Experimental findings on the underwater measurements uncertainty of speed of sound and the alignment system

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Abstract: Speed of sound is an important quantity to characterize reference materials for ultrasonic applications, for instance. The alignment between the transducer and the test body is an key activity in order to perform reliable and consistent measurement. The aim of this work is to evaluate the influence of the alignment system to the expanded uncertainty of such measurement. A stainless steel cylinder was previously calibrated on an out of water system typically used for calibration of non-destructive blocks. Afterwards, the cylinder was calibrated underwater with two distinct alignment system: fixed and mobile. The values were statistically compared to the out-of-water measurement, considered the golden standard for such application. For both alignment systems, the normalized error was less than 0.8, leading to conclude that the both measurement system (under- and out-of-water) do not diverge significantly. The gold standard uncertainty was 2.7 m·s^{-1}, whilst the fixed underwater system resulted in 13 m·s^{-1}, and the mobile alignment system achieved 6.6 m·s^{-1}. After the validation of the underwater system for speed of sound measurement, it will be applied to certify Encapsulated Tissue Mimicking Material as a reference material for biotechnology application.

1. Introduction

Speed of sound is an important quantity to characterize materials in ultrasonic applications. The accurate measurement of such property is a key step to certify reference materials used for calibrations in ultrasound field. The Inmetro's Laboratory of Ultrasound (Labus) has developed systems to calibrate the speed of sound of different materials (solids and liquids) [1][2][3], which are continually evaluated on metrological bases, and upgraded to improve the measurement uncertainty.

The implementation of new measurement procedure depends on their validation, and the guidelines for validating are presented in DOQ-CGCRE-8 [4]. Those guidelines are applicable to non-standard methods, standardized methods used outside of its original scope, methods modified to meet specific requirements, and new methods developed by the laboratory.

This article reports the improvement of the speed of sound measurement system developed at Labus/Inmetro. The new setup has more degrees of freedom in the mounting used to align the sample under test. The model to estimate the measurement uncertainty is presented and the obtained results are compared with a standardized method. The validate measurement system will be applied to certify the speed of sound of Encapsulated Tissue Mimicking Material (ETMM) for biotechnology application.

2. Methodology

The test body used in this work was an AISI 304 stainless steel cylinder (Figure 1), machined and polished to a surface roughness finishing better than 0.8 μm (Ra). Its thickness was calibrated using a caliper rule, and the result used as reference value (101.4 mm; u = 0.1 mm; k = 2.02; p = 0.95). Its

diameter is 100 mm, and no calibration is needed for this dimension in the present work. The longitudinal speed of sound was measured in the central region of the test body, using the system described in [1], developed according to the standard ABNT-NBR 15824:2010 [5]. The calibrated speed of sound was defined as reference value ($c = 5724.7$ m·s^{-1}; $u = 2.7$ m·s^{-1}; $k = 1.96$; $p = 0.95$).
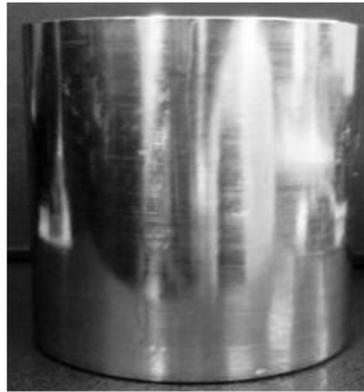
Figure 1. Stainless steel AISI 304
test body.

The new measurement system is composed of two ultrasonic transducers (Tx1 and Tx2), acting as a transmitter or receiver at different stages of the method, both with nominal central frequency of 5 MHz (Model v303, Panametrics, Olympus, MA, USA). The transducers and the test body were mounted on a mechanical system constructed to ensure their fixation and alignment. The transmitter transducer is mounted in a positioning with five degrees of freedom, while the receiver transducer and the test body are mounted on two degrees of freedom positioning system (Figure 2). All measurement system is immersed in a water tank filled with deionized water, and at least 30 min are necessary to achieve the thermal equilibrium before start the measurements. Here, it is important to highlight that the previous system set at Labus/Inmetro had only two degrees of freedom at receiver transduces, while the transmitter transducer and the test body were kept fixed (details in [3]).

An arbitrary function generator (33250A Agilent Technologies, CA, USA) is used to drive the transmitter transducer with a 20-cycles sine burst at 5 MHz, and 20 V peak to peak. The repetition period is defined as 10 μs. The signals acquired by the receiver transducer are digitized using the oscilloscope DSO 5012A (Agilent Technologies, CA, USA) with a sampling frequency of 500 MSa·s^{-1}.
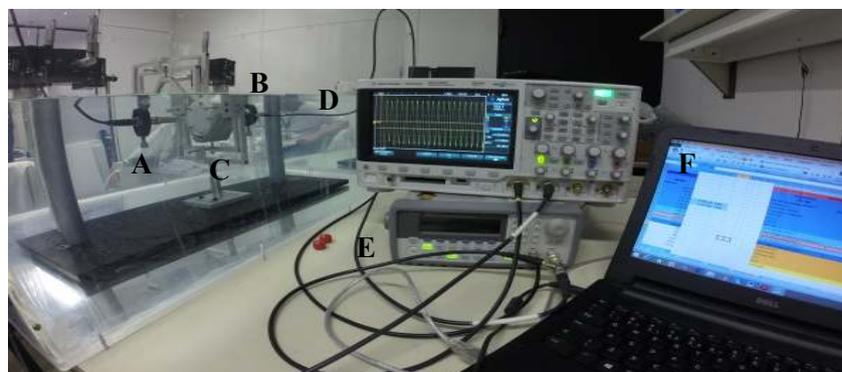

Figure 2. Experimental set-up for acoustic measurement. A,
transmitting transducer with five degrees of freedom;
B, receiver transducer with two degrees of freedom;
C, specimen; D, oscilloscope; E, signal generator; F, computer.

The temperature was monitored throughout the measurements with a thermometer (Thermoscheneider, Baden-Württemberg, Germany). The whole procedure was repeated five times by two distinct operators in intermediate precision condition of measurement.

Different flight times are determined and are called here: t_{ref1} (reflection at the test body face nearest to the transmitter transducer), t_{ref2} (reflection at the test body face far of the transmitter transducer), t_{CP} (transmission between transmitter and receiver transducers with the test body in the acoustic path) and t_w (transmission between transmitter and receiver transducers without the test body).

The longitudinal speed of sound c [m/s] was calculated by (1).

$$c = \frac{x}{t} \qquad (1)$$

where, x [m] is the thickness of the test body in calculated from (2), and t [s] is the time of flight of ultrasound in the test body calculated from (3).

$$x = \left[\left(2t_w - t_{ref1} - t_{ref2} \right) \cdot c_w \right] \qquad (2)$$

$$t = t_{CP} - \frac{\left(t_{ref1} + t_{ref2} \right)}{2} \qquad (3)$$

The ultrasound propagation velocity in water c_w [m/s] is calculated according to (4) [6].

$$c_w = 1404,3 + 4,7T - 0,04T^2 \qquad (4)$$

Where, T [°C] is the temperature in water.

The measurement uncertainty is estimated according to the guide to the expression of uncertainty in measurement [7]. The following sources of uncertainty were considered in measuring the speed of sound, as well the test body thickness: type A evaluation determined as the standard deviation between the five repetitions of the test; type B evaluation of the temperature obtained from the thermometer calibration certificate (0.03ºC); type B evaluation of the ultrasound propagation speed in water (0.018 m·s⁻¹) [6]; type B evaluation of the time base used to determine different times of flight from the oscilloscope calibration certificate (0.06%). The expanded uncertainty was calculated for a coverage probability of 0.95.

In this work, the benchmark is the normalized error (E_n) between the reference values, determined using the standardised measurement method, and the results achieved using the previous measurement system [3] and the improved one presented here. The results are considered satisfactory if $E_n \leq 1$.

3. Results

The results of speed of sound and thickness determined using the measurement system presented here (mobile system) and the previous system described in [3] (fixed system) are presented on Table 1 and Table 2, for operator 1 and 2 respectively.

One can observe that the results of thickness and speed of sound achieved using both systems when compared with the respective reference values presented $E_n \leq 1$. This result suggests that both methods can be considered validate for measuring the speed of sound, as well as the thickness of test bodies.

Table 1. Results of thickness (x) and speed of sound (c) achieved by operator 1 (Op. 1) using fixed and mobile systems.

Op. 1	Fixed System		Mobile System	
	x [m]	c [m·s⁻¹]	x [m]	c [m·s⁻¹]
Average Value	0.10130	5738	0.10130	5730
k	1.97	2.04	1.96	1.96
U	0.00011	13	0.00010	6.6
En	0.7	1	0.7	0.8

Table 2. Results of thickness (x) and speed of sound (c) achieved by operator 2 (Op. 2) using fixed and mobile systems.

Op. 2	Fixed System		Mobile System	
	x [m]	c [m·s⁻¹]	x [m]	c [m·s⁻¹]
Average Value	0.10134	5736	0.10134	5731
k	2.26	2.03	1.96	1.96
U	0.00020	12	0.00010	7.9
En	0.3	0.9	0.7	0.8

However, one can perceive that the speed of sound expanded uncertainties, achieved using the mobile system, are lower than the one obtained with the fixed system, for both operators. This result indicates that increasing the degrees of freedom in the system allowed a better alignment between the two ultrasonic transducers (transmitter and receiver), as well as between them and the test body, directly affecting the reduction of uncertainty.

4. Discussion and Conclusion

In literature, there are references mentioning speed of sound results for different materials [8][9]. However, rarely authors give attention to metrological rigors in their studies, or do not properly report their uncertainty results. Sometimes uncertainty is mistakenly confused with error or standard deviation and, when presented, the validation of measurement method is not detailed, neither it is explained how the uncertainties were calculated.

This work presented the validation of a new measuring system to determine the speed of sound of test bodies. The measuring system was first validated at 5 MHz, and new validation will be carried out considering other frequencies. The presented measuring system will be applied for certifying an Encapsulated Tissue Mimicking Material (ETMM) as a reference material for biotechnological applications.

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