Evaluating of the ultrasonic transducers’ diameter on velocity measurement in nondestructive testing

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Abstract: Nondestructive test (NDT) has been proved to be a valuable support for industry, saving money and time. International standards provide some requirements for transducers’ diameter concerning the area section of the workpiece to be inspected. This paper investigates the relationship between the ultrasonic transducer’s diameter and the area section to be measured, and its impact on the measured longitudinal ultrasonic velocity. Initial results showed a tendency of growth on the ultrasonic velocity with an increase of diameter.

Keywords: NDT; ultrasonic transducer; transducer diameter; uncertainties.

1. Introduction

Knowledge of the physical conditions of materials through non-invasive techniques has always motivated researchers in the development of data processing techniques and protocols to extract useful information through the advantages offered by non-destructive testing (NDT) [1].

Among the peculiarities of the NDT, the ability to collect information beyond the surface of a workpiece without damaging it is highlighted. As these methods provide data indirectly correlated with the elastic constants of the materials, the demands for these studies have grown to better qualify the experimental results.

The velocity of ultrasonic propagation in a medium is a physical quantity directly related to its physical properties [2]. Ultrasonic applications in non-destructive tests use transducers of different diameters (usually between 5.0 mm and 25.0 mm) and frequencies (generally between 0.5 and 10.0 MHz) [3]. The sensors are produced with piezoelectric or ceramic crystals, making it possible to emit and collect acoustic pulses propagating in materials where it is desired to collect information of interest. Time of flight is one of the most important quantities assessed in NDT applications with ultrasound.

This work aims to discuss the relationship between the diameters of the ultrasonic transducer and the section of the material’s surface where the test is performed, investigating the impact on the measured longitudinal ultrasonic velocities. For this study, transducers with diameters of 12.5 mm and 25.0 mm were selected, with a nominal frequency of 5.0 MHz.
2. Materials and Methods

2.1. Theoretical background

The application of ultrasonic pulses in materials is based on the transfer of mechanical energy through the local vibration of particles. The term "ultrasonic" is generally taken to mean the "frequency" of the wave is higher than the upper limit of human hearing [4], i.e., 20 kHz.

Literature does not present qualitative and quantitative studies reporting the effects on the ultrasonic pulse velocity behavior for different transducer diameters.

In the same way, no research was either found relating minimum thickness dimensions of the surfaces under investigation. The international standard ISO 16831:2012 (E) Non-destructive testing – Ultrasonic testing – Characterization and verification of ultrasonic thickness measuring equipment [5] recommends, in its section 6.3, that transducer’s diameter D should not be higher than one-third of the lowest dimension of the piece investigated.

2.2. Tested specimens

We used ten carbon steel pieces divided into two groups. The first group, denominated A, consisted of five blocks of circular section with a diameter of 7.5 cm and thicknesses: 2.0 mm, 4.5 mm, 7.5 mm, 9.5 mm, and 12.0 mm. The second group, denominated group B was formed by five blocks of square section with 7.5 mm by side and thicknesses: 6.8 mm, 6.9 mm, 7.0 mm, 7.1 mm, and 7.2 mm.

2.3. Ultrasonic measuring system

Measurements were performed using a measurement system consisting of an oscilloscope model DSO-X 2014A (Keysight, Malaysia), a function generator model 33250A (Agilent, Malaysia), two ultrasonic transducers, with 12.5 mm (model A-309S) and 25.0 mm (model A-307S), both from Olympus (USA) and with the nominal center frequency of 5.0 MHz.

The data generated for each acquisition were saved on a computer, where times of flight were assessed using software developed in LabView™ (National Instruments, USA).

2.4. Measurement methods

Tests for detection of the longitudinal ultrasonic propagation velocity were performed using the pulse-echo method [6], with which the time of flight of ultrasonic wave received by transducers allows calculating the time traveled round trip between faces in blocks [7].

The transit times collected in this research were calculated from the first reflection \( t_{R1} \) on the opposite side of each block and its first multiple reflections \( t_{M1} \) and between this and the second multiple \( t_{M2} \) according to figure 1. This type of procedure allows eliminating possible influences in the collection of times caused by differences in the match layers of the transducers.
Rearranging the times of flight:

\[ t_{R1} = 2t_{ML} + 2t_B \]
\[ t_{M1} = 2t_{ML} + 4t_B \]
\[ t_{M2} = 2t_{ML} + 6t_B \]

Note that:

\[ t_{M1} - t_{R1} = t_{M2} - t_{M1} = 2t_B \]

without the effect of \( t_{ML} \)

Figure 1 – Schematic arrangement of the method used.

The measurements were carried out nearby the central position of the blocks. The results refer to the mean value of 15 replicates at each location of the piece. Also, to guaranty repeatability, the transducer was removed from the block and repositioned again between each measurement. Measurements were carried out with the same operator, instruments, and methods.

2.5. Environmental conditions

The tests were performed in a room with a temperature varying between 23º to 25º and humidity about 50% to 75%. All repetitions were done in a single the same day for each experimental condition.

2.6. Velocities assessment

From times of flight, the longitudinal propagation velocities in the carbon steel blocks were calculated by (1).

\[ v = \frac{2 \times l}{t} \]

in which:

- \( v \) is the longitudinal ultrasonic propagation velocity [m s\(^{-1}\)];
- \( l \) is the thickness of the block [m]; and
- \( t \) is the time of flight the ultrasonic wave traveled within the block [s].

The thickness \( l \) of the blocks was obtained from their respective dimensional calibration certificates.
2.7. Calculation of uncertainties

Calculus of expanded uncertainty (U) starts with the determination of combined standard uncertainty and has been reported according to the *Evaluation of measurement data - Guide to the expression of uncertainty in measurement, 1st Ed.*\[8\], as follows:

\[
u^2 = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u_{x_i}^2 
\]

(2)

in which \( u_z \) is the combined standard uncertainty associated with the outcome of the measurement (or calculation) \( f \), and \( u_{x_i} \) the standard uncertainty, associated with each variable parameter \( x_i \) used to express the value of \( f \).

Therefore, since the velocity model depends only on the distance traveled and the time of flight, the velocity model for determining the standard uncertainty combined with the law of uncertainty propagation depends only on two independent variables:

\[
u = f(I, t) 
\]

(3)

After relevant unfolding and simplifications, the expression for the determination of the expanded uncertainty:

\[
u = \sqrt{4I^2 u_t^2 + 4t^2 u_r^2} 
\]

(4)

Lastly, the combined uncertainty can be calculated by:

\[
u = \nu * k 
\]

(5)

Expanded uncertainty of the measurements (\( \nu \)) was calculated from the combined standard uncertainties (\( U_t \) and \( U_r \)) multiplied by the coverage factor \( k = 2.0 \), which corresponds to a coverage probability of 95.45%.

2.8. Calculation of normalized error (\( E_N \))

Normalized error is commonly employed to assess whether two results cannot be considered statistically different. According to ISO / IEC 17043:2010 [9], it is obtained by:

\[
u = \frac{|V_1 - V_2|}{\sqrt{U_{V_1}^2 + U_{V_2}^2}} 
\]

(6)

where \( V_1 \) and \( V_2 \) are the measurands, and \( U_{V_1} \) and \( U_{V_2} \) are their respective expanded uncertainty. The comparative analysis of two results from normalized error indicates that when \( E_N \) is less than unity, there is no statistical difference between them.
3. Results and discussion

Tables 1 and 2 present the results obtained for the ultrasonic propagation velocities for groups A (circular section) and B (square section) of blocks with respective expanded uncertainties. The tables also present the values of $E_N$ between the results from each transducer working on the same frequency (5.0 MHz).

Table 1 – Longitudinal propagation velocity and respective uncertainties for the cylindrical blocks of group A.

| Block thickness (mm) | $v_1$ (m/s) | $U_v$ (m/s) | $v_2$ (m/s) | $U_v$ (m/s) | $E_N$ | $v_1- v_2$ (m/s) |
|----------------------|-------------|-------------|-------------|-------------|-------|-----------------|
| 12.0                 | 5918.8      | 1.3         | 5921.7      | 1.8         | 1.3   | -2.9            |
| 9.5                  | 5919.8      | 1.9         | 5921.3      | 1.8         | 0.6   | -1.5            |
| 7.0                  | 5915.64     | 0.89        | 5922.0      | 2.3         | 2.6   | -6.3            |
| 4.5                  | 5923.1      | 5.1         | 5932.2      | 4.5         | 1.4   | -9.1            |
| 2.0                  | 5916.7      | 8.4         | 5928        | 10          | 0.9   | -11.3           |

Table 2 – Longitudinal propagation velocity and respective uncertainties for the parallelepiped blocks of group B.

| Block thickness (mm) | $v_1$ (m/s) | $U_v$ (m/s) | $v_2$ (m/s) | $U_v$ (m/s) | $E_N$ | $v_1- v_2$ (m/s) |
|----------------------|-------------|-------------|-------------|-------------|-------|-----------------|
| 7.2                  | 5918.7      | 1.5         | 5924.3      | 3.2         | 1.6   | -5.6            |
| 7.1                  | 5918.2      | 2.1         | 5921.3      | 2.7         | 0.9   | -3.1            |
| 7.0                  | 5919.9      | 2.1         | 5920.8      | 2.5         | 0.3   | -0.9            |
| 6.9                  | 5917.8      | 1.9         | 5920.7      | 2.5         | 0.9   | -2.9            |
| 6.8                  | 5916.5      | 1.2         | 5920.1      | 3.0         | 1.1   | -3.6            |
In tables 1 and 2, it is possible to note that the propagation velocity measured increased consistently with the increase of the transducer diameter. However, for some cases the normalized error is less than unity, suggesting no statistical difference between the ultrasonic velocity values. Graphs presented in figures 2 and 3 help to visualize the behavior of the velocities of groups A and B for transducers with a diameter of 12.5 mm (blue bars) and 25.0 mm (red bars), allowing to identify the increasing tendency on the ultrasonic velocity.

This behavior can be attributed to the reduction in the relationship between transducer diameter and section area of blocks where measurements were made. The ratio between the 12.5 mm-transducer diameters and the squared section of 75 mm-side, as well as the 75 mm-block diameter, is 1:6. On the other hand, for the 25.0 mm-diameter transducers, this relationship reduces to 1:3, which is in the limit mentioned in standard ISO 16831:2012 [5].

![Figure 2](image2.png)

Figure 2 – Ultrasonic propagation velocities for groups A (circular section) of blocks with respective expanded uncertainties.

![Figure 3](image3.png)

Figure 3 – Ultrasonic propagation velocities for B (square section) of blocks with respective expanded uncertainties.
4. Conclusions
From the tests performed in this work, it was possible to identify a trend of growth of the ultrasonic longitudinal speed with the increase of the transducer diameter for the two groups of blocks analyzed.

The main responsible for this effect seems to be related to the proximity of the ratio of 1:3 between the diameter of the transducer and the surface area where the assays are performed. This behavior may be associated with possible differential interference at the edges of blocks. Based on the assays performed here, it is believed that the smaller diameter transducer provided more reliable results.

However, as mentioned throughout the discussions, the lack of unanimity in the analysis of the statistical similarity between the data obtained requires new experiments to confirm or not the direct relationship between the increase of velocity and the increase of the diameter of the sensors.

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