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REPEATABILITY AND ACCURACY ANALYSIS OF THE IMPACT EXCITATION OF VIBRATION TECHNIQUE FOR PRISMATIC STEEL SAMPLES

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Abstract

The accuracy of the impulse excitation of vibration technique, as described for instance in ASTM norms E1876-07, C1548–02 is analyzed by contrasting the results of experiments using several samples of different dimensions with independent measurements by the pulse-echo technique. The elastic moduli are recovered from the measured resonance frequencies either using the analytical expressions available or the results of highly accurate numerical solutions of the linear elasticity equations. On the basis of these measurements and analysis, we discuss the requirements to achieve accuracy better than 1%.

Resumen

En el presente trabajo se analiza la precisión de la técnica de impacto-eco descripta por ejemplo, en las normas ASTM E1876-07, C1548–02, comparando los resultados experimentales de varias muestras con mediciones independientes utilizando la técnica de pulso-eco. Los módulos elásticos se calculan a partir de la medición de las frecuencias de resonancia y utilizando tanto las expresiones analíticas disponibles como también resultados de simulaciones numéricas de gran precisión de las ecuaciones de elasticidad. A partir de estas mediciones y análisis, se discute los requerimientos para obtener una precisión mejor al 1% en los resultados.

1 Introduction

The impulse excitation of vibration (IEV) is a well known available tool to determine the dynamic Young and shear moduli of elastic materials that is frequently used for materials such as steel, concrete, glass, ceramic or graphite. In this work we discuss the implementation and accuracy of this technique using a very simple experimental setup applied to the determination of the acoustic velocities in steel samples by measuring their resonant frequencies. Once these frequencies are obtained they are used with either an analytical model (ASTM E1876-07) or the numerical solutions of the linear elastic problem (Etcheverry & Sánchez, 2008) to calculate the elastic moduli (or the shear and compressional wave velocities). Finally the obtained compressional wave velocities are compared against those measured by standard ultrasonic techniques.

1.1 Background

If a bar of length L, thickness t, width b and mass m is vibrating at its lowest flexural frequency f_f, the dynamic Young modulus E can be determined by the relation:

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

where T_1 is a correction factor that depends on the width-to-length and the Poisson ratios.

On the other hand, if the same bar is vibrating at its lowest torsional frequency f_t the dynamic shear modulus G can be calculated by:

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

As we are interested in calculating the compressional and shear wave velocities (c_l and c_t) we can use the relations:

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

In order to avoid measuring the density we can divide equations (1) and (2) by the sample density $\rho = m/(L.b.t)$ to get:

$$e = \frac{E}{\rho} = 0.9465 f_f^2 \frac{L^4}{t^2} T_1, \qquad g = \frac{G}{\rho} = 4L^2 f_t^2 R \tag{5}$$

Using this simplification, equations (3) get the simpler form:

$$c_l = \sqrt{\frac{4g - e}{3 - e/g}}, \quad c_t = \sqrt{g} \tag{6}$$

From expressions (6) it is now clear that the acoustic velocities do not depend on the density of the sample.

2 Experimental Setup

The greatest advantage of this experimental setup relies on its simplicity. It only requires a standard inexpensive 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.

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. To quantify the frequency shift induced by this way of holding the sample, the positions where the test specimen was held were moved all along the sample showing a difference in the measured frequencies smaller than 0.1%.

Using standard values of the acoustic velocities in steel with the theoretical model the sample dimensions were chosen in such a way as to avoid frequency overlapping and to ensure that all the desired frequencies were inside the microphone and soundcard bandwidths. This also helps to univocally identify each measured resonant 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 resonant mode.

3 Results

Seventeen samples of the same steel but different size were studied at room temperature. The first twelve had nominal dimensions of 100x12x5 mm^3, then two were of 100x30x7 mm^3, two more of 100x50x8 mm^3 and one of 230x50x6 mm^3. The dimensions of the samples and the corresponding resonant frequencies were measured with 0.1% precision. In figures 1 and 2 the compressional and shear wave velocities calculated using ASTM E1876-07 standards can be observed.

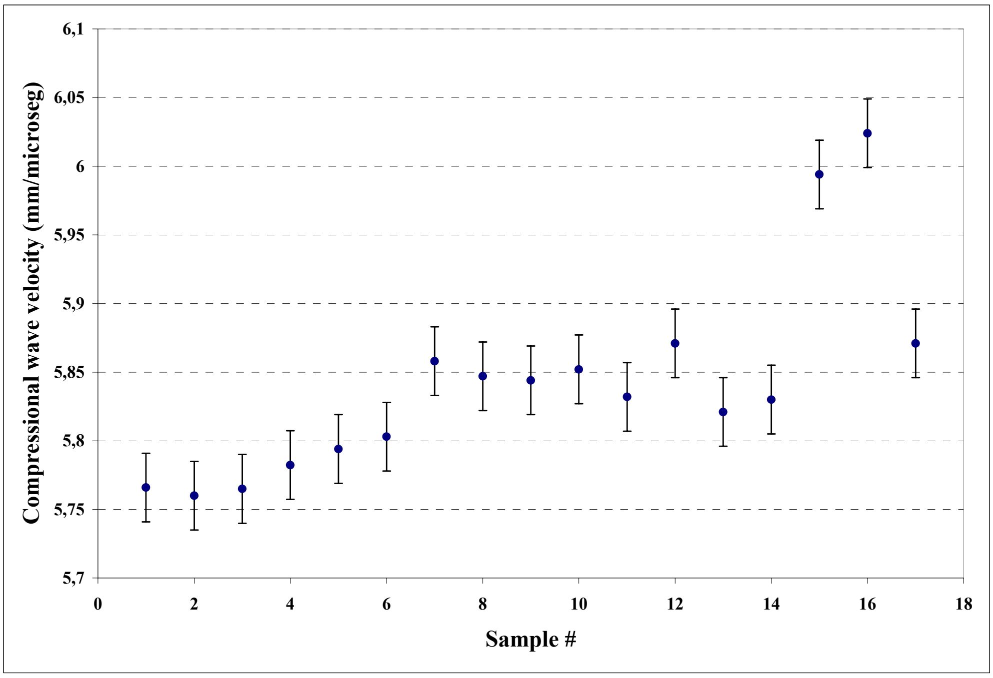

Figure 1: Measured compressional wave velocity

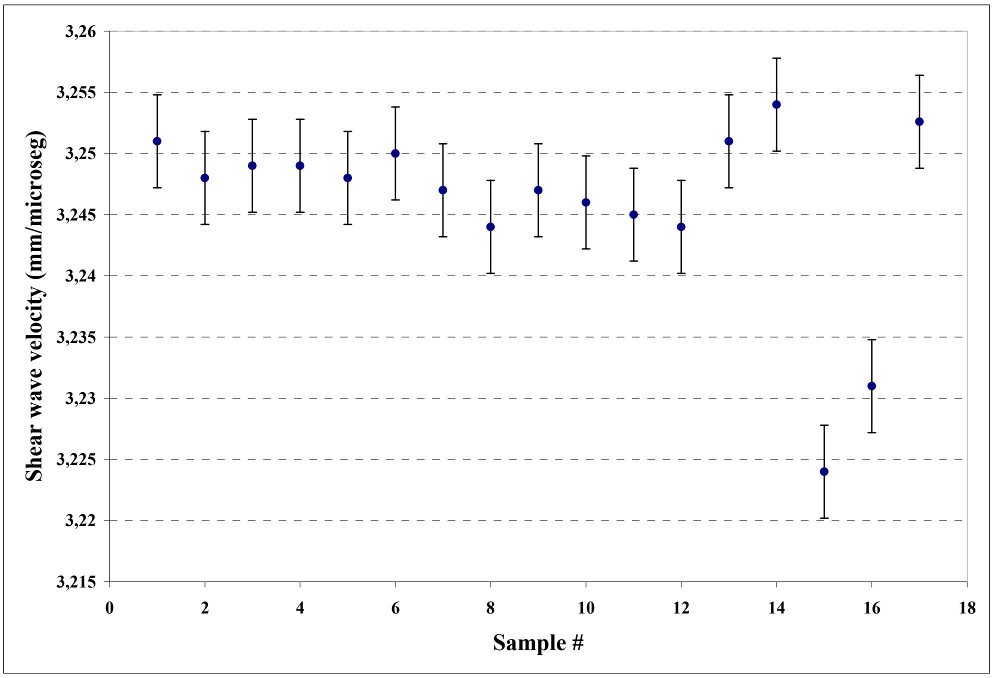

Figure 2: Measured shear wave velocity

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% can be observed for each wave velocity.

The differences for these samples cannot be explained by our experimental error but may be assigned to an intrinsic error of the method instead.

In order to analyze the precision of the method a numerical solution of the linear elasticity equations was implemented using a Galerkin method that will be fully reported elsewhere (Etcheverry & Sánchez, 2008). Using this method, solutions with accuracy better than 0.01% were obtained. Coupling this high precision method with the measured frequencies, an independent estimate of the acoustic velocities was obtained. The results are shown in figure 3, and present a variation of the compressional and shear wave velocities among samples smaller than 1% and 0.2%, respectively.

To validate and compare these methods 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 (3) presents the compressional wave velocity as determined by the ASTM norm, the results of the highly accurate numerical method and the pulse-echo technique. It is important to observe that the differences between the velocities measured by the impulse excitation method (either using the ASTM standards or our numerical solution) are bigger than the estimated experimental errors (computed by error propagation from the uncertainties of the basic measured variables). This implies that if accuracy better than 1% in the compressional velocity is required other variables in the experimental conditions such as anisotropy, dispersion, temperature dependence, magnetization state, etc., shall be included in the analysis.

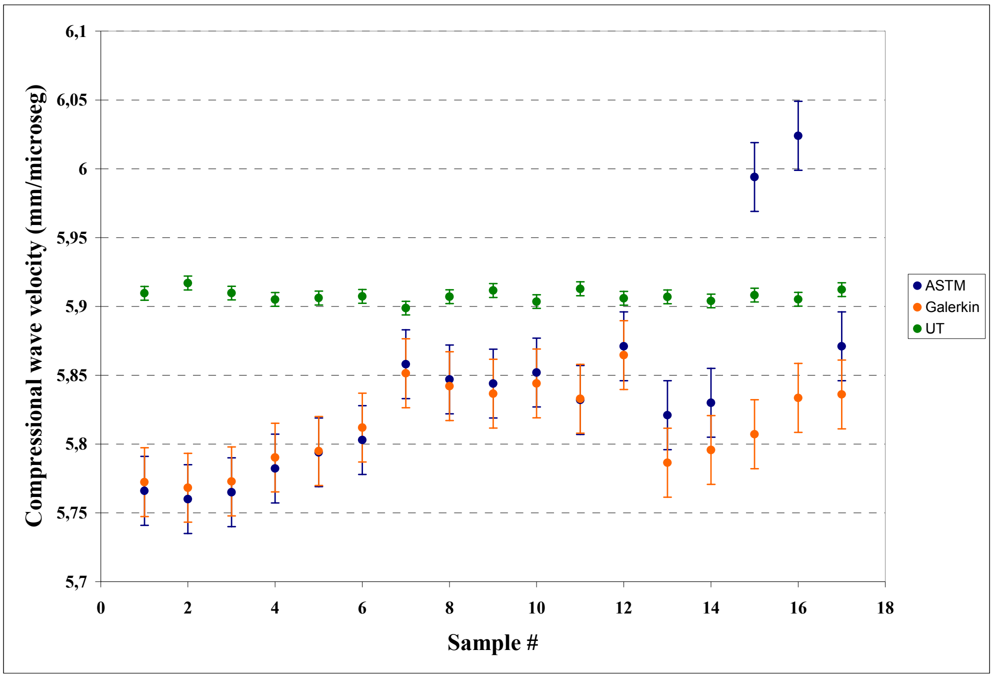

Figure 3: Measured compressional wave velocity by impulse excitation of vibration using ASTM standards (blue), using the Galerkin method (orange) and by ultrasonic pulse-echo technique (green)

4 Conclusions

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 of up to 2%. The developed numerical approximation method improves some spurious results obtained from application of the ASTM standards, but still does not fully explain these discrepancies, which prompt for further investigation on the experimental conditions.

References

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