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Error analysis of the impulse excitation of vibration measurement of acoustic velocities in steel samples

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Abstract

The knowledge of the acoustic velocities in solid materials is crucial for several nondestructive evaluation techniques such as wall thickness measurement, materials characterization, determination of the location of cracks and inclusions, TOFD, etc. The longitudinal wave velocity is easily measured using ultrasonic pulse-echo technique, while a simple and accurate way to measure the shear wave speed would be a useful addition to the commonly available tools.
In this work we use the impulse excitation of vibration, a very well known technique to determine the elastic constants of solid materials from the measurement of the lowest resonant frequencies excited by an impulse, to determine both longitudinal and transversal sound velocities for steel samples. Significant differences were found when comparing the longitudinal wave velocity with the one determined by a standard pulse-echo technique. Part of the difference was tracked back to the use of analytical formulas for the resonant frequencies, and corrected through the use of accurate numerical simulations. In this paper the systematic analysis of the possible error sources is reported.

Keywords: Impact excitation of vibration; Resonant ultrasound spectroscopy; Elastic constants; Acoustic velocity

1. Introduction

The Impulse excitation of vibration (IEV) is a standard method to determine the dynamic Young and shear moduli for refractory materials. The method is based on measuring the resonant frequencies of the test specimen after exciting the vibration by hitting the sample with a suitable device.

In this work we apply this technique to measure the compressional and shear wave velocities in steel samples. The acoustic velocities obtained by this method using ASTM standard E1876-07 [1] for several sample geometries

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are reported. For the compressional wave velocity a comparison is made with the results obtained using a numerical solution of the linear elastic problem and with the measurements by the standard ultrasonic pulse-echo technique.

2. Technique Background

In order to calculate the dynamic Young modulus of a bar using the measurement of the lowest flexural resonant frequency f_f, we can use the approximate expression ([1], [2] and [3]):

$$E = 0.9465 \frac{m f_f^2}{b} \left(\frac{L}{t}\right)^3 T_1 \tag{1}$$

where L, b, t and m are the length, width, thickness and mass of the bar respectively and T_1 is a correction factor that depends on the thickness-to-length ratio and the Poisson ratio. If the dimensions of the sample are chosen in a way such that $L/t > 20$, the dependence on the Poisson ratio can be neglected.

The dynamic shear modulus can be calculated using the fundamental torsional frequency f_t using expression:

$$G = \frac{4 L m f_t^2}{bt} R \tag{2}$$

where again R is a correction factor that depends only on the dimensions of the sample.

To calculate the compressional c_l and shear wave c_t velocities we can use the very well known relationships:

$$c_l = \sqrt{\frac{4G - E}{\rho(3 - E/G)}} \tag{3}$$

$$c_t = \sqrt{\frac{G}{\rho}} \tag{4}$$

Where $\rho = m/(L.b.t)$ is the material density. If we now define:

$$e = \frac{E}{\rho} = 0.9465 f_f^2 \frac{L^4}{t^2} T_1 \tag{5}$$

$$g = \frac{G}{\rho} = 4 L^2 f_t^2 R \tag{6}$$

Then the acoustic velocities can be expressed as:

$$c_l = \sqrt{\frac{4g - e}{3 - e/g}} \tag{7}$$

$$c_t = \sqrt{g} \tag{8}$$

From equations (7) and (8) is clear that the acoustic velocities only depend on the *e* and *g* (and accordingly, in the error propagation the error in the density does not appear because *e* and *g* can be directly determined from the resonance frequencies).

3. Experimental Set up

The greatest advantage of this experimental setup relies on its simplicity. It only requires a standard microphone connected to the soundcard of a PC (we used a 24 bit 96Khz soundcard but the common 16 bit 44Khz ones can be used too) as long as a suitable choice of the sample dimensions is made.

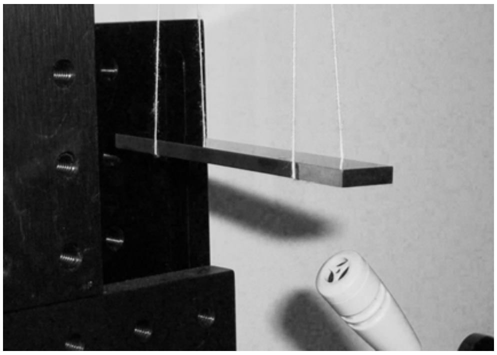

Fig.1 Photo of the experimental setup. The sample is held by thin threads on nodal lines and the signal is recorded using a standard microphone.

In order to satisfy as much as possible the Neumann boundary conditions (free stress on the surface) required by the theoretical model implicit above, the sample was held by thin threads positioned as close as possible to the nodes of each measured resonance mode (figure 1). The measured variations in resonance frequency due to changes in the holding positions of the sample prove to be less than 0.1%.

The sample dimensions were chosen using a theoretical model in a way such that frequency mode overlapping is avoided and that all the desired frequencies fall inside the microphone and soundcard bandwidths. This also helps to univocally identify each measured resonance frequency.

The bars were gently hit using a small exciter (a plastic stick with a small steel sphere collated in one end) in 3 different positions to excite each of the lowest resonant modes.

4. Results

Seventeen samples with different dimensions were cut from the same steel and studied at room temperature. Twelve had nominal dimensions of 100x12x5 mm^3, two 100x30x7 mm^3, two 100x50x8 mm^3 and one 230x50x6 mm^3. The dimensions of the samples and the corresponding resonant frequencies were measured with precision better than 0.1%. Figures 2 and 3 show the compressional and shear wave velocities calculated using ASTM E1876-07 standards.

The variation of the measured velocities is less than 1% for compressional wave velocity and 0.2% for shear wave velocity with the exception of samples 15 and 16 where variations up to 3% and 0.6% respectively can be observed.

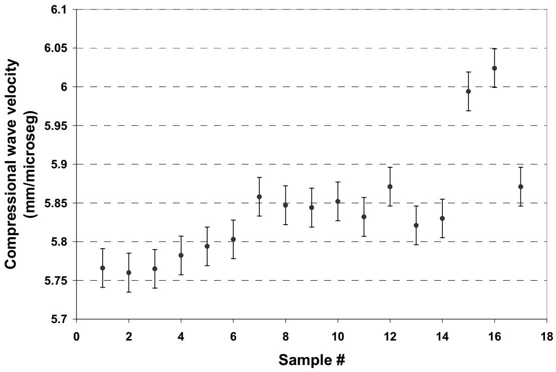

Fig. 2. Measured compressional wave velocity

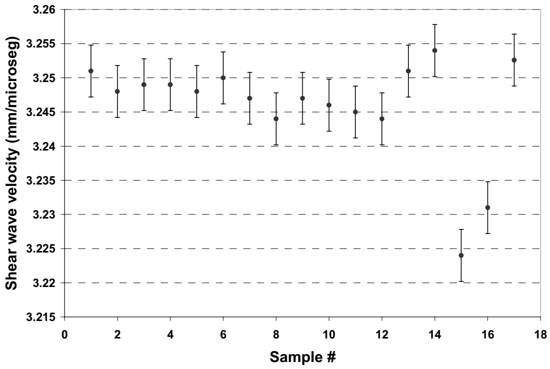

Fig.3 Measured shear wave velocity

To validate the results the compressional wave velocity was measured by the ultrasonic pulse-echo technique using 5 MHz and 15 MHz transducers. The ultrasonic pulse-echo technique is a very simple method for longitudinal wave speed determination, which provides an error smaller than 0.1% as long as a good measurement of the transversal dimension of the test samples is performed. Figure 4 presents the compressional wave velocity as determined by the ASTM standard and the pulse-echo technique.

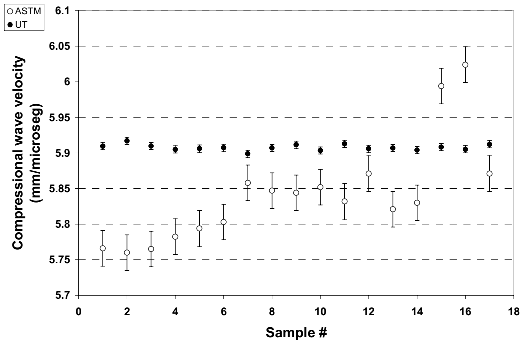

Fig.4 Measured compressional wave velocity by impulse excitation of vibration using ASTM standards (white circles) and by ultrasonic pulse-echo technique (black circles).

It is important to observe that the differences between the velocities measured by the impulse excitation method are bigger than the estimated experimental errors (computed by error propagation from the uncertainties of the basic measured variables), implying that other variables in the experimental conditions such as anisotropy, dispersion, temperature dependence, magnetization state, may be playing a role and that analytical expressions (1 - 2) may not be adequate for the level of precision required and a more detailed model should be developed.

4.1. Numerical Model

In order to analyze the precision of the model a numerical solution of the linear elasticity equations was implemented using a Galerkin approximation [4].

Using this method, solutions with accuracy better than 0.01% were achieved and used to obtain an independent estimate of the acoustic velocities. The calculated velocities plotted in figure 5 show that the numerical model improves the results, especially for samples 14 and 15 (of dimensions 100x50x8 mm^3), but it doesn't explain the differences with the ultrasonic measurements.

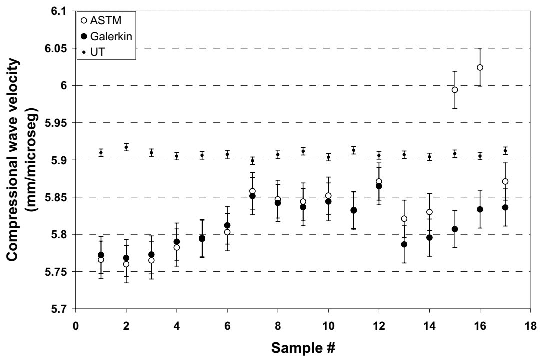

Fig.5 Measured compressional wave velocity by impulse excitation of vibration using ASTM standards (white circles), using the Galerkin approximation (black circles), and by ultrasonic pulse-echo technique (black dots).

4.2. Experimental Conditions

4.2.1. Temperature dependence

The compressional wave velocity was measured for sample 1 for different temperatures to evaluate the effect of temperature changes between experiments. In figure 6 the dependence of the compressional wave velocity with the temperature can be observed.

The linear fit has a slope of $-6.42.10^{-4}\,\mathrm{mm} / \mu\mathrm{s}\ ^{\circ}\mathrm{C}$. The difference of temperature between air and water (IEV and ultrasonic measurement) was not greater than 5°C so the contributions of temperature changes can be neglected in the analysis.

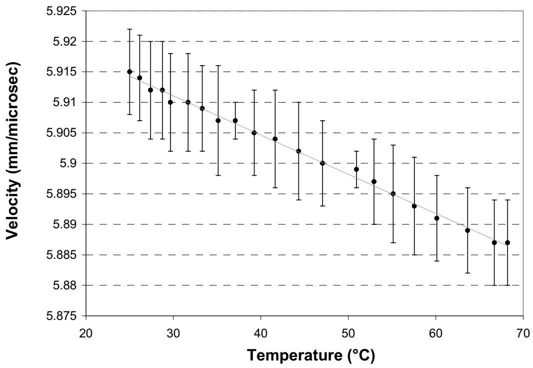

Fig.6 Temperature dependence of the compressional wave velocity.

4.2.2. Dispersion

The difference in the compressional wave measurement between the IEV method and the ultrasonic technique could be explained if there was some dispersion in the material. The frequencies of the normal modes measured with the IEV method are smaller than 10 kHz while the frequencies of the pulse emitted with the ultrasonic technique are bigger than 1MHz. If the acoustic velocities have some dependence with the frequency, these differences can be explained.

The compressional wave velocity was measured using the ultrasonic pulse-echo technique for frequencies from 1MHz to 20 MHz. Up to our experimental error we found no dispersion effect in the results. For lower frequencies were not able to perform measurements of frequency dependence of the acoustic waves but according to the literature [5] the dispersion can be neglected in steel. Nevertheless, future planned experiments will allow us to measure in the 50 KHz - 200KHz range to corroborate this assertion.

4.2.3. Anisotropy

To study the anisotropy of the material a cubic sample was accurately machined and the compressional wave velocity was measured in the three directions of the cube. No differences among the results were observed. This observation does not completely rule out the eventual influence of anisotropy, but suggests it could not be the relevant factor.

4.2.4. Magnetization

To study the influence of remanent magnetization on the normal modes frequency, samples 1, 7 and 13 were magnetized to saturation in different directions and demagnetized using an electromagnet. The resonance frequencies were recorded using the IEV method in each magnetization condition. The maximum change in frequency was less than 0.2%.

5. Conclusion

The impulse excitation of vibration technique is used to determine the acoustic wave velocities in steel samples. The results for the compressional wave velocity were compared to those obtained by the ultrasonic pulse-echo technique, showing differences up to 2%. A careful numerical computation of the resonance frequencies serves to eliminate the influence of the adequacy of the analytical formulas for different sample sizes, but does not explain the difference between IEV and pulse-echo results. The influence of several experimental conditions on the results was investigated, including temperature, residual magnetization and a preliminary analysis of anisotropy, without providing an explanation of the observed differences. Further research should be performed to fully understand this technique.

Future experiments that can measure the resonant frequencies in the 50-200 KHz range may help confirm the presence of some degree of velocity dispersion that might explain the difference observed between the data obtained at 10 KHz with the IEV and pulse echo at 10 MHz. Also, anisotropy effects should be thoroughly investigated by independent measurements, and their effect on the obtained velocities carefully quantified.

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