Numerical modelling of the impact-echo method for materials characterisation

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Abstract

The impact-echo method uses stress waves that propagate in media to detect internal flaws in materials and delaminations between layers of different materials. It can be used in certain heterogeneous media (concrete, asphalt) in which ultrasonic methods do not yield good results. This work evaluates, with finite elements simulation, the influence of several parameters that affect the results of the test: size of impact region, time of impact, border effects, time of recording or position of the transducer.

This study investigates how wave propagation in a concrete plate is affected by the interferences with waves generated when the original wave rebounds from the borders of a plate. This effect is shown graphically and the visual information thus obtained can be used to avoid the aforesaid problem changing the recording time. The influence of the positioning of the transducer has been investigated in order to optimise this variable. The same questions have been addressed for concrete slabs with asphalt overlays.

Lastly, the influence of the size of the impact region on the accuracy of the detection of cracks in concrete plates and delaminations in the asphalt-concrete interface has been investigated. The different ways in which the wave propagates are shown graphically for several experimental conditions, and are related to the size of the impact region.

It has been concluded that detection of cracks can be achieved with the impact-echo method but the results depend on different variables such as the position and size of the crack, the size of impact region, the location of transducer and the time of recording.
1 Introduction

The impact-echo method uses stress waves, generated by elastic impact with a short duration, that propagate in media to determine thickness or detect internal flaws in materials and delaminations between layers of different materials. If used correctly it can save millions of dollars in repair and retrofit costs. This method can be used in heterogeneous media (concrete, asphalt) instead of ultrasonic methods because it avoids the problem of developing a transducer which generates low-frequency and short duration pulses with enough energy to penetrate concrete (Sansalone [1]).

A short duration mechanical impact, for example by a small steel sphere, generates low-frequency waves that propagate into the structure and are reflected by the external surfaces or by flaws. All the displacements versus time are recorded in a transducer located on the impact surface and are transformed to the frequency domain. Multiple reflections are identified in the spectrum and used to evaluate the structure.

However, experience has shown that knowledge of the structure is very important to obtain successful results. Numerical studies provide an indispensable guide for the interpretation of experimental results and the understanding of the parameters that affect the results of the test. This paper studies, with finite elements simulation, the influence of several variables: size of impact region, time of impact, border effects and recording parameters (recording time and position of the transducer).

2 Modelling elements

The variation with time of impact force, generated by the elastic impact of a sphere on a solid, can be represented by a half sine curve. The duration of impacts (or contact time, $t_c$) usually ranges from 15 to 100 $\mu$s. The distribution of amplitudes and frequencies produced by the impact can be obtained by the Fourier transform of the half sine curve. Experience shows that above $1.25/t_c$, approximately, the amplitudes of stress waves are not useful for the test (Sansalone & Streett [2]). For modelling purposes, this paper makes use not only of the half sine curve but also of a rectangular pulse with the same duration, which is easier to use in the simulations. The Fourier transform of such a pulse indicates that the working range extends to $0.8/t_c$. The results of the modelling process, however, remain unchanged with both approaches.

The impact is simulated by applying a pressure load over several elements on the material surface.

Sample time, $\Delta t_c$, is determined by Nyquist frequency:

$$\Delta t_c = \frac{1}{2f_{\text{max}}}.$$  (1)
The maximum frequency, \( f_{\text{max}} \), depends on how the wave is reflected by flaws or surfaces in the material. For a wave propagating at \( c_p \) through the material and being reflected at a distance \( d \) from the surface, the theoretical arrival frequency at the surface is

\[
f_t = \frac{c_p}{2d}.
\]  

(2)

In practice, however, the frequency is given by \( f_p = \beta f_t \), where \( \beta \) is a geometry-dependent coefficient. In normal applications, frequencies do not exceed 80 kHz and therefore intervals below 6 \( \mu \)s are not necessary. However, for the sake of accuracy, sampling intervals that provide several samples per cycle are recommended.

Modelling has been performed with the aid of Ansys®, a finite-elements software. Grid spacing has to be small enough as to observe the effects of wave propagation. Although Ansys® recommends a minimum of 20 elements per wavelength in the direction of propagation, our results suggest that 10 elements are sufficient. The shortest wavelength can be calculated from the maximum frequency, \( f_{\text{max}} \), and the P-wave speed, \( c_p \), as \( \lambda_{\text{min}} = c_p / f_{\text{max}} \), whereby the grid spacing is established.

The frequency resolution is

\[
\Delta f = \frac{1}{n \Delta t},
\]  

(3)

where \( n \) is the number of samples.

All plates used in the simulations have axial symmetry, which can be simulated with axisymmetric 2D elements, thereby reducing the computational time. Young’s modulus of elasticity of the simulated concrete is \( E=27.9 \) GPa, its Poisson’s ratio is \( \nu=0.2 \) and its mass density 2280 kg/m\(^3\). The P-wave speed is, then, \( c_p=3687 \) m/s. The simulated asphalt has a mass density of 2400 kg/m\(^3\), a Young’s modulus of \( E=15 \) GPa, and a Poisson’s ratio of \( \nu=0.2 \), whereby \( c_p=2635 \) m/s.

### 3 Influence of recording time

Two concrete plates of 4 m radius have been used to assess the dependence of the method’s efficiency on recording time. The thickness of the plates is 40 and 20 cm, respectively. The expected frequencies are, respectively, 4607 Hz and 9114 Hz. The impact’s contact time has been modelled with a 25 \( \mu \)s rectangular pulse in all simulations, which enables us to use a constant sampling time within each one of them. The working range, with this contact time, extends to 32 kHz, which contains the expected frequencies. The impact region is 10 cm radius.
Each simulation is performed with a different sampling time, ranging from 2 to 25 μs. For 25 μs, the corresponding Nyquist frequency is 20 kHz, which is high enough to record those frequencies of interest, and allows to extend the recording time without increasing the number of sampled points. For the different simulations, no significant differences in the recorded spectra were detected. However, the spectra may change with varying recording times. Two different recording times of 4×10⁻³ and 10⁻² s were tested. Figure 1a shows the absence of interferences between P-wave reflections and lateral reflections in a 0.4 m-thick plate, even at 10⁻² s. For both recording times, the resulting frequency is 4300 Hz (fig. 1b). From this, a P coefficient of 0.93 is calculated.

In a 0.2 m-thick plate and beyond 2.66×10⁻³ s, however, (fig. 2a) there are interferences between P-waves and the Rayleigh-waves reflected from the lateral bound. As a consequence, the spectrum does not show a distinct resulting frequency. If we use a recording time of approximately 3×10⁻³ s (fig. 2b), this problem is avoided. It can be shown experimentally that these interferences are most intense when the transducer is near the impact region.

Figure 1: 0.4 m-thick plate. a) Wave propagation. b) Spectrum.

Figure 2: 0.2 m-thick plate. a) Waveform. b) Spectrum.
4 Response of layered structures

A plate made up of two layers is considered. The top layer has a thickness $d_1$, mass density $\rho_1$ and P-wave speed $c_{p1}$. The bottom layer has, respectively, $d_2$, $\rho_2$ and $c_{p2}$. Their acoustic impedances are calculated by $z_i=\rho_i c_{pi}$. The waveform is more complex than for a simple plate and multiple frequencies of P-wave reflections can appear, depending on the values of the reflection coefficient $C_r$ and the transmission coefficient $C_t$ at the interface (Achenbach [3]). A whole study about what frequencies can and cannot appear can be found in Sansalone & Carino [4].

The case considered in this study is $z_1<z_2$ (as in a concrete slab with asphalt overlay). The theoretical frequency of the $P$-waves reflected between the top surface and the interface is given by

$$f_1 = \frac{c_{p1}}{4d_1}$$

The theoretical frequency (a coefficient $\beta$ can appear multiplying $c_{p1}$) of the $P$-waves reflected between top and bottom surfaces is given by

$$f_c = \frac{1}{\frac{2d_1}{c_{p1}} + \frac{2d_2}{c_{p2}}}$$

However, the displacements caused by P-wave reflections from the interface are significant only when the coefficient $C_r$ is small enough (less than approximately 0.24). For the concrete slab and asphalt overlay in our experiment, the coefficient of reflection is 0.14 and the coefficient of transmission 1.14. Therefore, the response of the structure is dominated by the full thickness response $f_c$.

Figures 3a and 3b show the response of a 4 m-radius plate. The top layer

![Figure 3: Concrete slab with asphalt overlay. a) Waveform. b) Spectrum.](image-url)
Figure 4: 50 cm impact region. Wave propagation. a) 0.2 ms. b) 1 ms.

(aspalt) is 0.1 m-thick and the bottom layer (concrete) is 0.2 m-thick. The results confirm that it is necessary to take into account the recording time to avoid the effect of the interferences of the Rayleigh-waves. If the recording time is higher than $4 \times 10^{-3}$ s, interferences appear and the spectrum is difficult to interpret. With recording times below this value, the highest peak in the spectrum appears at $f_c=5420$ Hz and only another, small peak at $f_l=6587$ Hz can be observed.

5 Delaminations in plates

Shallow cracks (delaminations) are not uncommon in the contact zone between a concrete slab and its asphalt overlay. In this case, P-waves become reflected at the delaminations with a frequency $f_l=c_{pl}/2d$, as they would at an air-asphalt interface (Lin & Sansalone [5]). This frequency is displayed in the spectrum together with the asphalt-concrete frequency, $f_c$.

A 4 m-radius plate with a 0.2 m-thick top asphalt layer overlying a 0.3 m-thick bottom concrete slab has been used to assess the influence of a

Figure 5: 50 cm impact region. Spectrum.
delamination on the spectrum, as well as to determine the experimental conditions that will ensure detection of the delamination.

A first experiment is carried out for a 0.5 m-radius delamination. The theoretical frequency at the interface is 6587 Hz whereas the frequency from the bottom, $f_n$, is 3178 Hz. The impact has been simulated by a 20 kHz half-sine pulse. The impact region is 0.5 m-radius, sampling time is 1 μs, and recording time is 500 μs. The resulting wave is highly directional, with the energy remaining concentrated above the delamination (figure 4). The corresponding spectrum records - even at points that are quite distant from the delamination - the 6587 Hz frequency (figure 5), but not that arising from the bottom of the plate.

If the radius of the impact region is reduced to 0.1 m the resulting wave is not directional, but displays a pseudo-spherical wavefront (figure 6). In this case the 6587 Hz and the 3178 Hz frequencies are recorded in the spectrum (figure 7). As the recording point is moved further from the delamination, the 3178 Hz-peak increases in height and the 6587 Hz-peak nearly disappears, indicating that the wave is already rebounding outside the borders of the delamination. A similar process affects the first flexural mode of vibration of the delaminated layer (511 Hz), which is only observed in those recording points above the delamination, and disappears in those placed outside its boundaries. Combining these observations, the size of the delamination can be estimated.

For a 0.1 m-radius delamination and an impact region of 0.5 m-radius, the
resulting wave is again highly directional. When this P-wave impacts on the edge of the delamination (figure 8), a diffracted cylindrical wavefront centred on this edge is generated (Graff [6]). The recording points above the delamination register both the 6587 Hz and the 3178 Hz frequencies, as well as its multiples (figure 9). The 6587 Hz frequency disappears beyond the delamination, allowing again to determine its size. For a 0.1 m-radius impact region the results are similar.

6 Conclusions

Although the impact-echo method can successfully measure plate thickness and detect flaws in heterogeneous media, several factors can hinder the interpretation of the results, and is therefore advisable to perform a numerical analysis prior to its practical use. This study shows that it is necessary to control the total recording time in order to avoid registering the interferences between P-waves and Rayleigh-waves arising from reflections on the edges of the plate. This phenomenon also takes place in multi-layer plates. Detection of flaws or delaminations is further influenced by the size of the impact region. The dependence of the spectrum on the size of the impact region and the location of recording points relative to the delamination can be analysed to give an estimate of size of the delamination. Very small impact regions and impact regions larger than the delamination yield complex and unclear spectra.

Figure 8: 10 cm delamination. 50 cm impact region. a) 0.12 ms. b) 0.16 ms.

Figure 9: 10 cm delamination. 50 cm impact region. Spectrum.
References


