NON-CONTACT SURFACE WAVE MEASUREMENTS USING A MICROPHONE

Nils Ryden, Dep. of Engineering Geology, Lund Institute of Technology, Lund University, Sweden
Michael J. S. Lowe, Dep. of Mechanical Engineering, Imperial College, London, United Kingdom
Peter Cawley, Dep. of Mechanical Engineering, Imperial College, London, United Kingdom
Choon B. Park, Kansas Geological Survey, University of Kansas, Lawrence, Kansas, USA

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Abstract

Pavements are typically constructed using several layers of materials, and their durability depends on the quality of these strata. It is therefore very valuable to be able to determine the properties of the layers non-destructively. Accelerometers can be used as receivers in surface wave testing of pavements, but require good seismic coupling to the surface. We present experiments using a non-directional audio microphone as a non-contact receiver. Leaky air-coupled surface waves are measured and processed using the Multichannel Analysis of Surface Waves (MASW) technique. Results show that leaky surface waves can be accurately measured using an ordinary audio microphone. This opens up the possibility for fast on-the-fly surface wave testing of pavements. We present the method along with a case study where the thickness and the stiffness of a concrete slab are evaluated from a data set acquired using a microphone as a non-contact receiver.

Introduction

Since the early work by Jones (1962) surface wave methods have been recognized as a tempting approach for non-destructive testing (NDT) of pavements. The introduction of the Spectral Analysis of Surface Waves (SASW) method (Heisey et al., 1982) has resulted in a widespread use of the method (Nazarian et al., 1999). The SASW method is based on a continuous dispersion curve obtained from the phase difference between two receivers at the surface. An alternative procedure based on the Multichannel Analysis of Surface Waves (MASW) method (Park et al., 1999) has been proposed by Ryden et al. (2004). With this approach data are collected by progressively moving a hammer source away from a fixed accelerometer receiver, generating a synthetic source array. The top layer properties are evaluated with a Lamb wave analysis (Ryden et al. 2004).

There are inconveniences and limitations related to the use of an accelerometer as receiver. Good seismic coupling between the accelerometer and the pavement surface is critical, and a coupling agent like glue or grease is usually used. And more important is that the whole procedure relies on stationary measurements. To move towards faster and more efficient data acquisition non-contact sensors is an attractive alternative.

Laser-based vibration transducers are frequently used as non-contact receivers in ultrasonic applications (Gao et al., 2003). However, laser equipment is expensive and requires a surface with good reflectivity and light scattering properties. The use of air-coupled receivers has also been successfully used in the field of ultrasonics (Castaings and Cawley, 1996). Zhu and Popovics (2001) showed that a directional microphone can be used as an air-coupled sensor to pick up the out-of-plane motion created by surface waves propagating over a concrete surface. In subsequent publications, they have demonstrated the use of directional microphones for crack detection in concrete (Popovics and Zhu, 2003), and a theoretical study on the excitation effectiveness of leaky surface waves (Zhu et al., 2004).

Motivated by these publications we have studied the feasibility of using a non-directional audio microphone as a non-contact receiver, with the MASW technique. We present our result and findings using a microphone instead of an accelerometer in surface wave testing of a concrete slab.

Method and Results

To test and demonstrate the use of a microphone as a non-contact receiver we have collected data over a concrete slab with well known thickness using both a microphone and an accelerometer. The microphone data is compared to the accelerometer data, focused on phase velocity measurements for dispersion curve analysis.

Theory and Experimental Set-Up

Wave refraction is the physical principle that makes it possible to detect surface waves using an air-coupled sensor. Waves propagating in a fast medium along the interface to a lower velocity medium will bend or "leak" energy into the lower velocity medium according to Snell's law (Sheriff, 2002). The leaky angle (α), can be calculated from

$$\alpha = \sin^{-1}(v_1 / v_2) \tag{1}$$

where α=0 is defined as the normal to the interface, v_1 is the velocity in the air, and v_2 is the surface wave velocity. An inherent limitation with air coupled surface wave measurements is therefore the requirement of a higher surface wave velocity compared to the speed of sound in air, 343 m/s at 20° C. This criterion is satisfied for nearly all of the waves on asphalt or concrete slabs where the surface wave velocity is usually between 1000 to 2800 m/s (>5 kHz). In this velocity range the generated leaky surface wave will propagate with an angle between 20 to 7 degrees with respect to the normal of surface, see Figure 1.

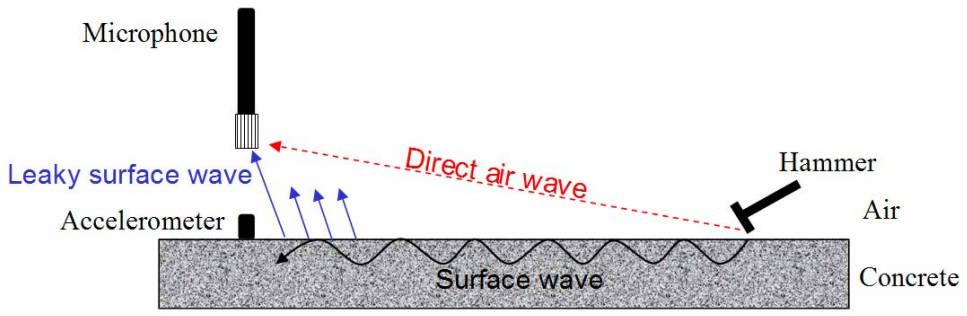

Figure 1: Schematic experimental set-up with accelerometer and microphone.

Data was collected on top of a 0.26 m thick concrete slab in a laboratory hall at Lund Institute of Technology, Sweden. The experimental set-up is schematically illustrated in Figure 1. No wind noise was present since data was collected indoors. However, there was some noise in the laboratory hall coming from fans and other machines operating during data collection. The hammer source is equipped with a force transducer used as a trigger device (time zero reference). The accelerometer and the microphone were both fixed at zero offset and impacts were generated from 0.40 to 1.85 m in 0.05 m increments (Ryden et al. 2001). A PCB 353B33 accelerometer (100 mV/g) and an ADK SC-1 condensor

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microphone (10mV/Pa) were used as receivers. The accelerometer was attached to the surface with sticky grease. The microphone was hanging upside down pointing towards the concrete surface with the tip 15 mm above the ground, see Figure 1. The signals from the accelerometer and the microphone were recorded simultaneously on separate channels using a sample rate of 192 kHz. All recorded signals from each receiver were then compiled to make an equivalent multichannel record which can be transformed to a phase velocity spectrum using the MASW transformation technique (Park et al. 1998).

Accelerometer Data

The accelerometer data (Figure 2a) and corresponding phase velocity spectrum (Figure 2b) is here used as a reference to be compared to the microphone data. Wave propagation in concrete slabs resting on a granular base layer is similar to Lamb wave propagation in a free plate (Ryden and Lowe, 2004). The fundamental anti-symmetric (A0) mode of propagation is the dominating mode generated from a vertical impact at the surface. The A0 dispersion curve is a function of the shear wave velocity (V_S), thickness (h), and Poisson's ratio (ν) of the plate. These properties can therefore be estimated by matching a theoretical dispersion curve to the measured data. The A0 dispersion curve trend is visible up to 10 kHz in Figure 2b. The matching A0 dispersion curve corresponds to a free plate with V_S=2600 m/s, h=0.26, and ν=0.20. The evaluated thickness agrees well with the true thickness (0.26 m) and the values of shear wave velocity and Poisson's ratio, are reasonable for good quality concrete.

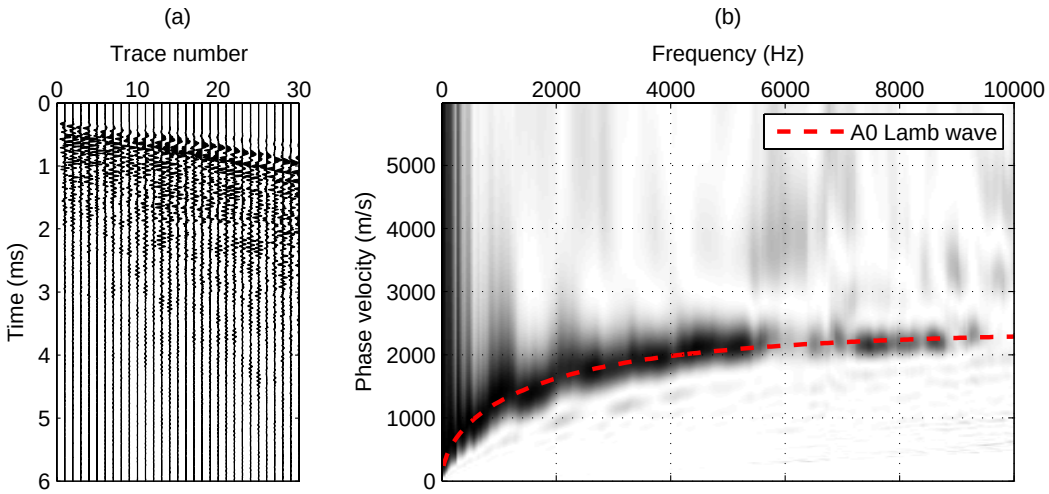

Figure 2: (a) The first 6 ms of the recorded raw data from the accelerometer. (b) Corresponding phase velocity spectrum with a matching A0 Lamb wave dispersion curve calculated from V_S=2600 m/s, h=0.26 m, and ν=0.20.

Microphone Data

The raw microphone data is presented in Figure 3. The leaky surface wave is marked with an [A] in Figure 3a. The slower direct air wave [B] is dominating the record. Figure 3b shows the corresponding phase velocity spectrum where the leaky surface wave [A] is only visible in the lower frequency range (<1kHz). The non-dispersive direct air wave [B] visible below 3430 Hz in Figure 3b runs into spatial aliasing at higher frequencies. Spatial aliasing occurs when the wavelength (λ) becomes shorter than twice the receiver spacing (2*dx). With dx=0.05 and V_{air}=343 m/s the direct air wave becomes spatially aliased at 3430 Hz. To improve the identification of the leaky surface wave in the phase velocity spectrum the direct air wave must be filtered out or suppressed. This can be done by f-k (frequency-wave number) filtering in the frequency domain or muting in the time domain record, Figure 3a. We have tried muting to suppress the direct air wave [B] in this study.

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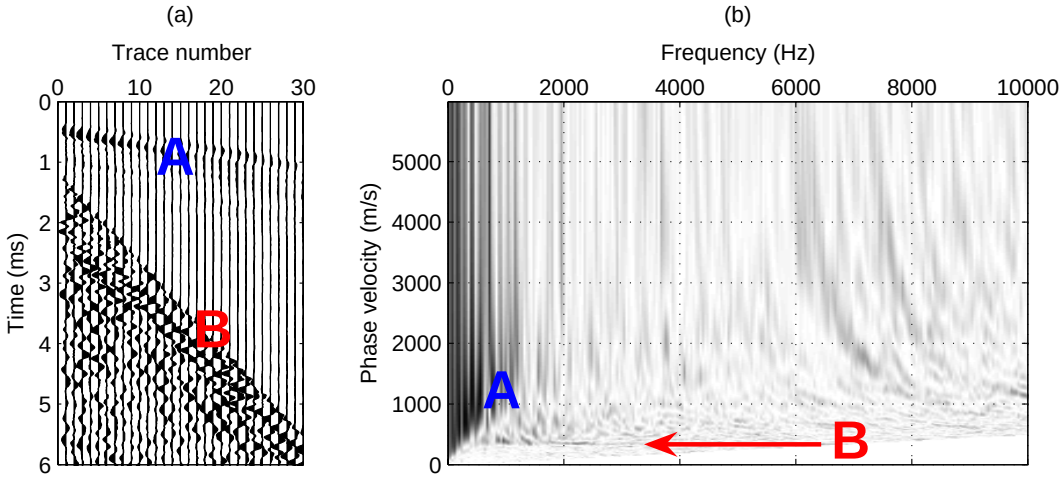

Figure 3: (a) Raw microphone data showing the leaky surface wave marked with [A] and the dominating direct air wave marked with [B]. (b) Corresponding phase velocity spectrum.

Muted Microphone Data

The term "mute" is used in seismic processing for a reduction in amplitude with time (Sheriff, 2002). After a certain time, defined by the "mute velocity", we have multiplied the amplitudes with an exponentially decaying function. This introduces a smooth gradual decrease in amplitude with time, thereby minimizing any potential velocity artifacts arising in the phase velocity spectrum.

In Figure 4 the microphone data has been muted with a mute velocity equal to 806 m/s and a smooth amplitude reduction of 17 dB/ms. The mute velocity is plotted as a line in Figure 4a defining the beginning of the amplitude reduction in each trace. Since all traces are normalized in the wiggle plot (Figure 4a) the leaky surface wave now becomes more pronounced. This is particularly evident in the phase velocity spectrum, Figure 4b, which now shows a clear dispersion curve trend similar to that observed with the accelerometer data (Figure 2b).

The A0 Lamb wave dispersion curve calculated from the same plate properties as used in Figure 2b has been plotted on top of the phase velocity spectrum in Figure 4b. It can be seen that the same A0 dispersion curve matches the microphone data equally well as the accelerometer data.

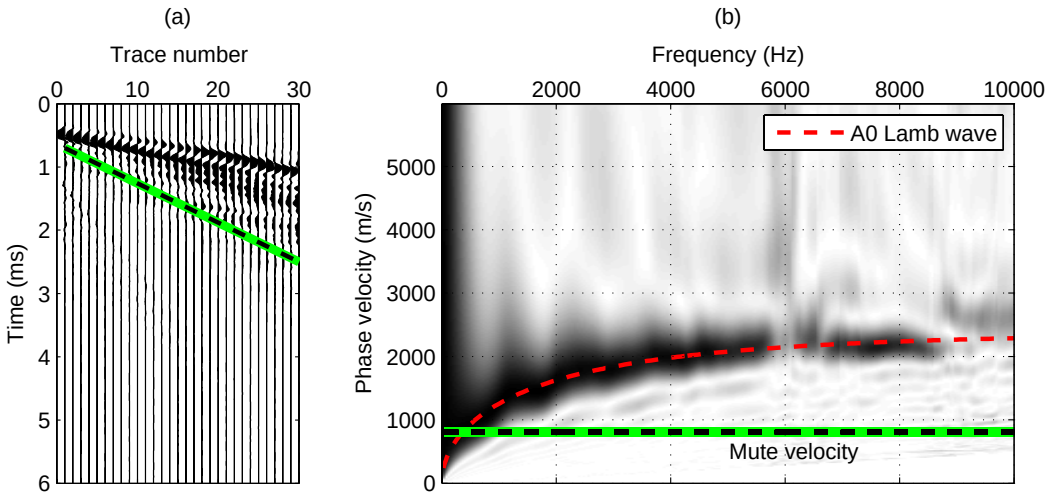

Figure 4: (a) Muted microphone data with the mute velocity indicated with a line at the beginning of the amplitude reduction. (b) Corresponding phase velocity spectrum after muting. The mute velocity is indicated with a straight line and the matching A0 dispersion curve is plotted with a thinner dotted line.

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Comparing extracted phase velocities

The extracted dispersion curves from the accelerometer (Figure 2) and microphone (Figure 4) data are plotted in Figure 5a. The extracted dispersion curves have been constructed from the peak amplitude at each frequency in the phase velocity spectra. The difference between the two dispersion curves is plotted in Figure 5b. The difference is below 5% in most of the frequency range except for the very low frequencies (<400 Hz) where the microphone data shows a higher phase velocity.

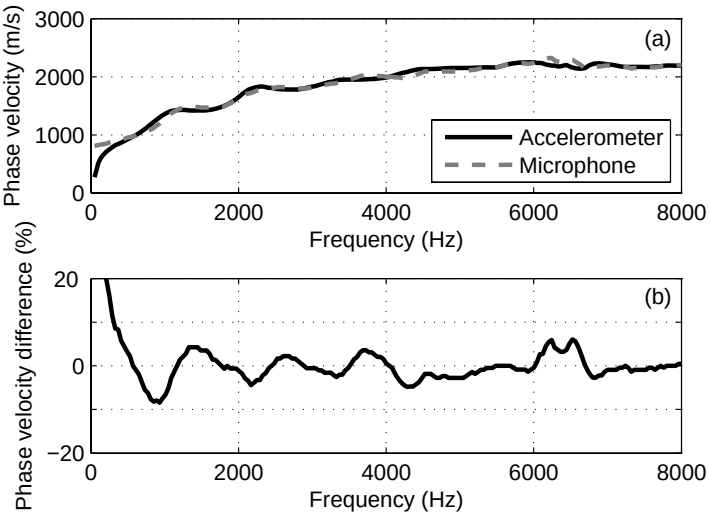

Figure 5: (a) Extracted accelerometer and microphone dispersion curves. (b) Difference plot between the two dispersion curves in (a).

Discussion

Suppression of the direct air wave is critical in non-contact surface wave measurements using a non-directional microphone. In this study the amplitudes of the direct air wave has been successfully reduced with muting. In applications where the surface wave velocity is slower, gradually approaching the air wave velocity, this suppression will become more difficult. Other approaches that may be usable are *f-k* filtering or direct air wave shielding (insulation) around the source and/or receiver.

Conclusions

The thickness and shear wave velocity of a concrete slab have been evaluated non-destructively using a microphone as a non-contact receiver. Results show that leaky surface waves can be accurately measured using an ordinary relatively cheap condenser microphone. This opens up the possibility for faster on-the-fly surface wave testing of pavements since surface contact is not required.

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