Guided wave evaluation techniques for testing of plate-like concrete structures

Oskar Tofeldt\textsuperscript{1}, Nils Ryden\textsuperscript{2}
1 University West, Sweden, oskar.tofeldt@hv.se
2 Lund University, Sweden

Abstract

There is a growing need for non-destructive techniques capable of investigating civil-engineering structures of concrete material. The Impact-Echo (IE) method is one such technique based on the study of a resonant and stationary mode. This mode corresponds to a Lamb mode. In turn, this accentuates that the IE method can easily be extended to include the analysis of propagating Lamb modes as well. Thereby a quantitative evaluation of the elastic plate properties and thickness is possible. Moreover, the use of Lamb waves lay the foundations for extended analysis which makes measurements based on an extension of the IE method an attractive complement to current ultrasonic techniques for plate-like concrete structures.

1. Introduction

Elastic waves represent a general framework applicable for non-destructive evaluation. Examples of recent development within this framework are seen in ultrasonic inspection techniques by means of synthetic aperture processing and wireless transducers [1]. However, for concrete structures with coarse aggregates, heavily reinforcement or large dimensions, scattering represents an inherently difficult problem [2]. An alternative methodology, less influenced from scattering and attenuation, is to operate in a lower frequency regime with longer spatial wavelength. In practical testing, this can be realized by using a mechanical impactor, such as a hammer, as the input source. Based on this methodology, the Impact-Echo (IE) method [3] is an established method.

Since a transient impact source generates a broad band of frequencies, which for plate-like structures creates a full wave field response of multi-modal dispersive characteristic, the IE analysis can be extended [4]. Essentially with the same equipment as used in IE testing, a full wave field response can be recorded by multiple impacts distributed along a line or over a surface [5]. Subsequently, this response can be processed according to guided wave (Lamb wave) theory [6]. The aim of this work is to present the basic theoretical aspects as well as the practical implementations of analysis techniques applicable for Lamb wave evaluation of plate-like concrete structures. These aspects are important for both the traditional IE method as well as techniques utilizing a Lamb wave interpretation and evaluation of the measurement data.

2. Interpretation of the Impact-Echo (IE) method

The classical interpretation of the IE method is illustrated in Fig. 1. Major similarity between this interpretation and the concept of ultrasonic pulse echo can be noticed. If a
change in travel time of the reverberating pulse occur due to change in material, defects, anomalies or varying thickness, a deviation in the resonant frequency will appear. That is, by studying relative variations in the frequency spectrum (see Fig. 1) a non-destructive evaluation of the structure can be performed. The classical IE measurement can be extended into a quantitative evaluation of plate-like structures through the empirical formula given by:

\[ f = \frac{\beta V_L}{2h} \]

where \( f \), \( \beta \), \( V_L \), \( h \) is the frequency, a correction factor, the longitudinal wave velocity and plate thickness, respectively. However, note that for a correct quantitative thickness evaluation as example, the correctional factor \( \beta \) and the longitudinal wave velocity \( V_L \) must be known, measured or calibrated in addition to the measured frequency.

Historically, the correctional \( \beta \) factor was assumed to account for the “plate geometry” [3]. However, as established by Gibson and Popovics [7], the \( \beta \) factor is only a function of Poisson’s ratio. More importantly, the work by Gibson and Popovics creates an important link to Lamb wave theory since they verify that the resonant mode used in IE testing indeed corresponds to the S1-ZGV Lamb mode (see Fig. 1); this link is of fundamental importance since it pave the way for further and extended analysis based on Lamb waves with outset in the IE measurement.

Figure 1. Classical interpretation of the IE method (top-left) and Lamb mode interpretation (top-right). Example of measured frequency spectrum in an IE measurement (bottom-left). Location of the “IE resonant mode” in frequency-phase velocity plane according to Lamb wave theory.
3. Lamb wave evaluation

Whereas the classical IE method embraces the analysis of one single resonant and stationary Lamb mode (S1-ZGV), the IE measurement can easily be extended to incorporate propagating Lamb modes as well. An example of such extended measurement is shown in top left part of Fig. 2. This type of measurement can be viewed as a combined IE and surface wave measurement [4]. The benefit of this type of measurement is that a full-wave field response of wide frequency-bandwidth containing both stationary and propagating Lamb modes is acquired. This allows an analysis based on Lamb wave theory which means that the acoustic velocities (material stiffness or Young’s modulus), Poisson’s ratio and plate thickness can be evaluated quantitatively. This evaluation is possible also under one-sided access test condition without the need for calibration or à-priori information [6]. In addition to quantitative estimates, the Lamb wave interpretation also facilitates a number of processing techniques that can be used for improving the general accuracy of the IE test through the usage of the S1-ZGV Lamb mode shape [8], [9].

The illustration in top-left part of Fig. 2 shows a measurement along a straight line located at the surface of the plate. However, data can also be recorded within a surface, as shown in bottom-left part of Fig. 2. With this type of dataset, a manifold of interesting possibilities for the data evaluation unfold, with one example being shown in bottom-right part of Fig. 2. The figure shows a phase velocity image map projected over the corresponding measurement domain. This image map is obtained through a Lamb wave phase velocity analysis based on subsets (synthetic arrays) within the complete measurement domain [5]. This type of imaging technique can for example be used as a tool for verifying the homogeneity of the plate structure.

![Figure 2. Measurement procedure for a combined IE and surface wave measurement which enables the possibility for a Lamb wave evaluation of the propagating wave field (top). Example of measurement collecting data over a surface (bottom-left) and corresponding data evaluated using a Lamb wave phase velocity imaging approach [5] (bottom-right).](image-url)
4. Conclusions

The resonant and stationary mode utilized in IE testing corresponds to the S1-ZGV Lamb mode. It is therefore natural to extend the IE measurement to include Lamb wave analysis with both stationary and propagating Lamb modes. Quantitative estimates are thereby obtained without the need for calibration or à-priori information. Furthermore, this enables a manifold of different processing and evaluation techniques which represent attractive complements to current ultrasonic techniques for plate-like concrete structures.

References


