

Advances in Non-Contact Impact-Echo Scanning

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Abstract

Impact-echo has proved to be an effective method for the nondestructive evaluation of in-situ concrete members over the past 20 years. The method is based on measuring the S1 Lamb wave frequency under resonance conditions, which is usually excited using a light steel impactor. The dynamic response is typically measured near the point of impact with a high-frequency accelerometer or displacement transducer coupled to the surface. The dominant frequency of the response is a function of thickness as well as section stiffness, therefore once fundamental material properties have been established impact-echo is a useful tool for measuring thickness as well as verifying the internal continuity of a concrete section. This study presents the development of both a theoretical basis and a practical tool that allows the S1 resonance frequency to be measured by a moving air-coupled acoustic sensor, leading to the advantages of rapid IE scanning over traditional point-by-point testing. Various challenges associated with noise control, integrating the source to a rolling instrument, data acquisition, processing and imaging are addressed. Data obtained from scanning various control slabs over a range of scanning velocities are presented alongside results from traditional point-by-point impact-echo testing. Potential applications of this method include thickness measurement and identification of flaws in concrete pavements, reinforced concrete pipes, bridge decks, as well as quality assurance of grouting in post-tensioning tendon ducts. The concept and feasibility of using an array of sources and receivers for rapid impact-echo 3D imaging of pavements and bridge decks is also presented.

Introduction

Impact echo is a practical and effective tool to measure thickness and verify the internal continuity of concrete slabs, beams and pipes. The method has been used commercially in civil engineering NDT applications for the past 20 years, and is standardized under ASTM C1383. Recent studies¹ have demonstrated that the underlying theory of impact echo measurements is governed by stationary resonance of the S₁ Lamb mode, effectively redefining the conventional understanding of the method. The more accurate theoretical basis makes way for an expansion of the practical applications and viable experimental configuration, such as the use of acoustic sensors for rapid impact echo scanning which is the subject of this study.

The use of non-contact sensors for NDT of concrete structures is a subject that has been explored in recent years, both for impact echo testing² and dispersion analysis³ using microphones of suitable sensitivity and frequency range. These studies have demonstrated that high-end microphones are a practical tool of measuring transient vibrations in a concrete surface. However, the direct acoustic (air wave) arrival, which has been used in the past to characterize shallow delaminations based on flexional modes⁴, should be avoided or eliminated for analysis of guided waves. This can be achieved either through adequate acoustic insulation and/or a sufficient source-receiver separation to delay the acoustic wave as the speed of sound in air is typically low in relation to propagation velocity in solids.

The principal advantages of an air-coupled impact echo system would include a faster testing speed and the potential for improved spectral consistency and test repeatability. Commercially available impact echo systems typically make use thin lead strips or flexible urethane to couple the vibration energy from the concrete surface to a piezo-element. This requires the equipment to be held in a stationary at each test-point while the test is carried out, thus limiting the speed at which data can be collected on large areas such as pavements and bridge decks. Although contact sensors are more practical for field applications than fixed mounted sensors, the spectral content of impact echo data obtained on rough and mechanically inhomogeneous surfaces

such as concrete is often inconsistent. From the author's experience the repeatability of measurement of both fundamental thickness frequency and subtle features that could be interpreted as flaws is sometimes hard to achieve, limiting the value of the method as a practical quality assurance tool under challenging field conditions.

Dimensional Analysis

All problems addressed in this study are dimensionally homogeneous, therefore it is convenient to define normalized (dimensionless) units to express the theoretical and experimental examples below. For the sake of clarity the most commonly used variables in traditional impact echo analysis, double thickness (2h) and compression wave velocity (C_P), have been chosen as the normalization parameters as outlined in Table I.

Table I – Definition of Normalized Units

Variables	Symbol (units)	Normalized units
thickness	h (m)	0.5
P-wave velocity	C_P (m/s)	1
velocity	c (m/s)	$\mathbf{c}^n = c/C_P$
wavenumber	k	$\mathbf{k}^n = hk/\pi$
frequency	f (1/s)	$\mathbf{F}^n = (f)2h/C_P$
Time	t (s)	$\mathbf{t}^n = (t)C_P/(2h)$
source-receiver spacing	x (m)	$\mathbf{x}^n = x/(2h)$

Impact Echo Theory

The impact echo test consists of dynamically exciting the surface of a plate with a light, high-frequency impact. Of the transient resonances produced, the dominant frequency measured by an adjacent sensor is the 1st order symmetrical (S_1) mode Lamb wave at zero group velocity, due to its high out-of-plane excitability and the fact that its energy does not propagate away⁵

Lamb wave dispersion relations are defined by the Rayleigh-Lamb equation⁶ and were calculated using an iterative root finding algorithm⁷. The dispersion properties are typically expressed in terms of frequency vs. wavenumber, and can be converted to frequency vs. wavelength ($\lambda=2\pi/k$) and further expressed in terms of the normalized variables defined in this paper. Such a dispersion relationship for the S_1 mode is shown in Figure 1. Based on the calculated dispersion curves it is possible to calculate phase velocity (ω/k) and group velocity ($\partial\omega/\partial k$), which defines the frequency minima of the curves in Figure 1 as the zero group velocity frequency for this mode.

Using dimensional analysis it is possible to eliminate dependence on all specific material properties with the exception of Poisson's ratio (itself dimensionless), as evident by the different curves in Figure 1. Poisson's ratio in concrete typically ranges between 0.17 and 0.22, and Lamb wave dispersion properties have been shown to have low sensibility within this range⁸. Unless otherwise stated an assumed Poisson's ratio of 0.2 will be used for all further analysis in this paper.

For typical concrete material properties the S_1 resonance conditions occur 0.945 to 0.958 of \mathbf{F}^n , which closely matches the empirical impact echo correction factor β specified under ASTM C1383 as 0.96 for slabs.

$$F = \frac{\beta C_p}{2h} \dots\dots\dots(1)$$

The recommended source-receiver spacing for impact echo is $x^n = 0.2 (0.4h)^9$, due to attenuation of the signal with distance and reinforced by the traditional longitudinal wave resonance hypothesis. Using the more recent Lamb wave theoretical basis it is possible to explore the effects of altering the experimental configuration, such as increasing the source receiver separation, an important consideration for acoustic scanning for reasons discussed above.

For the following analysis group velocity is understood to dictate the distance energy of the related frequency travels from the source over a given time. It follows that for each mode a time - frequency relationship can be calculated based on group velocity dispersion and spacing. This procedure is used to investigate the frequency content of a given time-domain window, and results used as a basis to define the beginning and end of Hanning windows to apply to experimental data.

Figure 2a shows the time-frequency relation of the S_0 and S_1 modes for a spacing of $x^n = 0.2$, a representative of a conventional impact-echo configuration. The Rayleigh and S_0 mode components take up a relatively small portion of the time-window and S_1 mode component frequency appears to quickly converge towards its zero group velocity value. This configuration is unfeasible for non-contact acoustic measurements due to interference caused by the direct acoustic arrival, which occurs before the S_1 mode frequency can be defined with sufficient resolution. Figure 2b shows the same time-frequency relation resulting from a greater source-receiver separation ($x^n = 1.5$). In this case there is sufficient separation of the acoustic air wave to resolve the S_1 mode, which shows slight frequency variation in the defined time-domain window. Attention should be paid to the larger band of potential interference before and after the Rayleigh wave arrival including a relatively slow S_0 mode component.

Experimental Method and Results

A series of experiments were conducted with the purpose of testing the validity of the revised configuration and feasibility of acoustic impact echo measurements. All measurements were performed on a concrete floor slab of 109 mm nominal thickness. A pointed steel-tip piezo-crystal displacement transducer was used for contact surface measurements. Acoustic data were measured with a 1/4" condenser microphone, of 100 kHz resonance frequency and 4 mV/Pa sensitivity. For acoustic measurements the microphone was encased in a double walled housing with acoustic padding in order to minimize ambient noise contamination. A light instrumented steel tip impactor was used to provide the excitation and trigger the data acquisition system on impact. Data was collected and analyzed using a PC based acquisition system at 1 Mhz sampling frequency. A Hanning window is applied to all time-domain data, with the function of eliminating Rayleigh wave and S_0 interference at the start and direct acoustic arrivals at the end in the case of the microphone data. Frequency-domain data is obtained by applying a Fast-Fourier Transform and are presented as the square of the power spectrum. Control tests referred to below as "conventional impact echo" indicate compliance with ASTM C1383-04, and a source receiver spacing of $x^n < 0.2$.

Effect of source-receiver spacing

Feasibility of measuring the S_1 resonance at unconventionally high spacing from the impact location was investigated using the contact displacement transducer. With the sensor fixed in place, a series of impact echo data was collected while the source-receiver spacing was increased incrementally up to $x^n = 2.28$. In addition, conventional impact echo measurements were taken at selected intervals matching the previously described impact positions. Although the measured amplitudes were found to drop away from the impact position, when the spectral data was normalized a clear consistent S_1 mode resonance was measured, as shown in the 3D contour plot

in Figure 3a. Frequencies obtained at selected impact points with a conventional impact echo configuration are shown in similar format in Figure 3b. These results show that with appropriate attention to time-domain windowing the S_1 mode resonance is continuously measurable, and dominant, at source-receiver spacing greater than those traditionally specified for impact echo testing.

Acoustic vs. displacement response

The following results show a comparison of the acoustic and contact measurements of the transient dynamic response at $x^n=1.75$ from the impact location, as shown in Figure 4. In each case the time-domain signal and windowing function is displayed in the upper window and the frequency-domain display obtained through an FFT function is displayed at the bottom of the figure. In both cases a low-frequency component was measured, which is common in impact echo data and usually eliminated using a high-pass filter. Also evident in both datasets is a clear S_1 mode resonance, indicating that with appropriate measures to eliminate S_0 mode and acoustic interference, non-contact pressure sensors are a viable means of measuring impact echo frequencies.

Scanning acoustic measurements

The acoustically shielded microphone and instrumented impact source was mounted on a wheeled frame for in-motion measurements. The source receiver separation was selected with the objective of allowing enough usable data to be recorded prior to the direct acoustic wave arrival, in this case $x^n=1.55$. A scan line was set up on the floor-slab and conventional impact-echo tests performed at 85 mm intervals, corresponding to the calibrated impact interval of the wheel-mounted scanner. Figure 5 shows a comparison between 2 in-motion acoustic scans and conventional impact echo results corresponding to the acoustic receiver locations. Scanning data for points 37-39 is lost due to the presence of a vertical crack in the floor slab between the scanning source and receiver positions.

Conclusions

Feasibility of acoustic impact echo scanning is contingent on the elimination of the direct acoustic (air wave) arrival. A practical way of accomplishing this is to provide greater source-receiver separation than allowed by conventional impact echo analysis. Using the more recent Lamb wave interpretation, such an experimental setup can be shown to be theoretically legitimate, and was experimentally validated in this study. The theoretical development indicates special attention should be paid to time-domain windowing in order to prevent interference of faster S_0 modes as well as the slower acoustic arrival. Experimental results show that acoustic measurement of a valid S_1 mode resonance is feasible using both stationary and moving sensor configurations. Planned further development of the prototype acoustic scanner include more detailed analysis of the accuracy and resolution of scanning results, leading to the refinement of rapid impact echo scanning capabilities as well as fusion with acoustic sounding and dispersion analysis.

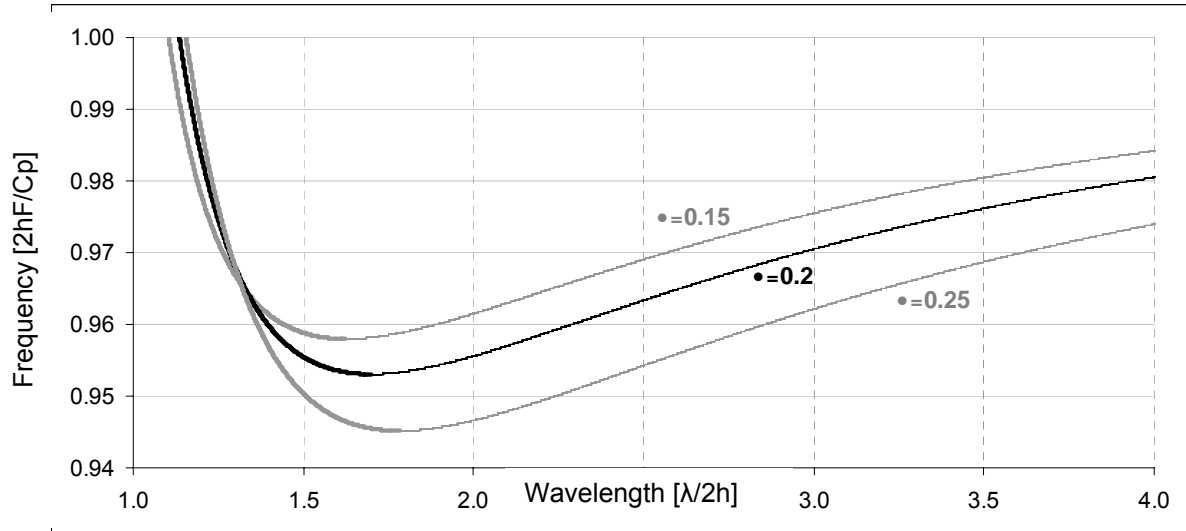


Figure 1 – Normalized plate dispersion relationship for the S_1 mode corresponding to Poisson's ratio of 0.15, 0.2 and 0.25. The dotted sections of each line represent negative group velocity components and the minima correspond to stationary conditions.

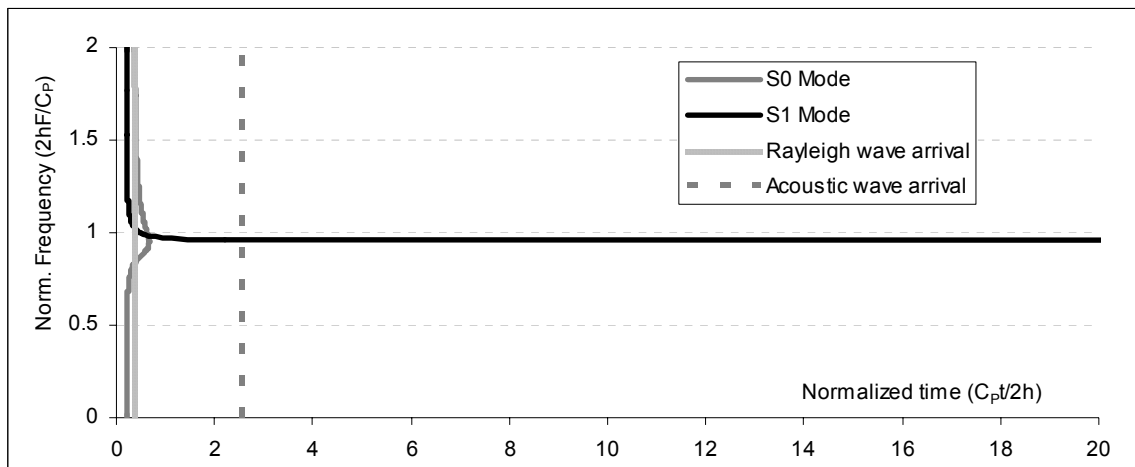


Figure 2a– Time vs. frequency relations of the S_0 and S_1 modes based on group velocity at a normalized source-receiver spacing $x^r=0.2$ ($0.4h$)

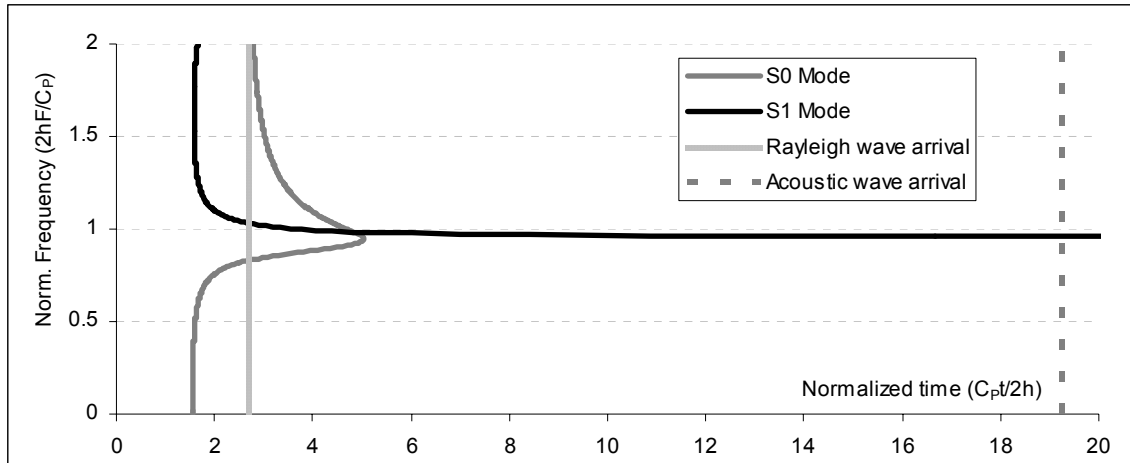


Figure 2b – Time vs. frequency relations of the S_0 and S_1 modes based on group velocity at a normalized source-receiver spacing of $x^n=1.5$ (3h)

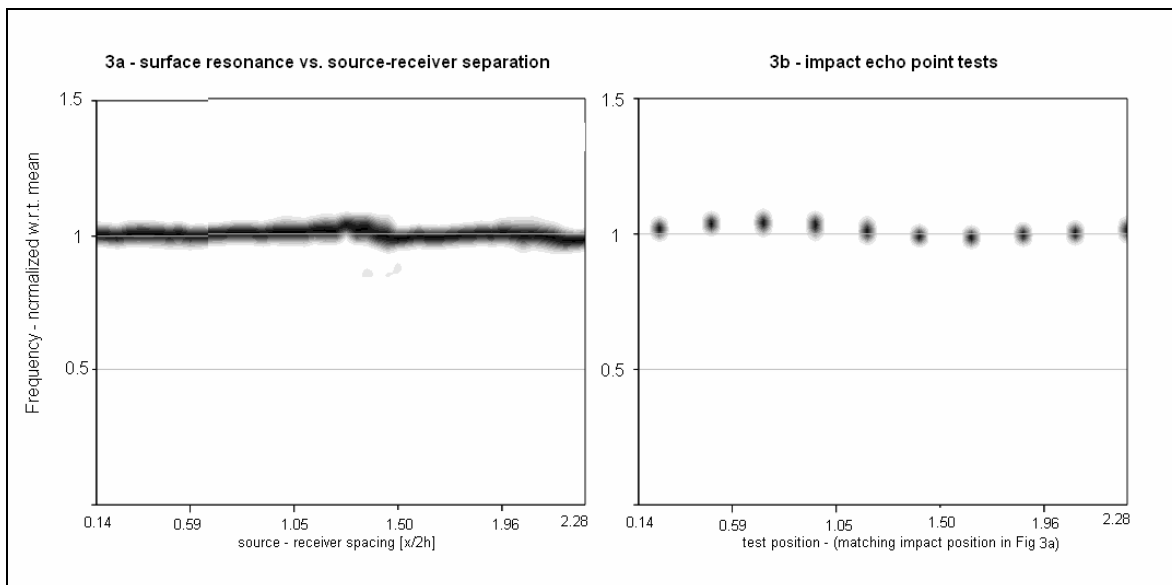


Figure 3 – (a) Effect of source-receiver separation on experimentally measured S_1 mode frequency using a fixed displacement transducer compared to (b) selected point impact echo tests at locations matching the impact points used in (a).

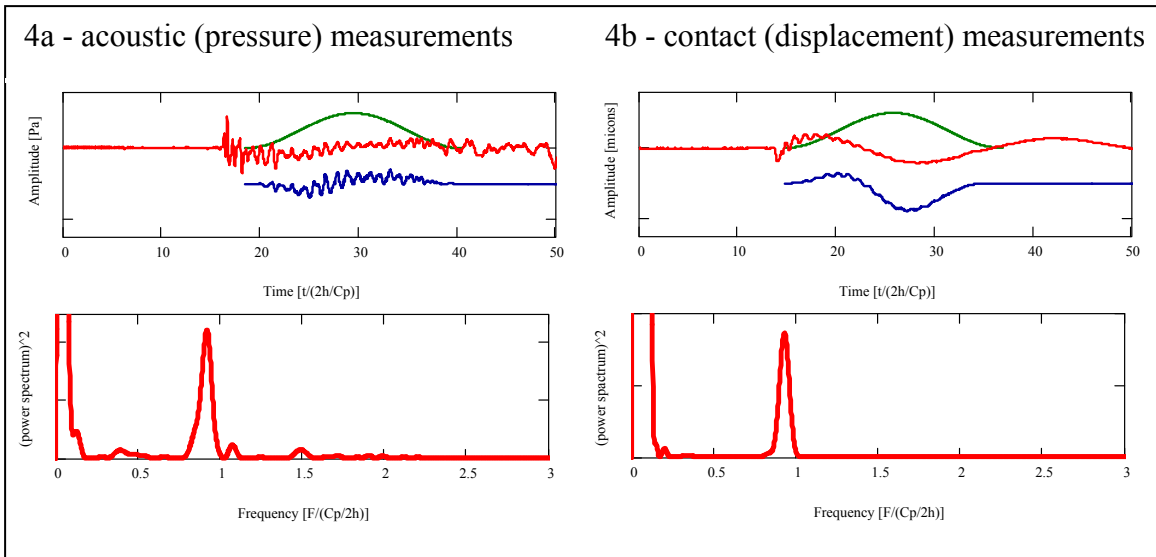


Figure 4 – Time and frequency response at $X=1.75$ ($3.5h$) obtained experimentally using a) microphone b) displacement transducer. The upper time-domain plot shows the raw signal, a Hanning window and the windowed data. The lower plot shows the spectra over a given frequency range of the windowed data.

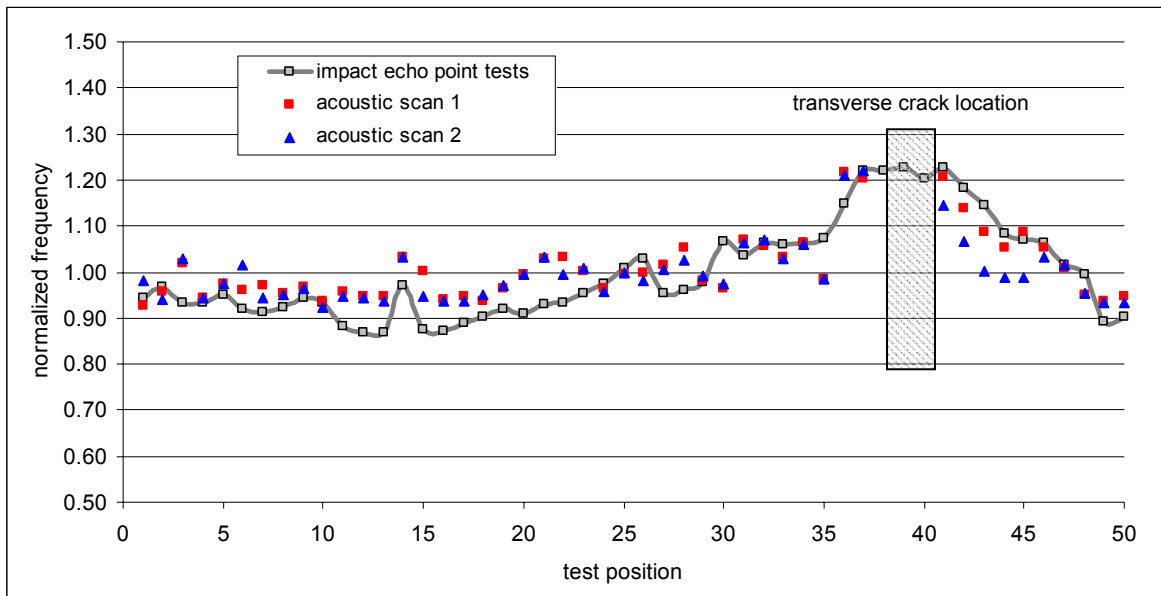


Figure 5 – Comparison between 2 in-motion acoustic scans and conventional impact echo point tests at locations matching acoustic receiver locations.

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