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NON-DESTRUCTIVE EXAMINATIONS OF NON-METALLIC MATERIALS BY ULTRASONIC METHODS

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Rezumat. *Lucrarea prezintă metode nedistructive de evaluare a materialelor nemetalice: metoda impuls, metode de examinare, măsurarea directă a vitezei de propagare, metoda impuls-ecou, evaluarea acustică etc. Metodele sunt adecvate pentru materiale nemetalice, deoarece acestea au structură neomogenă şi neregulată, coeficienţi de atenuare ridicaţi pentru propagarea undelor ultrasonice în materiale. Prin utilizarea metodelor evaluării nedistructive ultrasonice parametrii principali de material şi caracteristicile de material (coeficienţi de elasticitate, densitatea, viteza de propagare, atenuarea ultrasunetelor etc.) se pot determina. De exemplu, metoda impuls-ecou se potriveşte detecţiei fluxului în structura materialului, localizării golurilor, aspectului spongios, exfolierii, adâncimii deschiderii crăpăturii faţă de suprafaţă, măsurării grosimii etc.*

Abstract. *This paper presents some non-destructive evaluation methods of non-metallic materials: pulse method, examination methods, direct measurement of the propagation velocity, pulse-echo method, acoustic emission evaluation etc. The methods are suitable for non-metallic materials because they have rugged and non-homogeneous structure, high attenuation coefficients for ultrasound propagation waves into materials. Utilizing non-destructive ultrasonic evaluation methods of non-metallic materials it can be determined the main material parameters and material characteristics (elasticity coefficients, density, propagation velocity, ultrasound attenuation etc.). For instance, the pulse-echo method is suitable for flaw detection into material structure, locating voids, honeycombing, delaminating, depth of surface opening cracks, thickness measurement etc.*

Keywords: Non-destructive testing, Non-metallic materials, Ultrasound, Pulse-echo method

1. Introduction

Ultrasonic methods for the establishment of physical-mechanical properties of non-metallic materials are: pulse method, examination methods, and direct measurement of the propagation velocity and pulse-echo method. Utilizing these non-destructive evaluation ultrasonic methods it can be determined the main material parameters and material characteristics (elasticity coefficients, density, propagation velocity, ultrasound attenuation, etc.) of non-metallic materials. These methods are suitable for non-metallic materials because the non-destructive methods for metallic materials cannot be utilized, due to their rugged and non-homogeneous structures and great attenuation coefficients of ultrasound

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propagation through materials. Also, the pulse-echo method is a technique for flaw detection in non-metallic materials based on stress wave propagation. Studies have shown that the pulse-echo method is effective for locating voids, honeycombing, delaminating, and depth of surface opening cracks, and measuring member thickness. By the test method one can determine ultrasonic pulse velocity, propagated in concrete specimen. A device generates low frequency pulses and measures the time taken for pulses to pass between the two transducers placed at the end of the specimen being tested. It meets the testing standard BS1881: Part 203; ASTMC597 [1], [2]. Nowadays, Non-destructive methods (NDT) for materials testing based on propagation of sonic and ultrasonic waves are being increasingly used in testing engineering materials [5].

2. Non-destructive testing methods for non-metallic materials

Ultrasonic methods for the establishment of physical-mechanical properties of non-metallic materials are: pulse method, examination methods, directly measurement of the propagation velocity, resonance method and pulse-echo method.

2.1. Ultrasound pulse method

The ultrasound pulse method correlates compression strength with the longitudinal propagation velocity of ultrasounds.

Considering v_L the longitudinal propagation velocity of ultrasounds, the E_d dynamic elasticity modulus could be calculated by the following relation:

$$E_d = v_L^2 \rho_a \frac{(1+\nu)(1-2\nu)}{1-\nu} \qquad [1]$$

where: ρ_a – apparent density [kg/m^3]; v_L - longitudinal propagation velocity of ultrasounds; ν - Poisson dynamic coefficient (0,2).

2.2. Resonance method

The resonance method is used to determine the dynamic elasticity modulus considering the bending at the resonance frequency. By experimental data correlation concerning E_d we can determine the Poisson coefficient value, ν.

2.3. Pulse-echo method

Figure 1 presents the pulse-echo method for frequency analysis based on the reflection principle, where: P-wave has multiple reflections between the reflecting surfaces. P-wave comes to the tested surface at periodic time intervals, resulting a frequency curve with the wave shape, depending the distance till reflecting surface.

Therefore, the material layer thickness can be determined by *Pulse-echo method*.

The pulse-echo method is a technique for flaw detection in concrete based on stress wave propagation [3, 4]. A transient stress pulse is introduced into a test object by mechanical impact on the surface. The stress pulse propagates into the object along spherical wave-fronts as P- and S-waves. In addition, a surface wave (R-wave) travels along the surface away from the impact point. If the receiver is placed close to the impact point, the displacement waveform is dominated by the displacements caused by P-wave arrivals. The displacement waveform can be used to determine the travel time, from the initiation of the pulse to the arrival of the first P-wave reflection. If the P-wave speed, in the test object is known, the distance to the reflecting interface can be determined.

The P-wave generated by the impact propagates back and forth between the top and bottom surfaces of the plate. Each time the P-wave arrives at the top surface it produces a characteristic displacement. Thus the waveform is periodic, and the period, t, is equal to the travel path, 2T, divided by the P-wave speed (Figure 1).

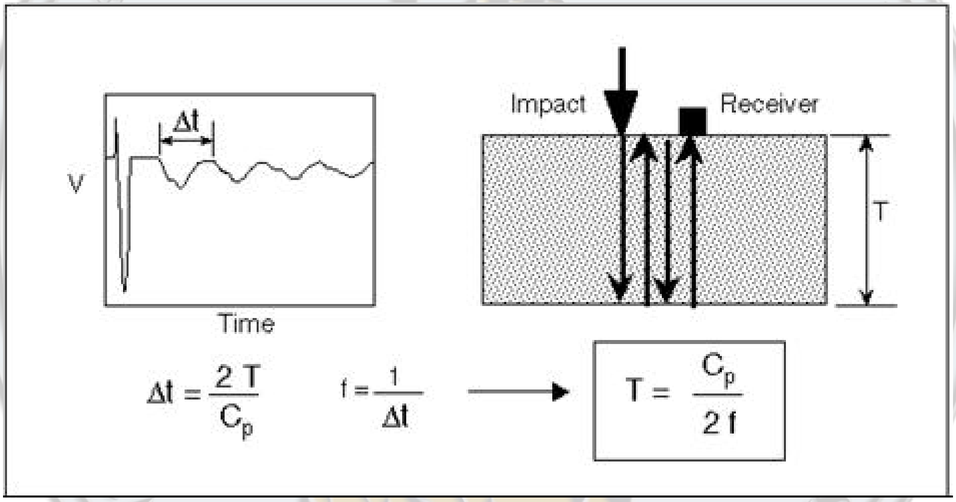

Figure 1. Frequency analysis based on the principle that the P-wave undergoes multiple reflections between the reflecting surfaces

Since frequency is the inverse of the period, the f_p frequency of the characteristic displacement pattern is:

$$f_p = \frac{C_p}{2T} \tag{2}$$

Thus, if the frequency of an experimental waveform can be determined, the thickness of the plate (or distance to a reflecting interface) can be calculated:

$$T = \frac{C_p}{2 f_p} \tag{3}$$

Note that Equation (3) is an approximation that is suitable for most applications in plate-like structures.

The calculus relationships to determine the elasticity coefficients (G transversal and E longitudinal), propagation velocities (v_T transversal and v_L longitudinal) are the following:

$$G = \frac{E}{2(1+\nu)} \tag{4}$$

$$\frac{v_L}{v_T} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{5}$$

$$v_L = \sqrt{\frac{E}{\rho}} \tag{6}$$

$$v_T = \sqrt{\frac{G}{\rho}} \tag{7}$$

$$E = v_L^2 \rho \tag{8}$$

$$G = v_T^2 \rho \tag{9}$$

Weather we consider for $\nu = 0.25$, that it is close to reality for most solids, it is resulting the relation $v_L/v_T = \sqrt{3}$ or $v_T = 0.58\, v_L \approx 0.6\, v_L$, and the result is:

$$\nu = \frac{\left(\frac{v_L}{v_T}\right)^2 - 2}{2\left(\frac{v_L}{v_T}\right)^2 - 2} \tag{10}$$

As important observation is that ν dynamic is different from ν static, where (v_s) ν static is the ratio between the transversal and longitudinal strains under static load.

$$v_S = \frac{0{,}87 + 1{,}12\nu}{1+\nu}\sqrt{\frac{G}{\rho}} \tag{11}$$

2.4. Vibration analysis

Vibration analyses can be carried out on a wide range of structures such as bridges, dams, buildings, etc. The tests are designed to determine the dynamic characteristics of the structures such as natural frequency, modes of vibration and damping. The results are used to gain basic information for the evaluation of earthquake safety, long-term monitoring, short-term condition tests and optimizing of analytic models. The two methods available are ”ambient vibration analysis” and ”forced vibration analysis”.

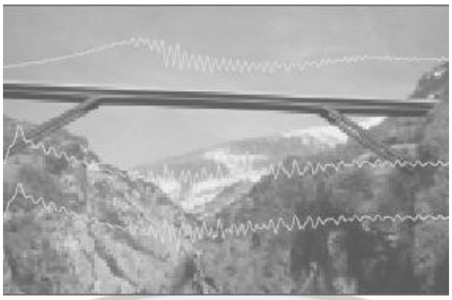

Figure 2. Impulse excitation for large structures

2.5. Acoustic emission analysis

Acoustic emission analysis uses sensors mounted on the surface of parts or structures to record elastic waves caused inside by microscopic processes such as, e.g., crack growth. In principle, the analysis allows a qualitative and, under certain conditions, quantitative assessment of the integrity of the part or structure. Acoustic emission analysis is also suited for other industrial applications, e.g., process monitoring.

3. Model of transducer

The active element of transducer is a piezoceramic disc. Emitter transducer converts the electrical energy into mechanical vibration energy respectively the sensor converts the vibrating energy into an electrical energy.

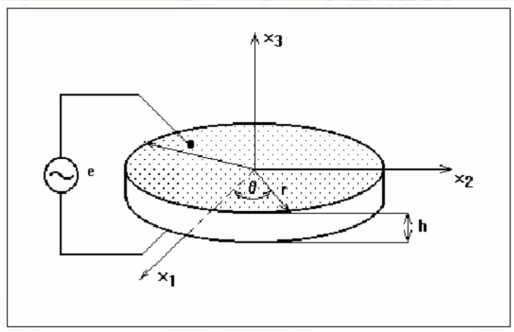

Figure 3. Piezoceramic disc

The theoretical study of the resonance spectrum of PZT discs and plates is rather presented in literature from 1973 [5]. However, there are also several new attempts of theoretical description of these spectra, as those accomplished in frame of the works [5] and [6].

The vibration movement of the piezoelectric element is described by the differential equation of the radial vibration disc, in ([5], [6], and [8]) as follows:

$$c_{11}^{p}\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}-\frac{u_r}{r^2}=\rho\frac{\partial^2 u_r}{\partial t^2} \quad (12)$$

where ρ is density, $\mathbf{u_r}$ is the radial displacement component, and $\mathbf{c_{11}^p}$ is described by the relationship:

$$c_{11}^{p} = \frac{s_{11}^{E}}{\left(s_{11}^{E}\right)^{2} - \left(s_{12}^{E}\right)^{2}} \qquad (13)$$

where: s_{ij}^{E}, i and j = 1 or 2 are the PZT compliance coefficients when electrical field *E* is constant.

Consequently, the vibratory equation solution is:

$$u_r = A \cdot J_1\left(\frac{\omega r}{v^p}\right) e^{j\omega t} \qquad (14)$$

where: ω is the applied field frequency, J_1 - Bessel function by first rang and first case, and

$$v^{p} = \sqrt{\frac{c_{11}^{p}}{\rho}} \qquad (15)$$

Electrical admittance Y_e is:

$$Y_e = \frac{j\omega \varepsilon_{33}^{p} \pi a^2}{h} \cdot \left[\frac{2\left(k^p\right)^2}{1 - \sigma_p - \overline{J_1}} - 1\right] \qquad (16)$$

and $\overline{J_1}$ is defined by the relationship:

$$\overline{J_1}(z) = z \cdot \frac{J_0(z)}{J_1(z)} \qquad (17)$$

where: J_0 is the Bessel function by first rang and zero case, and $\boldsymbol{\sigma_p}$ the planar Poisson rapport:

$$\sigma_p = -\frac{s_{12}^{E}}{s_{11}^{E}} \qquad (18)$$

The k^p coefficient is the planar coupling piezoelectric coefficient for thin discs and it has the relationship:

$$\left(k^p\right)^2 = \frac{\left(e_{31}^{p}\right)^2}{c_{11}^{p} e_{33}^{p}} \qquad (19)$$

where: e_{31}^{p} and e_{33}^{p} are the PZT piezoelectric coefficients.

The relation between k^p coefficient and the usual k_p PZT coupling coefficient is the following:

$$\left(k^p\right)^2 = \frac{1+\sigma_p}{2} \cdot \frac{k_p^2}{1-k_p^2} \tag{20}$$

and k_p is related by k_{31} relation:

$$k_p^2 = \frac{2k_{31}^2}{1-\sigma_p} \tag{21}$$

As result of the above relations combination it can be obtain:

$$Y_e = j\omega\varepsilon_{33}^p \frac{\pi a^2}{h}\left(1-k_p^2\right)\cdot\left(\frac{\overline{J}_1 - 1 + \dfrac{\sigma_p + k_p^2}{1-k_p^2}}{\overline{J}_1 - 1 + \sigma_p}\right) \tag{22}$$

The resonance frequencies are the solutions of the transcendental equation (16):

$$\overline{J}_1\left(\frac{\omega a}{v_p}\right) = 1 - \sigma_p \tag{23}$$

and the antiresonance frequencies ($Y_e = 0$) are the solutions of the transcendental equation:

$$\overline{J}_1\left(\frac{\omega a}{v_p}\right) = 1 - \sigma_p - 2\left(k^p\right)^2 \tag{24}$$

4. Discussions

These methods are suitable for non-metallic materials because they have rugged and non-homogeneous structure, high attenuation coefficients for ultrasound propagation waves into materials. Utilizing non-destructive ultrasonic evaluation methods of non-metallic materials it can be determined the main material parameters and material characteristics (elasticity coefficients, density, propagation velocity, ultrasound attenuation, etc.).

The pulse-echo method is suitable for flaw detection into material structure, locating voids, honeycombing, delaminating, depth of surface opening cracks, thickness measurement, etc. The model of piezoceramic disc is used to modeling the transducer (emitter or sensor).

Conclusions

Signal graphic representation analysis determines the propagation time and attenuation coefficients of pulses propagated into material. Also, could be the signal processing, in order to determine the propagation velocity into material.

As result, this pulse-echo method is suitable for non-metallic materials with rugged and non-homogeneous structures, such as the asphalt layer. Also, it is a non-destructive method at low frequencies, proper to construction materials with high attenuation coefficients of ultrasound signals. The ultrasonic pulse wave analysis has the ability of being a quick and simple test with the added bonus of being a true non-destructive test, appropriate as quality control and assurance in road constructions and can yield certain benefits, such as the road thickness measurement [9], [10].

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