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Application of acoustic methods for a non-destructive evaluation of the elastic properties of several typologies of materials

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ABSTRACT

In solid phase materials, differently from what happens in the fluid phase, elastic waves propagate both through longitudinal and transverse waves. From the speed of propagation of longitudinal and transverse waves, it is possible to evaluate important elastic properties of the solids under study, namely the Young's modulus, the Poisson's coefficient, the bulk modulus and the shear modulus. This work suggests an accurate method for measuring wave propagation speeds in homogeneous and non-homogeneous materials with the purpose to evaluate their mechanical properties and the associated uncertainty.

First of all, to assess the performance of the proposed methodology, based on the "pulse-echo" technique, in terms of accuracy and precision, measurements of wave propagation speeds have been carried out, in atmospheric conditions, in well-known homogeneous and isotropic materials, such as copper, aluminum, stainless steel and also polymethyl methacrylate (Plexiglas®), Teflon® and optical glass BK7. These results were compared with the values reported in literature (if present), showing how published speed of sound data are very disperse and not so reliable owing to the lack of a precise uncertainty evaluation and of the temperature value associated to the measurement. Then, the same experimental apparatus was used for measuring speed of sound as a function of temperature (from 274.15 to 313.15 K) for 304 stainless steel and oxygen free copper, showing a good accuracy of the results also for temperature conditions far from ambient. Finally, the same procedure was applied to a non-homogeneous solid, obtaining some very preliminary results in typical mediterranean building material, as Carrara marble.

1. Introduction

Different types of elastic waves can propagate in solids. Besides longitudinal waves, also transverse, torsional, Rayleigh and flexional waves are present. All these waves are characterized by a different particles movement with respect to their propagation direction.

Since the propagation speed of waves depends on the elastic properties of the sample which they go through, the measurement of speed of sound in solids can be used to determine their elastic constants and thermodynamic properties, as described in detail in Ref. [1].

In particular, once the speed of longitudinal and transverse waves is known, it is possible to determine, with high accuracy, Young's modulus E, shear modulus G, bulk modulus K and Poisson's ratio ν of the sample.

The earliest methods used to measure the elastic modules of solids were static tensile, compressive and torsional tests, but since the 1950s, these ones have been largely supplanted by dynamical methods [2–4].

Elastic properties of solids (but also of liquids and gases), based on experimental values of sound velocity and density in a wide range of state parameters, have provided a rich database upon which to build physical models of matter. This aspect contributed to increase the interest of different research fields, such as civil engineering, medical industry and regenerative medicine in the investigation of elastic properties of materials.

Very accurate determination of the elastic properties can be useful also for some *state-of-art* metrological experiments. For example, there is currently a great interest in the international metrological community for new accurate determinations of the Boltzmann constant k_B, with the prospect of a new definition of the unit of thermodynamic temperature, the kelvin.

One of the most accurate ways to access the value of the Boltzmann constant is from measurements of the velocity of the sound in a noble gas. In one of the last and most relevant publication on this topic [5], the experiment was performed in a closed quasi-spherical acoustic and electromagnetic cavity. To improve the accuracy of acoustic frequency measurements, the understanding

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of coupling effects between the gas and the shell containing the fluid may reveal fundamental. For this reason, the Laboratoire Commun de Métrologie LNE-Cnam requested the measurement of the elastic properties of the copper used to build the ellipsoidal resonator assembled from two copper hemispheres (Cu-ETP copper, ISO norm), named BCU3, which was utilized for the determination of the Boltzmann constant, k_B.

Since it is particularly difficult to find accurate values of elastic properties of solids and often the archived tables report materials data [6–8] without a declared uncertainty budget, in this work the authors propose an accurate method of measurement of waves propagation speed in isotropic solids and non-homogeneous materials, which allows to evaluate the mechanical properties of several material typologies and their associated uncertainty values.

2. Theoretical base of the measurement

Depending on the direction of wave propagation, waves in solids can be distinguished in torsional waves, surface waves, flexional waves and, of particular interest for this work, longitudinal and transverse waves.

It is well known that, in an isotropic boundless body, a plain elastic wave can be described by the d'Alembert equation [9]:

$$\nabla^2 u = \frac{1}{w^2}\frac{\partial^2 u}{\partial t^2}, \tag{1}$$

where u is the solid particle displacement caused by the wave. As the derivatives with respect to y and z are null, the following equations [9]:

$$\frac{\partial^2 u_x}{\partial x^2} = \frac{1}{w_l^2}\frac{\partial^2 u_x}{\partial t^2}, \tag{2}$$

$$\frac{\partial^2 u_y}{\partial x^2} = \frac{1}{w_t^2}\frac{\partial^2 u_y}{\partial t^2}, \tag{3}$$

for longitudinal and transverse waves can be obtained, where w_l and w_t are longitudinal and transverse speed of sounds respectively.

Since the wave propagation phenomenon strongly depends on the intrinsic capability of a solid to get deformed along different axes after an excitation, w_l and w_t can be linked to the elastic properties of the body according to the following equations [9]:

$$w_l = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \tag{4}$$

$$w_t = \sqrt{\frac{E}{2\rho(1+\nu)}}, \tag{5}$$

where ρ is the density, E is the Young's modulus and ν is the Poisson's coefficient.

Considering that ν can assume only values between 0 and 1/2 [9], w_l is always larger than w_t according to:

$$w_l \geqslant \sqrt{2}w_t. \tag{6}$$

Moreover, from Eqs. (4) and (5), it comes out that the elastic properties of solids depend on longitudinal and shear speed of sound according to the following relations [9]:

$$\nu = \frac{1-2\left(\frac{w_t}{w_l}\right)^2}{2-2\left(\frac{w_t}{w_l}\right)^2}, \tag{7}$$

$$E = 2\rho w_t^2(1+\nu), \tag{8}$$

$$G = \frac{E}{2(1+\nu)}, \tag{9}$$

$$K = \frac{E}{3(1-2\nu)}, \tag{10}$$

where G and K are respectively the shear and the bulk modulus.

3. Experimental apparatus

The experimental apparatus, realized at the Thermophysics Laboratory of INRiM, has been designed to allow two different measurement methods:

1. the "pulse-echo" method, chosen fundamentally to measure wave propagation speed in isotropic and homogeneous materials;
2. the "through transmission" technique, chosen for solids with high absorption properties and for non-homogeneous solids.

In order to generate the pulses, which produce longitudinal and transverse elastic waves in the solid, it is necessary to use contact piezoelectric ultrasonic transducers. The transducers are devices that convert a mechanical work into an electrical work or *vice versa* and they can be used both to generate and to detect sound. If a piezoelectric crystal is subjected to a mechanical stress, the resulting deformation produces an electric field within it and positive and negative charges appear on opposite faces [10]. A scheme of a generic contact piezoelectric transducer is shown in Fig. 1.

The "pulse-echo" technique uses only one transducer, working as transmitter and receiver, while in the "through transmission" technique, two transducers are used, one working as transmitter and the other one as receiver.

The samples are placed in contact with the sensible element of the transducers by a thin layer of a proper coupling fluids (e.g. glycerin or silicon oil). The transducers used in this work are Panametrics Video Scan V108 with a diameter of 0.75 in (19.05 mm) for longitudinal waves and V150 with a diameter of 0.5 in (12.7 mm) for transverse waves. Afterwards, the components are assembled on a particular support that guarantees a good coupling between the sample and the transducers and, in the case of "through transmission"method, also a good alignment between the two transducers. Fig. 2 shows a scheme of the support designed and realized at INRiM and used for the "through transmission" technique. The structure is made of an aluminum alloy, the transducer on the bottom is fixed to the base, while the upper one is free to move on two metallic guides with their own spring. The downwards sliding

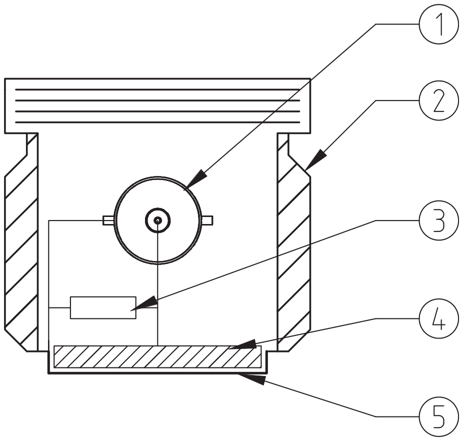

Fig. 1. Scheme of a generic contact piezoelectric transducer. (1) BNC connector; (2) external housing; (3) electrical leads and network; (4) active element; and (5) wear plate.