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Monte Carlo uncertainty assessment of ultrasonic beam parameters from immersion transducers used to non-destructive testing

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ABSTRACT

The uncertainty of ultrasonic beam parameters from non-destructive testing immersion probes was evaluated using the Guide to the expression of uncertainty in measurement (GUM) uncertainty framework and Monte Carlo Method simulation. The calculated parameters such as focal distance, focal length, focal widths and beam divergence were determined according to EN 12668-2. The typical system configuration used during the mapping acquisition comprises a personal computer connected to an oscilloscope, a signal generator, axes movement controllers, and a water bath. The positioning system allows moving the transducer (or hydrophone) in the water bath. To integrate all system components, a program was developed to allow controlling all the axes, acquire waterborne signals, and calculate essential parameters to assess and calibrate US transducers. All parameters were calculated directly from the raster scans of axial and transversal beam profiles, except beam divergence. Hence, the positioning system resolution and the step size are principal source of uncertainty. Monte Carlo Method simulations were performed by another program that generates pseudo-random samples for the distributions of the involved quantities. In all cases, there were found statistical differences between Monte Carlo and GUM methods.

1. Introduction

When reporting measurement result of a physical quantity, some quantitative indication of the quality of the result shall be given, to allow assessing its reliability. The "Guide to the expression of uncertainty in measurement" (GUM) [1] provides general guidance on many aspects of uncertainty evaluation, as a framework for the uncertainty propagation and the stages of uncertainty evaluation. The GUM uncertainty framework has been adopted by many organizations, is widely used, and has been implemented in standards, guides on measurement uncertainty and in software [1]. However, the GUM approach presents some limitations or drawbacks, as reported in the GUM itself. For instance, the characterization of the output quantity by a Gaussian distribution or a scaled and shifted *t*-distribution, and the restriction of using first-order Taylor series expansion, when the functional relationship between output quantity and its input quantities is nonlinear. Owing such presented limitations, the GUM points out to other analytical or numerical methods [1], such as Monte Carlo Method (MCM).

The Bureau International des *Poids et Mesures* (BIPM) has published the GUM-S1: "Evaluation of measurement data — Supplement 1 to the Guide to the expression of uncertainty in measurement — Propagation of distributions using a Monte Carlo Method" [2] that provides guidelines for the use of MCM, which can be applied to evaluate measurement uncertainties using the concept of propagation of distributions. This concept constitutes a generalization of the law of propagation of uncertainties given by the GUM uncertainty framework. MCM has attracted interest as an alternative method for the evaluation of measurement uncertainties, once MCM can overcome the limitations of the traditional GUM. MCM uses random number generation to simulate values of the involved variables rather than performing analytical calculations. Moreover, MCM approach allows easily taken into account non-linearity in measurement model [2].

Many works in literature have developed and assessed simulations of ultrasonic Non-Destructive Testing (NDT) for evaluating performances of inspection techniques [3–6]. Moreover, the use of realistic data as input parameters for NDT numerical models has also been evaluated [5,7]. However, few of them have presented any concern about measurement uncertainty and its impact on the results of numerical model simulation [5,7], and none even mention the GUM.

Ultrasonic probes play a key role in any ultrasonic measurement system since they both generate and receive the ultrasonic waves. To quantitatively describe the effect of the probe(s) on measured signals during an ultrasonic test, it is necessary to

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characterize both the transducers' transmitting and receiving properties. Despite the fact the beam pattern of an ultrasonic transducer can be theoretically predicted, ultrasonic probe's behaviour can varies from one unit to other, due mostly to their assembly. Because of that, final users should have the most important parameters of ultrasonic probes determined experimentally instead of just consider theoretical formulations [8]. Moreover, it is important to have in mind that the determination of the probe parameters is essential to assess if the ultrasonic probes comply with reference standards, which is intent to assure the quality of probes. According to EN 12668-2 Non-Destructive Testing – Characterization and Verification of Ultrasonic Examination Equipment – Part 2: Probes [9], the beam parameters of immersion ultrasonic probes shall be measured in water and shall comply with their respective acceptance criteria. Besides, those parameters should be verified during the probe's lifetime in order to check if the probe is still adequate to what it was manufactured for. If the beam parameters are determined without estimating their respective measurement uncertainties, the compliance to the acceptance criteria is not properly performed [8].

Inmetro's Laboratory of Ultrasound has developed a measurement system to assess beam parameters of immersion probes and their respective uncertainties, in the frequency range of 0.5 MHz to 10 MHz [10], in accordance with item 7.7 of EN 12668-2 Non-Destructive Testing – Characterization and Verification of Ultrasonic Examination Equipment – Part 2: Probes [9]. To validate the results of the uncertainty calculated according GUM uncertainty framework, the uncertainty using MCM was also calculated. This paper presents the calculation of ultrasonic beam parameters (focal distance, focal length, focal widths and beam divergence) from NDT immersion probes, and its uncertainty evaluation using GUM uncertainty framework and Monte Carlo Method.

2. Beam parameters for immersion probes from EN 12668-2:2010

Immersion probes are specifically designed to transmit ultrasound in applications where the test parts are partially or wholly immersed in water. The relevant beam parameters, as described within this paper, are to be used as defined and assessed, as the beam is formed in water prior to reach the material to be inspected. The measurement procedure used in this paper applies only for those probes. For other types, for instance those generically named "contact probe", there are other approaches to assess its beam parameters, using electromagnetic-acoustic receivers and reference blocks.

Testing beam parameters for immersion probes applied in non-destructive testing is defined in EN 12668-2:2010 standard [9], specifically in the 7.7 subtitle – Beam parameters for immersion probes. Basically, the measurement technique consists at studying the probe ultrasonic beam in water, using a hydrophone receiver. Parameters should be determined by scanning the immersion probe as follows: axial profile (focal distance and length of the focal zone), transverse profile (focal width) at X and Y directions, as well as beam divergence.

Considering V_p as the signal amplitude at the last maximum over the beam axis, the focal distance F_D is given as:

$$F_D = |Z_P - Z_0|, \tag{1}$$

in which Z_P is the position of V_P and Z_0 is the position of the probe face or its acoustic lens (focused probe) (Fig. 1a). For simplicity, assuming $Z_0 = 0$, then $F_D = Z_P$.

The focal length is given by:

$$F_L = |Z_{L2} - Z_{L1}|, \tag{2}$$

in which Z_{L1} and Z_{L2} are the beam axis positions where V_P is reduced by 3 dB (Fig. 1b).

The focal widths on X-axis (W_{x1}) and Y-axis (W_{y1}) at focal point (F_D) are given by the differences:

$$W_{x1} = |X_2 - X_1| \text{ and} \tag{3}$$

$$W_{y1} = |Y_2 - Y_1|, \tag{4}$$

in which X_1 and X_2 (Y_1 and Y_2) are the X (Y) transverse axis positions where V_P is reduced by 3 dB (Fig. 2a). Similarly, the focal widths on X-axis (W_{x2}) and Y-axis (W_{y2}) at Z_{L2} are given by:

$$W_{x2} = |X_{2\_2} - X_{1\_2}| \text{ and} \tag{5}$$

$$W_{y2} = |Y_{2\_2} - Y_{1\_2}|, \tag{6}$$

in which X_{1_2} and X_{2_2} (Y_{1_2} and Y_{2_2}) are the X (Y) transverse axis positions where V_P is reduced by 3 dB (Fig. 2b).

The beam divergence is only required for non-focused probes, therefore excluding those with focusing means, such as acoustic lens or curved piezoelectric elements. Beam divergence parameters are evaluated after the measurement of focal width on F_D and Z_{L2}, as given in (7) and (8):

$$\Omega_x = \frac{360}{2\pi}\arctan\left[\frac{(W_{x2} - W_{x1})}{2(Z_{L2} - F_D)}\right], \tag{7}$$

$$\Omega_y = \frac{360}{2\pi}\arctan\left[\frac{(W_{y2} - W_{y1})}{2(Z_{L2} - F_D)}\right], \tag{8}$$

in which W_{x2} and W_{y2} are the focal width determined on X-axis and Y-axis on Z_{L2} position.

According to EN 12668-2:2010 [9], focal distance, focal length, and focal widths shall be within ±15 % of the manufacturer's specifications, whereas the divergence angles shall not differ from values declared by the manufacture by either ±10% or ±1°, whichever is the largest. It is worth to emphasise that these acceptance criteria are not considered in this study.

3. Measurement system and procedure

The typical system configuration used during the mapping acquisition (Fig. 3) comprises a personal computer connected to an oscilloscope, a signal generator, a needle hydrophone as receiver, and axes movement controllers [10]. A water bath with dimensions of 1700 mm × 1000 mm × 800 mm was used. The positioning system (Newport Corporation, Irvine, CA, USA) comprises X, Y and Z axes movement, and it allows moving the transducer (or hydrophone) in the water bath. The X and Y-axes present accuracy and repeatability better than 1.25 µm, whilst Z achieves a maximum of 5.0 µm in positioning accuracy. Additionally, there is a 360° rotation system, with a 0.01° resolution. 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) [11]. 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 was developed to automatically perform the raster scans necessary to calculate the immersion probes beam parameters as described in EN 12668-2:2010 [9].

The tests were performed using 10 different NDT ultrasonic unfocused probes varying from 0.5 MHz to 10 MHz nominal frequencies. All probes have 12.7 mm of nominal diameter, except 0.5 MHz frequency probe with 25.4 mm of nominal diameter (Panametrics, Olympus-NDT, USA).