UNCERTAINTY ESTIMATION OF THE ULTRASONIC BEAM DIVERGENCE FROM NDT PROBES USING MONTE CARLO METHOD

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Abstract: This paper presents the calculation of ultrasonic beam divergence from Non-Destructive Testing probes, and its uncertainty estimation using Monte Carlo Method. Results show that due to the nonlinear nature of beam divergence parameter, the Monte Carlo Method should be used instead of the Guide to the Expression of Uncertainty in Measurement, GUM.

Key words: ultrasound, beam divergence, non-destructive testing, uncertainty, Monte Carlo method.

1. INTRODUCTION

Ultrasound is often used as a Non-Destructive Testing (NDT) technique to detect internal and surface flaws at components and structures. Instrument calibration and proper assess of related uncertainties tends to guarantee reliable measurements. An important component of an ultrasonic system is its probe, which characterization should be performed according to EN 12668-2:2001 – *Non-destructive testing – characterization and verification of ultrasonic examination equipment – part 2: probes*, particularly subtitle 7.7. *Beam parameters for immersion probes* [1]. The measurement technique consists of studying probe ultrasonic beam in water, using a reflector target or a hydrophone. Parameters that should be assessed are beam divergence, focal distance, width, and zone length.

The Inmetro's Laboratory of Ultrasound (Labus) developed a measurement system to test ultrasound immersion probe beam parameters in accordance with EN12668-2, and estimates respective measurement uncertainty.

In a previous work, the beam parameters focal distance, focal zone length, and focal width at X and Y directions were assessed, and their respective uncertainties were estimated [2]. In this paper, ultrasonic beam divergence is estimated for NDT probes in the frequency range 0.5 - 3.5 MHz, and respective uncertainties are estimated using the ISO-GUM [3] and Monte Carlo Method (MCM) [4].

2. MATERIAL AND METHODS

2.1. Beam parameters from EN 12668-2:2001

Beam parameters should be determined by mapping the immersion probes as follows: axial profile – focal distance and length of the focal zone, transversal profile – focal width, X and Y directions, as well as beam divergence.

The focal distance is given by $F_D = |Z_P - Z_0|$, 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 $F_L = |Z_{L2} - Z_{L1}|$, 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 $W_{x1} = |X_2 - X_1|$ and $W_{y1} = |Y_2 - Y_1|$, 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 unfocused probes (naturally focused). These are estimated by the measurement of focal width on F_D and Z_{L2} given as $\Omega_x = \frac{360}{2\pi}\cdot\arctan\left[\frac{(W_{x2} - W_{x1})}{2(Z_{L2} - F_D)}\right]$ and $\Omega_y = \frac{360}{2\pi}\cdot\arctan\left[\frac{(W_{y2} - W_{y1})}{2(Z_{L2} - F_D)}\right]$, where W_{x2} and W_{y2} are the focal width determined on X-axis and Y-axis on Z_{L2} position. The divergence angles shall not differ from values declared by the manufacture by either ± 10% or 1° whichever is the largest.

2.2. Measurement system and procedure

Labus is equipped with a water bath measuring 1.7 m × 1.0 m × 0.8 m, and a positioning system used to move the transducer (or hydrophone) in the water bath, which allows movement of 300 mm along the X and Y-axes (resolution = 1.25 µm), and of 600 mm along the Z-axis (resolution = 5.0 µm) (Newport Corporation, Irvine, CA, USA). Additionally, there is a 360° rotation system (resolution = 0.01°). The typical system configuration during the mapping acquisition comprises a computer connected to an oscilloscope, a signal generator, and axes movement controllers [5]. 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) [6]. The software was upgraded and allows automatically perform raster scans and calculate immersion probes beam parameters, as described on EN 12668-2:2001.

Studied probes were excited by using a 30-cycle sine wave burst generated by a function generator AFG 3252 (Tektronix, Beaverton, Oregon, USA). The waterborne signals were acquired using needle hydrophones presenting active elements of 0.5 mm (Precision Acoustics Ltd., Dorchester, Dorset, UK), and an oscilloscope TDS 3032B (Tektronix, Beaverton, Oregon, USA). Measurement procedure starts by aligning the set probe and hydrophone. After, a scan along the beam axis using steps of 1.0 mm is carried out to determine the position of the last maximum pressure of the transducer beam (F_D). Then, the probe is 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 is carried out at Z_{L2} position. The complete measurement procedure is repeated 4 times.

2.3. Determination of standard uncertainty of Type A and Type B

As presented at item 2.1, all parameters, except beam divergence, are calculated directly from the raster scans of axial and transversal beam profiles. Hence, the raster scan resolution and the step size (s) are principal source of uncertainty to F_D, F_L, Z_{L1}, Z_{L2}, W_{x1}, W_{x2}, W_{y1} and W_{y2}. The positioning system resolution is assumed to present a rectangular distribution; hence the Type B uncertainty is estimated by dividing the resolution by $2\sqrt{3}$. Considering the step size as also presenting a rectangular distribution, its Type B uncertainty is defined as used step size divided by $2\sqrt{3}$. The Type A uncertainties were estimated as the standard deviation from 4 repeated measurements, divided by $\sqrt{4}$. Finally, the Ω_x and Ω_y uncertainties take into account uncertainties obtained from each one of parameters used in beam divergence calculation.

2.4. Monte Carlo Method Simulation

Monte Carlo Method simulations were performed by a program developed in LabVIEW to generate pseudo-random probabilities for the distributions of the involved quantities. Hence, 200.000 possible random values were generated for each quantity, according to their distribution functions, to estimate studied parameters uncertainties.

3. RESULTS

The standard uncertainty values estimated to the beam divergence parameter (u_Ω_x and u_Ω_y) using the ISO-GUM and MCM are presented on Table 1 and Table 2, respectively, and it can observed that the mean values calculated by both approaches are quite similar. However, MCM approach gives higher values of combined uncertainties and larger coverage intervals. Hence, probability density functions provided by GUM take smaller values than those provided by the MCM in the neighbourhood of the expectation. The coverage intervals were compared take into account the calculation of the numerical tolerance, as defined in [4] and results point out that they are statistically different. Hence, considering the beam divergence parameter studied here, a more conservative uncertainty approach will be achieved using MCM uncertainty framework.

Table 1. Beam divergence results, and respective uncertainties and coverage intervals calculated using the ISO-GUM approach.

Freq. [MHz]	Ω_x [º]	u_Ω_x [º]	Coverage Interval [º]	Ω_y [º]	u_Ω_y [º]	Coverage interval [º]
0.5	2.92	0.11	[2.62, 3.23]	2.974	0.082	[2.764, 3.184]
1.0	2.839	0.082	[2.669, 3.009]	2.815	0.073	[2.669, 2.961]
2.25	1.443	0.032	[1.380, 1.506]	1.443	0.032	[1.380, 1.506]
3.5	0.886	0.023	[0.838, 0,934]	0.921	0.024	[0.868, 0.974]

Table 2. Beam divergence results, and respective uncertainties and coverage intervals calculated using the MCM approach.

Freq. [MHz]	Ω_x [º]	u_Ω_x [º]	Coverage interval [º]	Ω_y [º]	u_Ω_y [º]	Coverage interval [º]
0.5	2.92	0.18	[2.59, 3.27]	2.98	0.24	[2.53, 3.46]
1.0	2.839	0.095	[2.655, 3.027]	2.815	0.083	[2.654, 2.980]
2.25	1.444	0.081	[1.288, 1.605]	1.444	0.066	[1.316, 1.577]
3.5	0.886	0.042	[0.804, 0.968]	0.922	0.046	[0.833, 1.011]

4. CONCLUSION

The ultrasonic beam divergence uncertainty should be estimated using the Monte Carlo Method approach.

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