on echo envelope of an artificial point discontinuity has been studied. It has revealed great differences in length and shape of an echo envelope, depending on a type of probe and orientation of a probe separation plane to the moving direction. Eventually, the analysis of practical consequences of dual transducer probes usage for characterization of a type, dimensioning and evaluation of internal discontinuities, in accordance to the methodology specified in EN 10228, has been conducted.

Keywords: non destructive testing, ultrasonic testing, double transducer probe.

1. Introduction

Dual element longitudinal probes are commonly used in ultrasonic testing of forgings, castings, welded joints directly from a face area of a joint (after removal of excess metal) and for detection of delamination in metal plates. Moreover, they are also used for ultrasonic thickness measurements [1-6]. In ultrasonic testing of forgings, dual probes are used to detect inner (surface breaking and embedded) discontinuities in the objects of thicknesses up to about 200 mm. This technique is also recommended as a tool in scientific research on a field of materials engineering and welding technologies, such as coatings, laser welding and micro-jet cooling technology [7-11]. The technique is also useful for research on new materials and materials for responsible structures [12]. Compared to the single probes, they produce very small or virtually none dead zone at all in a tested object. This advantage determine the above-described area of applications, allowing the detection of discontinuities that are very close to the scanning surface of a test piece. Such a property of a dual element probe is achieved through the use of two elements, transmitting and receiving one, spaced a substantial distance from the contact surface of the probe and a test piece using a delay line. This results in a significant delay between the initiation time of a pulse from a transmitter and the entry time of an ultrasonic wave into a test piece. To the echo signal of discontinuity be shown on a flaw detector, a flaw must be within beam range sent from a transmitter, and a reflected wave must reach the receiver. Distribution of sensitivity of dual element probes is different from the distribution of sensitivity of other types of probes and depends on several factors, e.g.:

- the shape and size of transducers,
- the distance between the transducers,
- the angle of tilt of the transducers relative to the geometrical axis of a probe,
- the length of delay lines [1].

Due to its construction, double transducer probe does not have rotational symmetry of sensitivity field, as it is the case for the single probes with the circular transducer. For this reason, it shows different width of the beam measured in a direction perpendicular and parallel to the separation plane of a probe (i.e. layer of acoustic dampening between transmitter and receiver). The difference in width of ultrasonic beam in two mutually perpendicular directions turns out to be crucial for the final result of ultrasonic inspection. As revealed by the study, the characteristics of the three most commonly used dual transducer probes are so diverse, that their ignorance can lead to serious errors in the assessment of detected discontinuities. For this reason, the article presents the characteristics of the studied dual transducer probes of various parameters (frequency, element size) in two mutually perpendicular directions – parallel and perpendicular to the separation plane. The impact of these characteristics upon correctness of ultrasonic inspection has been also analyzed. As an acceptance criteria to refer to, the guidelines for ultrasonic testing and evaluation of forgings presented in EN 10228-3 standard has been adopted.

2. Methodology and results

To determine the characteristics of dual element probes, three types of probes of different characteristics have been used. Frequency and element size of the probes are: 4 MHz

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and 6 x 20 mm, 2 MHz and 7 x 18 mm and 4 MHz and 3.5 x 10 mm respectively (table 1). The tilt angle of all studied probes was 4 ° (probes of transducers angle 0 ° e.g. DL4R - 6 x 20 - 0 or SEB 4-0 ° have not been studied).

TABLE I
List of probes used to determine the characteristics

Nr	Frequency MHz	Transducer size mm	Type of probe / catalog number
1	4 MHz	6 x 20 mm	DL4R-6x20 (nr 867964)
2	2 MHz	7 x 18 mm	SEB2 (nr 57467 4075)
3	4 MHz	3,5 x 10 mm	DL4R-3,5x10 (nr 889152)

TABLE II
List of probes used for verification of the results for probe No. 1

Nr	Frequency MHz	Transducer size mm	Type of probe / catalog number
4	4 MHz	6 x 20 mm	SEB4 (nr 57469 7817)
5	4 MHz	6 x 20 mm	DL4R-6x20 (nr 871257)
6	4 MHz	6 x 20 mm	SEB4 (nr 57469 7457)

The characteristics of the probes where determined using, non-alloyed steel test piece at which the point discontinuity 1, that is the flat-bottomed hole diameter 2 mm at a depth of z = 40 mm, has been machined. This depth has been chosen, as it lies in a middle of the range of inspection of double transducer probe commonly used in practice. In the case of thicknesses of an element greater than 100 mm, single probes are usually employed. For each type of probe characteristics have been determined for two mutually perpendicular directions – parallel and perpendicular to the separation plane (acoustic isolation between transducers) of a probe. The perpendicular orientation refers to an orientation of a probe that the plane of acoustic separation extending perpendicularly to the direction of movement of the probe. In turn, the parallel orientation of a probe is that, with the plane of separation parallel to the direction of the probe movement (Fig. 1).

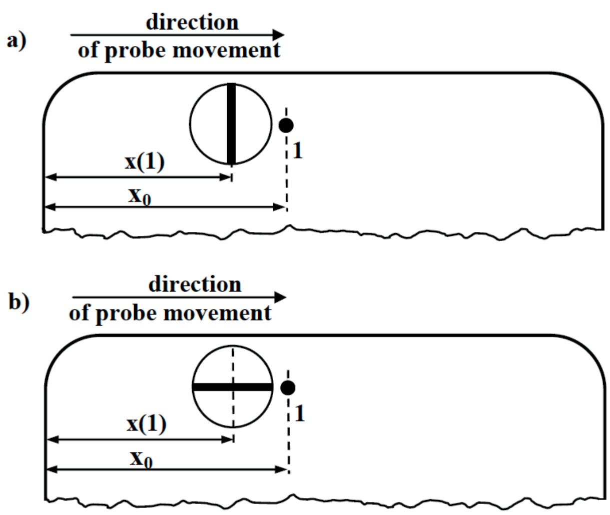

Fig. 1. The adopted probe orientation relative to direction of movement of a probe when determining the envelope of a point discontinuity: a) perpendicular orientation, b) parallel orientation

Determination of the characteristics was based on measurements of envelope of the echo from the discontinuity when moving the probe above the reflector. Two parameters have been recorded:

- amplitude of the echo H relative to the reference level set as a distance-gain-size curve DGS for the equivalent of flat-bottomed hole having a diameter DDSR = 1.5 mm
- probe position x as a distance of geometric center of a probe, relative to the center of the discontinuity, i.e. X = x (1) - x0.

In this way, the two envelopes of the echo of each of the three probes used (1 to 3); one envelope has been determined for perpendicular orientation and second one for parallel orientation to the direction of movement of a probe.

The obtained characteristics for each of the three dual transducer probes are shown on graphs of Amplitude H as a function of probe position X (Fig. 2 to 4).

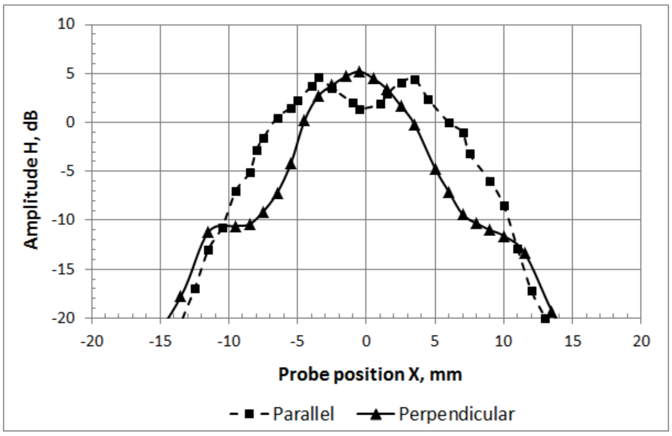

Fig. 2. The echo signal envelope received from point discontinuity obtained by dual element probe No. 1 (DL4R-6x20)

Because of unique and surprising character of the echo envelope that has been demonstrated for probe No. 1 (4 MHz, 6 x 20 mm) with the orientation parallel to the direction of probe movement, the result was verified using three successive probes of the same parameters, denoted by numbers 4, 5 and 6 (Tab. 1). During the test it was examined, whether the echo envelope also demonstrates two maxima of amplitude offset from the geometric center of a probe of about 3.5 mm (A, C Fig. 2) and the local minimum of echo in the center (B Fig. 2). For each one of the probes, the specific shape of the envelope, similar to that of probe No. 1 has been confirmed. Probe position X and the amplitude H in each of the three local extrema (maxima A, C and minimum B) has been recorded. Results, obtained for the probes No. 4, 5 and 6 were compared with the analogous values for the probe No. 1 in Table (Tab. 2). In order to more easily interpret the data, they are also shown on the graph (Fig. 5) as depending on an amplitude difference ΔH of probe position X. As we see (Table. 3) amplitude H differs greatly between the results obtained for the different probes.

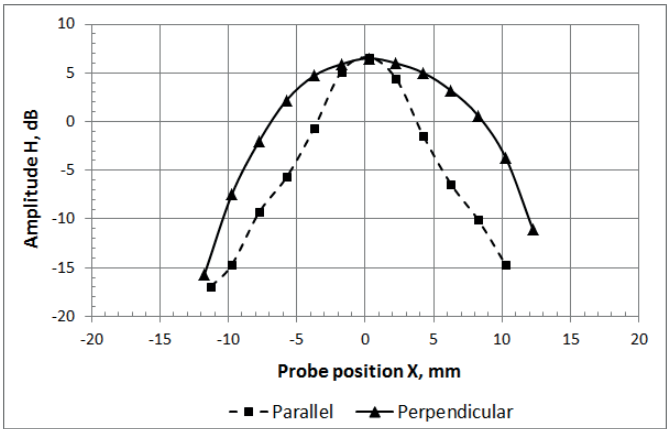

Fig. 3. The echo signal envelope for two specific orientations of probe No. 2 (SEB2)

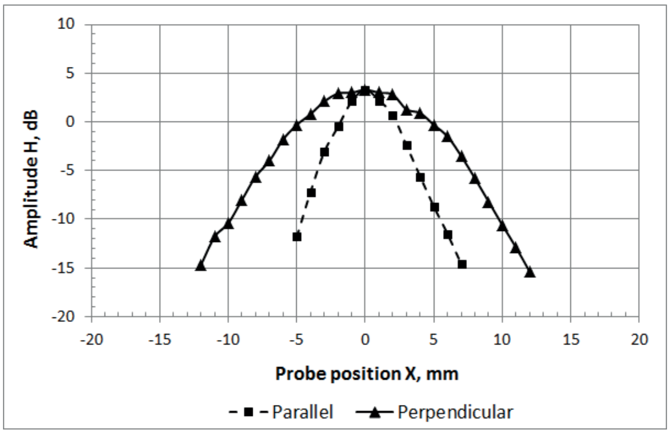

Fig. 4. The echo envelope of point discontinuity on two mutually perpendicular orientations probe No. 3 (DL4R-3.5x10)

TABLE III

The results of the verification of the characteristics of the probe 1 with a parallel orientation carried out using the probes 1, 2 and 3

Parameter	Max A	Min B	Max C
Probe 1 (DL4R-6x20 nr 867964)			
X, mm	-3,5	- 0,5	3,5
H, dB	4,6	1,4	4,4
Probe 4 (SEB4 nr 57469 7817)			
X, mm	-4,0	0	4,0
H, dB	5,3	3,0	5,1
Probe 5 (DL4R-6x20 nr 871257)			
X, mm	-4,0	0	3,0
H, dB	5,4	2,0	4,5
Probe 6 (SEB4 nr 57469 7457)			
X, mm	-3,5	0	3,0
H, dB	5,3	2,9	5,4

Therefore, the graph (Fig. 5) shows the values ΔH, which is a difference between an amplitude H and a maximum amplitude value obtained at a given test probe (i.e. the absolute value of the difference of amplitude H of the points A or C). For example, for the probe No. 1 amplitude ΔH of point C is: ΔH = 4.4 - 4.6 = 0.2 dB. Therefore, the graph (Fig. 5) shows the values ΔH which is a difference between the given amplitude and a maximum amplitude value obtained at a given test probe (i.e. the value of the amplitude H of the point A or C, depending on which is higher). In this way, comparing the value of ΔH shown in diagram (Fig. 5) illustrates the differences in the characteristics of the probes, while the influence of the differences in sensitivity of the tests has been eliminated.

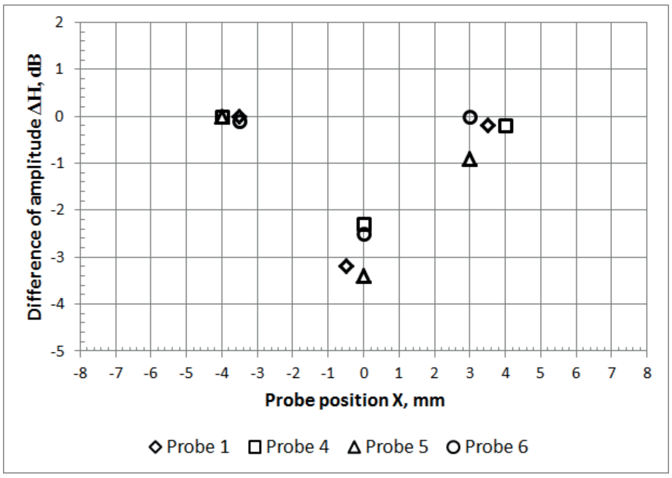

Fig. 5. Graphical comparison of local extremes Max A, Min B, Max C of the probes 1, 4, 5 and 6 with a frequency of 4 MHz and transducer size 6 x 20 mm

3. Analysis of the results

To illustrate the possible consequences of incorrect application of dual transducer probes at the results of quality inspection of forgings one need to refer to EN 10228-3 standard. This standard classifies discontinuities into two types:

- the point discontinuities, that shows the type 1 envelope according to EN 10228 (Fig. 6a) and their dimensions are equal to, or less than, the width of the ultrasonic beam measured by 6 dB echo drop. Two indications are classified as groped indications when distance between the maxima of amplitude of the two is less than or equal to 40 mm. When distance between the maxima exceeds 40 mm, indications are classified as point insulated indications.
- extensive discontinuities that shows type 2 envelopes according to EN 10228 (Fig. 6b) or their dimensions are larger than the width of a contour of a beam for a 6 dB echo drop [5].

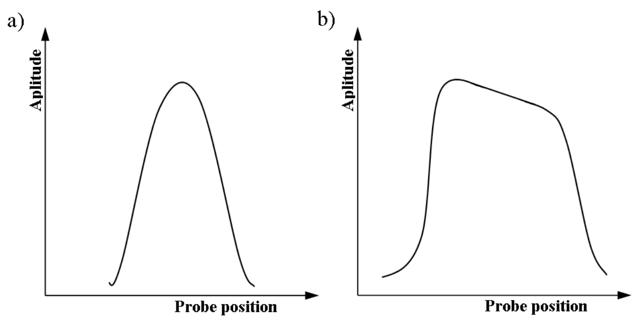

Fig. 6. Classification of indications in accordance to EN 10228-3 based on the shape of an envelope of the echo: a) echo envelope typical for point discontinuity - figure 1 b) echo envelope typical for extensive discontinuity - figure 2

Consequently, in order to properly assess a detected indication, it is necessary to properly differentiate which form of the echo envelope one have to deal with. In turn, presented characteristics of dual transducer probes (Fig. 2 to 4) shows, that each of them gives a considerably different envelope of echo, depends on the orientation of the probe relative to direction of movement, i.e. parallel or perpendicular. This is the case, despite the fact that each characteristic has been obtained at the same discontinuity using the same probe, test equipment and settings. The only variable factor in this case is the orientation of a probe relative to direction of movement. Considering the characteristics of the probe No. 1 with a frequency of 4 MHz and the transducer size of 6 x 20 mm (Fig. 2), if the detected discontinuity would be evaluated with the perpendicular orientation, the shape of an envelope similar to type 1 indication (according to EN 10228) clearly indicates, that it is a point discontinuity. However, if the evaluation of discontinuity would be carried out with the parallel orientation of the probe, the shape of the envelope would indicate that it is indication of extensive discontinuity. This is a case, because when moving the probe upon the discontinuity, amplitude smoothly increases to a maximum, then remains unchanged or with changes, and finally smoothly falls to zero (v. 13.1 in [5]). This situation therefore suggests the existence of different type of discontinuities, depending on the orientation of probe when testing - and what goes with it – usage a different evaluation criteria (amplitude based acceptance criteria for extensive discontinuities are sharper than for isolated point discontinuity). In addition, the most common technique of 6 dB drop of echo amplitude is used to determine dimensions of extensive discontinuities. As can be seen on the characteristics obtained for parallel orientation (Fig. 2), discontinuity length determined in this way would be about 14 mm long. It is worth remembering, that the actual dimension of the discontinuity was only 2 mm (circular disc reflector - flat-bottomed hole, 2 mm in diameter). Thus we see, that in the case of probe No. 1 correct recognition of a type of discontinuity is not obvious and requires the perpendicular orientation of the probe. The use of the parallel orientation may result in the incorrect interpretation of a type of discontinuity, and therefore, the adoption of too harsh acceptance criteria and result in great error in sizing.

Let's examine the characteristics of the probe 2 at 2 MHz and transducer dimensions of 7 x 18 mm (Fig. 3). As it can bee, the type 1 envelope clearly indicates a point discontinuity obtained with a parallel orientation. Thus, in the case of this probe, the parallel orientation facilitates the correct interpretation of the type of discontinuity. The use of the perpendicular orientation causes the shape of the envelope is similar to the type 2 indication (according to EN 10228-3), which in turn leads to an incorrect classification of the type of point discontinuity as extensive. The length of the discontinuity, determined in this way, assumes existence of extensive discontinuity and lads to use technique of 6 dB drop of echo. Measured length would be about 14 mm in length (Fig. 3). The echo amplitude from the discontinuity at relatively large range of a probe positions remains at a similar level. At the positions of the probe X = - 4mm, X = 0 mm, X = 4 mm, the amplitude equals H = 4.5 dB, H = 6.5dB, H = 5.0 dB respectively. Therefore, changing amplitude of only 2 dB for displacement of probe of 8 mm may easily be interpreted as indication from an extensive discontinuity.

A similar situation can be observed on the chart showing the echo envelope obtained using probe No. 3 with a frequency of 4 MHz and dimensions of transducers 3.5 x 10 mm. Similar to probe No. 2 envelope at the parallel orientation is narrow, amplitude increases rapidly, reaches a maximum at the probe position of X = 0 mm and then quickly drops down. This shape clearly shows the existence of a point discontinuity. In turn, at the perpendicular orientation envelope is much wider, amplitude slowly increases to maximum which is maintained constant by moving probe a few millimeters to fall slowly later. This type of shape of the envelope can easily be interpreted as a type 2 indication, according to EN 10228-3, leading to misclassification of type of discontinuity. The measured size of discontinuity using 6 dB drop technic, if considered as an extensive, would be about 14 mm.

In addition to significant differences in beam width, that depends on the orientation of the probe, the research highlights also an additional factor that may influence an outcome of ultrasonic examination of forgings. Namely, the envelope obtained with a parallel orientation of the probe No. 1 at a frequency of 4 MHz and transducer dimension of 6 x 20 mm shows two local maxima (point A and C) offset of about 3.5 mm with respect to the geometric center of the probe (Fig. 2). This characteristic was verified using three other probes (No. 4 ÷ 6) of identical parameters from different manufacturers. The results confirmed the existence of the phenomenon in each one of them (Tab. 2). All probes have shown a similar location of maxima A and C as well as minimum B. They are also offset by 3 ÷ 4 mm from the geometric centers of the probes. The amplitude difference ΔH between maxima A and C is similar and the difference between them does not exceed 1 dB.

Possible consequences of the existence of such characteristic of a probe with a frequency of 4 MHz and dimensions of transducers of 6 x 20 mm has been discussed in the article [6]. Since determination of a position of a point discontinuity involves measurements of a probe position at which the maximum amplitude of an echo of a discontinuity, due to the discussed probe characteristics, it may be subject to considerable errors. This happens, when the measurement of an discontinuity location is done with a separation plane of a probe orientated parallel to the direction of probe movement. Then, the measurement of a probe position is being made when its center is offset by 3.5 mm along the separation plane of a probe with respect to the actual center of point discontinuity. The error can be doubled when determining the distance between two point discontinuities. This situation is shown in Fig. 7, taking the actual distance between centers of two discontinuities equal 40 mm. If the measured distance between them is measured using disadvantaged (parallel) orientation of the probe, in the two extreme cases the distance to be determined is 33 mm and 47 mm, resulting in 14 mm difference between the two possible measured distances (Fig. 7a). This situation causes, for testing of forgings, a change in classification of the type of point discontinuity, according to EN 10228, from isolated to grouped and - what goes with it - a significant change in the evaluation criteria [6].

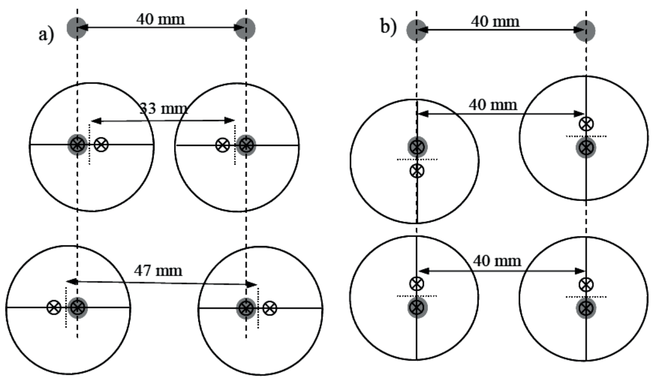

Fig. 7. The distance between two point discontinuities spaced of 40 mm at a disadvantage (a) and preferred (b) the orientation of the probe (4 MHz, 6 x 20 mm) [6]

4. Conclusions

Based on the study and analysis the following conclusions have been formed:

- Double transducer probes for longitudinal waves have a very heterogeneous distribution of sensitivity in two mutually perpendicular directions, perpendicular and parallel, relative to the transducer separation plane of a probe.
- Misinterpretation of a type of discontinuity in ultrasonic testing of forgings and erroneous classification of a point discontinuity as extensive one leads to determination of the dimensions of these discontinuities by 6 dB drop of echo amplitude, which in this case gives completely erroneous result of sizing. The dimension of a point discontinuity measured in this way, wrongly classified as extensive when it's not the case, can be up to an order of magnitude greater than its real value.
- In order to properly interpret the type of discontinuity it is necessary to adopt such an orientation of a probe for examination, for which the beam width is as small as possible (in a direction of probe movement) and demonstrates just one maximum of sensitivity in the centre of a probe. Only then the echo envelope from the point discontinuity is similar to the type 1, according to EN 10228-3, indicating the presence of the point discontinuity.
- The width of a beam in two mutually perpendicular directions, parallel and perpendicular to the separation plane vary widely. Depending on the type of probe, it may be greater in parallel or perpendicular orientation to the separation plane between transducers. Therefore, there is no universal orientation of a probe which in any case leads to a correct result. This requires a detailed knowledge of a characteristics of a probe before using it for inspection.
- It would be welcome, that the manufacturers of probes provide in data sheets of double transducer probes charts of distributions of sensitivity on two planes, parallel and perpendicular to the plane of separation of transducers.
- It is advisable to personnel performing the test had access to information about the distribution of sensitivity for both orientations of a probe or had the opportunity to check the characteristics on an appropriate calibration block. If this is not possible it may be useful to compare an envelope of echo when moving a probe above the discontinuity using orientations of the probe: parallel and perpendicular to the direction of movement. If in at least one of the cases envelope shows up the shape contour type 1, according to EN 10228-3, it may indicate a point type discontinuity.

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