Ultrasonic immersion probes characterization for use in non-destructive testing according to EN 12668-2:2001

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Abstract. Ultrasound is often used as a Non-Destructive Testing (NDT) technique to analyze components and structures to detect internal and surface flaws. To guarantee reliable measurements, it is necessary to calibrate instruments and properly assess related uncertainties. An important device of an ultrasonic instrument system is its probe, which characterization should be performed according to EN 12668-2. Concerning immersion probes beam profile, the parameters to be assessed are beam divergence, focal distance, width, and zone length. Such parameters are determined by scanning a reflector or a hydrophone throughout the transducer beam. Within the present work, a methodology developed at Inmetro’s Laboratory of Ultrasound to evaluate relevant beam parameters is presented, based on hydrophone scan. Water bath and positioning system to move the hydrophone were used to perform the scan. Studied probes were excited by a signal generator, and the waterborne signals were detected by the hydrophone and acquired using an oscilloscope. A user-friendly virtual instrument was developed in LabVIEW to automate the system. The initial tests were performed using 1 and 2.25 MHz-ultrasonic unfocused probes (Ø = 1.27 cm), and results were consistent with the manufacturer’s specifications. Moreover, expanded uncertainties were lower than 6% for all parameters under consideration.

1. Introduction

The normal practice in most ultrasound non-destructive testing is the calibration of probes and ultrasonic measurement systems to ensure the accuracy and repeatability of the test. Ultrasonic transducers play a key role in any ultrasonic measurement system since they generate and receive the ultrasonic waves. To quantitatively describe the effect of transducers on the measured signals in an ultrasonic test, it is necessary to characterize both the transducer’s transmitting and receiving properties. It is shown that these properties can be completely determined by four types of quantities: (1) the transducer’s electrical impedance; (2) its sensitivity; (3) its radiation impedance; and (4) the beam parameters, such as: focal length, distance, and width; and beam divergence. It is also known that all of these properties can be obtained through a series of calibration methods depends on kind of probe [[1]]. The aim of this work was implements a method to assess the ultrasound immersion probes beam parameter in accordance with EN12668-2. This one can potentially influence the outcome of an inspection if it were not in accordance with the standard cited above. The initial tests using 1 and
2.25 MHz-ultrasonic unfocused immersion probes (\( \Theta = 1.27 \) cm) showed that results are consistent with the manufacturer’s specifications.

2. Theoretical Approach

Testing beam parameters, for immersion probes applied in non-destructive testing, is defined in EN 12668-2:2001 standard – Non-Destructive Testing – Characterization and Verification of Ultrasonic Examination Equipment – Part 2: Probes [1], specifically in the 7.7 subtitle - Beam parameters for immersion probes. The measurement technique consists of studying the probe acoustic beam in water, using a reflector target or hydrophone receiver. Labus chose to use a hydrophone receiver whereas the signals captured by hydrophone have better relation signal-noise than the one obtained by reflector target.

Parameters should be determined by mapping the immersion probes as follows: axial profile - focal distance and length of the focal zone; transverse profile - focal width, X and Y directions as well as beam divergence.

The focal distance is given as [2]:

\[
F_D = |Z_p - Z_0|, \tag{1}
\]

where \( Z_p \) is the last maximum position of ultrasound beam (\( V_p \)), and \( Z_0 \) is the coordinate of the probe or its acoustic lens (non-focused probe).

The focal length is given by [2]:

\[
F_L = |Z_{l1} - Z_{l1}|, \tag{2}
\]

where \( Z_{l1} \) and \( Z_{l2} \) are the beam axis coordinates where \( V_p \) is reduced by 3 dB. Focal distance and focal length shall be within ± 15% of the manufacturer’s specifications.

The focal widths on X-axis and Y-axis at focal point are given by the differences [2]:

\[
W_{x1} = |X_2 - X_1| \quad \text{and} \quad W_{y1} = |Y_2 - Y_1|, \tag{3}
\]

where \( X_1 \) and \( X_2 \) (\( Y_1 \) and \( Y_2 \)) are the \( X \) (\( Y \)) transverse axis coordinates where \( V_p \) is reduced by 3 dB. The focal widths shall be within ± 15% of the manufacturer’s specifications.

The beam divergence is only required for probes that have unfocusing means, such as acoustic lens or curved piezoelectric elements. These are estimated by the measurement of focal width on \( F_D \) and \( Z_{l2} \) given as (5) and (6):

\[
\Omega_x = \frac{360}{2\pi} \cdot \arctan \left( \frac{W_{x2} - W_{x1}}{2(Z_{l2} - F_D)} \right), \tag{5}
\]

\[
\Omega_y = \frac{360}{2\pi} \cdot \arctan \left( \frac{W_{y2} - W_{y1}}{2(Z_{l2} - F_D)} \right), \tag{6}
\]

where \( W_{x2} \) and \( W_{y2} \) are the focal width determined on X-axis and Y-axis on \( Z_{l2} \) position. The angles of divergence shall not differ from the manufacture’s specified values by either ± 10% or 1º, whichever is the largest.

3. Experimental Procedure

Labus is equipped with a water bath measuring 1700 mm × 1000 mm × 800 mm, which is large enough for most usual measurements and calibrations in the megahertz frequency range. The specified positioning system, used to move the transducer (or hydrophone) in the water bath, allows movement of 300 mm along the X and Y axes, and of 600 mm along the Z axis (Newport Corporation, Irvine, ...)
The X and Y axis present resolution and repeatability better than 1.25 µm, whilst Z achieves a maximum of 5.0 µm. Additionally, there is a 360° rotation system, with a 0.01° resolution.

The typical system configuration used during the mapping acquisition comprises a personal computer connected to an oscilloscope, a signal generator, and movement controllers [4]. To integrate all system components, and also to provide a user-friendly interface, a virtual instrument (VI) was developed in LabVIEW (National Instruments Corporation, Austin, TX, USA) [4]. The VI allows movement control along all the axes, acquisition of waterborne signals, and the calculation of essential parameters to assess and calibrate US transducers. In addition, the software automatically performs the raster scans necessary to calculate the parameters related to the beam parameters for immersion probes applied in non-destructive testing, based on EN12668-2.

The $F_D$, $F_L$, $W_{x1}$, $W_{x2}$, $\Omega_x$, and $\Omega_y$ parameters were determined on two probes of 1.27 cm diameter, and frequencies of 1.0 and 2.25 MHz. The probes were excited by using a 20-cycle burst of a sine wave generated by a function generator AFG 3252 (Tektronix, Beaverton, Oregon, USA), and waterborne signals were acquired using an oscilloscope TDS 3032B (Tektronix, Beaverton, Oregon, USA). Needle hydrophones were used in the mapping procedure and, for this, active elements of 0.5 mm were applied (Precision Acoustics Ltd., Dorchester, Dorset, UK).

After aligning the probe and the hydrophone, the scan along the beam axis using steps of 1.0 mm was carried out to determine the position of the last maximum pressure of the transducer beam ($F_D$). Then, the probe was mapped over two transverse axes to beam axis (X and Y), at $F_D$ position, with steps of 0.1 mm, in a dimension enough to obtain signals lower than 10 dB of the amplitude value found at $F_D$. The same procedure was carried out at $Z_{L2}$ position. All mappings were recorded, and employed to calculate the previously cited parameters. Details about the measurement procedure are described below.

3.1 Virtual Instrument

Figures 1 and 2 show the VI windows. The controls of the function generator and oscilloscope are presented in [4]. The “Mapeamento” (Mapping) tab (figure 1) is used to define a beam mapping in one or two dimensions, covering the region defined by the user. On the left lower corner, there are radio buttons to select what kind of mapping (line or plane), and controllers to define the step and length, in millimetres, of the displacement in each axis. Note that unused axis is set disable. The files obtained from mappings are analyzed in the “END” tab (figure 2), where files are uploaded and showed, and the values of focal distance ($F_D$), focal length ($F_L$), focal width on $F_D$ ($W_{x1}$ and $W_{y1}$), focal width on $Z_{L2}$ ($W_{x2}$ and $W_{y2}$) and divergence angles ($\Omega_x$ and $\Omega_y$) are calculated and presented.
4. Determination of standard uncertainty of Type A and Type B

Herein, the finite resolution of the positioning system used to perform the raster scans is assumed to present a rectangular distribution. Hence, the Type B uncertainty of $s$ ($u_{s(\text{Type B})}$) is estimated by dividing the equipment resolution ($1.25\times10^{-4}$ cm) by $2\sqrt{3}$ . The Type A uncertainty ($u_{s(\text{Type A})}$) of the position system is estimated, for each of the three axes, as the standard deviation of the mean of four measurements of their linear translation. This consideration, takes in account that the $F_D$ conventional value can have a uniform probability between two mapping consecutive points. Type A uncertainty for $F_D$ ($u_{F_D(\text{Type A})}$) measurements was estimated as the standard deviation of the mean of 4 measurements, divided by $\sqrt{4}$ .

The Type B uncertainty of $Z_{1,1}$ ($u_{Z_{1,1}(\text{Type B})}$) and $Z_{1,1}$ ($u_{Z_{1,1}(\text{Type B})}$) were estimated considering the used step ($s$) divided by $2\sqrt{3}$ , taking the same consideration made in $F_D$. The Type A uncertainty of $Z_{1,1}$ ($u_{Z_{1,1}(\text{Type A})}$) and $Z_{1,1}$ ($u_{Z_{1,1}(\text{Type A})}$) were estimated as the standard deviation of the mean of 4 measurements, divided by $\sqrt{4}$ .

In $W_{1,1}$, $W_{1,2}$, $W_{1,1}$, $W_{2,1}$ uncertainty determination, the Type B for $X_2$ ($u_{X_2(\text{Type B})}$), $X_1$ ($u_{X_1(\text{Type B})}$), $Y_2$ ($u_{Y_2(\text{Type B})}$), $Y_1$ ($u_{Y_1(\text{Type B})}$), $X_2$ ($u_{X_2(\text{Type B})}$), $X_1$ ($u_{X_1(\text{Type B})}$), $Y_2$ ($u_{Y_2(\text{Type B})}$), $Y_1$ ($u_{Y_1(\text{Type B})}$) were estimated considering the used step ($s$) divided by $2\sqrt{3}$ , taking the same consideration made in $F_D$ estimative. The respective Type A uncertainty was estimated as the standard deviation of the mean of 4 measurements, divided by $\sqrt{4}$ .

Lastly, $\Omega_x$ and $\Omega_y$ uncertainty determination considered the uncertainty obtained of the used parameters to its determination.
5. Results and discussion
The performance of the implemented system was evaluated by determination of FD, FL, Wx1, Wx2, Wy1, Wy2 and Ωx and Ωy values, as well as respective measurement uncertainty, to 1.0 and 2.25 MHz NDT probes. Tables 1 and 2 show the evaluated parameters and the respective uncertainty to 1 and 2.25 MHz probes. The obtained values to $F_D$ and $F_L$ are different from the theoretical values available in the manufacturer’s technical notes [5]. It is important to note that if the obtained result $F_D$ (29.50 mm) was applied to calculate $F_L$ by equation $F_L = F_D \cdot \left[ \frac{2}{(1+0.5)} \right]$ found at manufacturer’s technical notes [5], the $F_L$ would be 39.33 mm, which would be coherent with the obtained value of 41.25 mm, considering the estimated uncertainty. Therefore, the measured values of $F_D$ and $F_L$ to 1 MHz probe should be reassessed. The tested values and uncertainty calculated to 2.25 MHz probe are in accordance with the theoretical values presented manufacturer’s technical notes [5] and in EN 12668-2, respectively. The $W_{x1}$, $W_{x2}$, $W_{y1}$, $W_{y2}$ e $Ω_x$ and $Ω_y$ parameter required in actual standard were not found manufacturer’s technical notes [5], however, the estimated uncertainties were in accordance with the ones stated in EN 12668-2.

Table 1. Parameter values, and respective values of uncertainty, for the 1 MHz NDT probe ($Ø = 12.7$ mm), panametrics A303S, serial number 541428.

| Parameter | Unit | Theoretical values [5] | Results | Expanded Uncertainty | Expanded Uncertainty [%] |
|-----------|------|------------------------|---------|----------------------|-------------------------|
| $F_D$     | [mm] | 26.49                  | 29.50   | 0.87                 | 2.9                     |
| $F_L$     | [mm] | 35.32                  | 41.25   | 0.97                 | 2.4                     |
| $W_{x1}$  | [mm] | 3.78                   | 3.80    | 0.10                 | 2.6                     |
| $W_{y1}$  | [mm] | 3.80                   | 3.80    | 0.09                 | 2.4                     |
| $W_{x2}$  | [mm] | 6.73                   | 6.73    | 0.14                 | 2.1                     |
| $W_{y2}$  | [mm] | 6.73                   | 6.73    | 0.10                 | 1.5                     |
| $Ω_x$     | [°]  | 2.84                   | 2.81    | 0.13                 | 4.6                     |
| $Ω_y$     | [°]  | 2.84                   | 2.84    | 0.08                 | 2.8                     |

Table 2. Parameter values, and respective values of uncertainty, for the 2.25 MHz NDT probe ($Ø = 12.7$ mm), panametrics V306, serial number 536444.

| Parameter | Unit | Theoretical values [5] | Results | Expanded Uncertainty | Expanded Uncertainty [%] |
|-----------|------|------------------------|---------|----------------------|-------------------------|
| $F_D$     | [mm] | 60.30                  | 60.50   | 0.87                 | 1.4                     |
| $F_L$     | [mm] | 80.67                  | 83.00   | 4.25                 | 5.1                     |
| $W_{x1}$  | [mm] | 3.40                   | 3.45    | 0.15                 | 4.3                     |
| $W_{y1}$  | [mm] | 3.45                   | 3.45    | 0.15                 | 4.3                     |
| $W_{x2}$  | [mm] | 6.55                   | 6.55    | 0.35                 | 5.3                     |
| $W_{y2}$  | [mm] | 6.60                   | 6.60    | 0.17                 | 2.6                     |
| $Ω_x$     | [°]  | 1.44                   | 1.44    | 0.05                 | 3.5                     |
| $Ω_y$     | [°]  | 1.44                   | 1.44    | 0.05                 | 3.5                     |
Figure 3. Example of mappings and parameters value obtained from test 1 performed on 1 MHz NDT probe (Ø = 12.7 mm), panametrics A303S, serial number 541428.

6. Conclusion
The mapping system of ultrasound immersion NDT probe was assessed in determining the focal distance, length and width and divergence beam for 1 and 2.25 MHz probes. The values obtained to 1 MHz probe were different to the theoretical values found in the manufacturer’s technical notes and should be reassessed. Nevertheless, results achieved to 2.25 MHz probe were in accordance to the values presented manufacturer’s technical notes. Finally, the presented estimated uncertainties were in accordance with EN 12668-2:2001 standard.

References
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