# Air-coupled microphone measurements of guided waves in concrete plates

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# Abstract

Quality control and quality assurance of pavements is today primarily based on core samples. Air void content and pavement thickness are parameters that are evaluated. However, no parameter connected to the stiffness is evaluated. There is a need for fast and reliable test methods that are truly non-destructive in order to achieve an effective quality control and quality assurance of pavements.

This licentiate thesis presents surface wave testing using air-coupled microphones as receivers. The measurements presented in this work are performed in order to move towards non-contact measurements of material stiffness. The non-contact measurements are compared to conventional accelerometer measurements in order to compare the non-contact measurements to a “reference test”. The two appended papers are focused on evaluating one parameter in each paper. In the first paper all equipment needed to perform non-contact measurements are mounted on a trolley in order to enable measurements while rolling the trolley forward. It is shown that rolling measurements can provide rapid and reliable measurements of the Rayleigh wave velocity over large areas. However, the measurements are shown to be sensitive to misalignments between the microphone array and the measured surface. An uneven surface can thus cause major errors in the calculated results.

The second paper presents an alternative method to evaluate the thickness resonance frequency of a concrete plate. It is demonstrated how the established Impact Echo method can give erroneous results when air-coupled microphones are used as receivers. Instead a method based on backward wave propagation is introduced. It is demonstrated how waves with negative phase velocities can be identified in a narrow frequency span close to the thickness resonance.

## Keywords

Non-destructive testing; Lamb waves; surface waves; air-coupled microphones; non-contact measurements.

# Sammanfattning

Kvalitetskontroll av asfaltsbeläggningar är idag huvudsakligen baserade på borrkärnor. Hålrumshalt och beläggningstjocklek är parametrar som utvärderas. Ingen av dessa parametrar är dock knuten till styvheten som används vid dimensionering. Det finns ett behov av snabba och pålitliga oförstörande testmetoder för att åstadkomma en effektiv kvalitetskontroll och kvalitetssäkring.

Den här licentiatavhandlingen presenterar ytvågsmätningar där mikrofoner används som mottagare. De kontaktlösa mätningarna jämförs med konventionella accelerometermätningar för att väga de båda metoderna mot varandra. De två bifogade artiklarna är fokuserade på att utvärdera en parameter i vardera artikeln. I första artikeln monteras all utrustning som är nödvändig för att utföra kontaktlösa mätningar på en vagn i syfte att möjliggöra mätning medan vagnen rullas framåt. Resultaten visar att rullande mätningar kan tillhandahålla snabba och pålitliga mätningar av Rayleighvågshastigheten över större ytor. Dock uppvisar mätningarna stor känslighet för vinkeldifferenser mellan mikrofonerna och den uppmätta ytan. En ojämn yta kan alltså skapa stora fel i de beräknade resultaten.

I den andra artikeln presenteras en alternativ metod att bestämma tjockleksresonansen i en betongplatta. Den etablerade Impact Eho-metoden kan ge felaktiga resultat då mikrofoner används som signalmottagare. Istället introduceras en metod som är baserad på vågutbredning med negativa fashastigheter. Det demonstreras hur vågor med negativa fashastigheter kan identifieras i ett smalt frekvensintervall nära tjockleksresonansen.

## Nyckelord

Oförstörande provning; Lamb-vågor; ytvågor; mikrofoner; kontaktlösa mätningar.

# Preface

The presented thesis has been carried out at the division of Highway and Railway Engineering at KTH Royal Institute of Technology. I would like to express my sincere gratitude to my supervisor, Nils Ryden, for all the support and help I have gotten. Thanks also to my assisting supervisor, Björn Birgisson, for your guidance during the work.

I am grateful towards the Swedish construction industry's organization for research and development (SBUF) and the Swedish Transport Administration (Trafikverket) for their financial support.

Thanks to my family and friends for their support and encouragement during my years of studying. My gratitude also goes to the other Ph.D. students, thanks for some nice years, I'm looking forward to the rest.

Henrik Bjurström

Stockholm, 2014

# Appended papers

The appended papers in this thesis present non-destructive seismic testing methods on a concrete plate. Non-contact measurements are used in order to collect data over large areas rapidly and almost continuously. The two presented papers are mainly focused on stiffness and thickness estimation of concrete plates.

**Paper I.**
Bjurström, H., Ryden, N. and Birgisson, B., 2014, *Non-contact surface wave testing of pavements: comparing a rolling microphone array with accelerometer measurements*, accepted for publication in the special issue on Advanced Sensing Technologies for NDE and SHM of Civil Infrastructures, Smart Structures and Systems.

**Paper II.**
Bjurström, H., Ryden, N. and Birgisson, B., 2014, *Detecting the thickness mode frequency in a concrete plate using backward wave propagation*, to be submitted to the Journal of the Acoustical Society of America.

# Related papers

Bjurström, H. and Ryden, N., 2013, *Air-Coupled Detection of the S1-ZGV Lamb Mode in a Concrete Plate Based on Backward Propagation*, 39th Annual Review of Progress in Quantitative Nondestructive Evaluation, Denver, Colorado, AIP Conference Proceedings 1511, pp. 1294-1300.

Bjurström, H. and Ryden, N., 2014, *Effect of Surface Unevenness on Non-Contact Surface Wave Measurements Using a Rolling Microphone Array*, accepted to 41st Annual Review of Progress in Quantitative Nondestructive Evaluation, Boise, Idaho, AIP Conference Proceedings.

**Awarded 3rd price in the annual conference student poster competition.**

# List of notations

$V_P$ = longitudinal wave velocity

$V_S$ = shear wave velocity

$c$ = phase velocity

$\omega$ = angular frequency

$k$ = wave number

$\rho$ = density

$\nu$ = Poisson's ratio

$E$ = elastic modulus

$d$ = plate thickness

# Contents

# 1. Introduction

Quality control (QC) and quality assurance (QA) of pavements are today mainly based on coring. Numerous circular cores are drilled and taken from newly built roads in Sweden and analyzed in a laboratory environment. The cores are examined to find air void content and thickness of the asphalt concrete layer. The air void content is compared to table values specified by the Swedish Transport Administration (Trafikverket, 2011) to verify that the correct packing quality has been achieved. The actual material stiffness which is used in the design of pavements and known to be directly correlated to the mechanical quality of a pavement is not tested. Furthermore, core samples only give information about the specific positions where the cores have been taken and no continuous information along the pavement is evaluated. There is a need for a more analytical pavement design and QC/QA based on the actual material stiffness.

Seismic waves are stress waves propagating in a solid material. The waves carry information about the affected material, the material that the waves propagate through. If the waves are collected and interpreted in a correct manner, information about the solid's elastic properties can be obtained. Surface waves are seismic waves propagating along the free surface of a material. These waves can be acquired at the surface and used for material characterization and damage detection.

The work presented in this thesis is mainly focused on non-contact measurements using air-coupled microphones as receivers. The target is to design a data acquisition package that can be mounted on a vehicle to perform continuous measurements over larger areas than what is possible today with maintained accuracy. Such a vehicle would substantially reduce the time and costs needed for QC and QA.

This thesis presents non-contact multichannel measurements performed on a concrete plate, using both a rolling and a stationary approach. Since the main target of this thesis is to establish new measuring techniques and since asphalt is a more complex material than concrete (viscoelastic with more surface roughness), the measurements were here first performed on concrete in order to arrange proper equipment setup and settings. The presented multichannel measurements were performed using a stationary and a rolling approach, the latter in a fraction of the time needed for stationary measurements.

Lamb wave theory is presented shortly to explain wave propagation in plate structures. Using the Multichannel Analysis of Surface Waves (MASW) (Park *et al.*, 1999) Rayleigh wave velocity and thickness resonance frequency of the concrete plate were determined with satisfying results. These parameters are directly connected to Young's modulus and plate thickness respectively.

It is shown that the compliance between non-contact rolling measurements and conventional accelerometer measurements regarding both Rayleigh wave velocity and thickness resonance frequency is good, something that in the future can enable faster measurements with maintained high quality.

# 2. Background

There is a wide spread of available non-destructive test (NDT) methods today. NDT using seismic waves utilizes low strain levels in order to determine linear material properties. Pioneering work using surface waves on pavements was laid out by Pickett (1945). Guided wave propagation in multilayered media using superposition of P- and S-waves with appropriate boundary conditions between the layers was presented by Thompson (1950) and Haskell (1953). Steady state measurements on pavements were carried out by Van der Poel (1951) and Jones (1955). A vibrator source was used to transmit seismic waves to be collected by a geophone positioned at multiple distances from the source. Amplitude maxima were studied at specified frequencies in order to determine the wavelengths. Phase velocity could then be calculated as the product of wavelength and frequency. Dispersion curves were then derived for the examined frequency range. Results by Heukelom and Foster (1960) from steady state measurements are given in Figure 1. The pavement construction has been divided into three parts corresponding to three different layers.

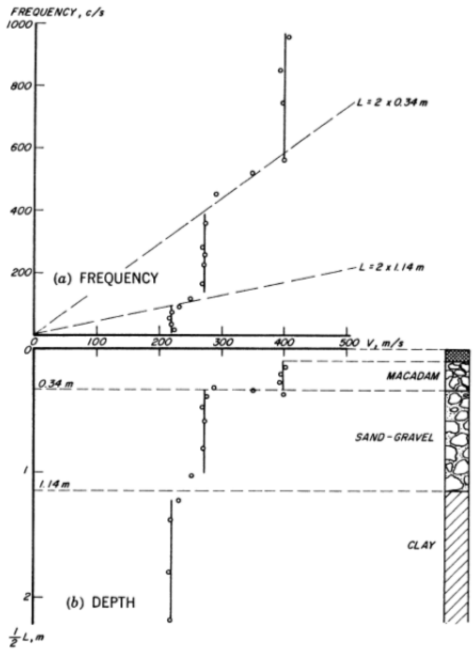



**Figure 1. Estimated dispersion curves using the steady state measurements. Original figure presented by Heukelom and Foster (1960).**

The Spectral Analysis of Surface Waves (SASW) was first introduced by Heisey *et al.* (1982). Numerous papers have been published on the SASW method since then (Nazarian *et al.*, 1983; Nazarian *et al.*, 1987; Rix *et al.*, 1991, Stokoe *et al.*, 1994). The basic principle of the SASW method is to determine the phase shift of surface waves between two receivers separated by a known distance. Usually, only a limited range of wavelengths, set differently by different authors, can be used from each measurement. Due to these wavelength filter criteria, multiple measurements with altered receiver spacing have to be performed in order to acquire valid data for a wider frequency range. A calculated dispersion curve using SASW, presented by Ganji *et al.* (1998), is shown in Figure 2. However, due to the low number of receivers, multimodal dispersion curves cannot be estimated.

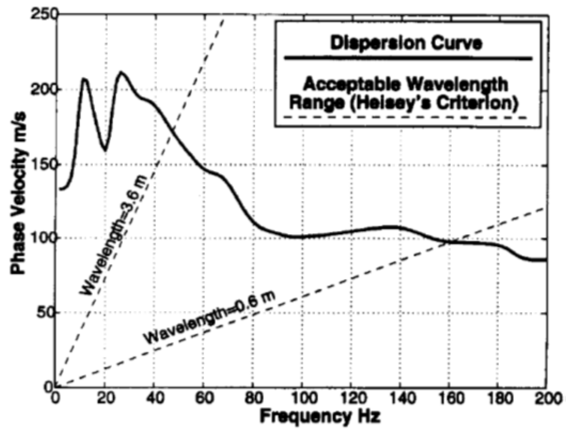



**Figure 2. Calculated dispersion curves using the SASW method. Only certain wavelengths from each measurement according to wavelength filter criteria can be used. (Results originally presented by Ganji *et al.* (1998))**

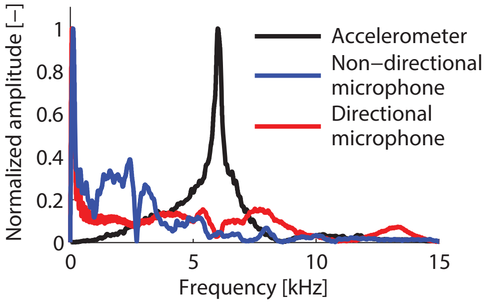
Using several receivers collecting data simultaneously, multimodal dispersion can be estimated from one impact. Park *et al.* (1999) introduced the Multichannel Analysis of Surface Waves that allows a collected data record to be transformed from time-space domain into frequency-phase velocity domain in order to estimate multiple dispersion curves.

NDT of material properties using seismic wave velocities has been hampered by the need for full contact between the receiver and pavement. Seismic NDT is today mainly based on contact measurements using accelerometers as receivers (Nazarian *et al.*, 1999; Yuan *et al.*, 1999; Ryden and Park, 2006). Using non-contact sensors the measurements can be performed more rapidly.

Lukkala *et al.* (1971) initiated wave transmission through a paper sheet using air-coupled transducers. Castaings and Cawley (1996) successfully demonstrated generation and detection of Lamb waves in the field of ultrasonics using air-coupled transducers on single-sided inspections of plates. Zhu and Popovics (2002) conducted experiments where a directional microphone was used in the audio frequency range to detect the out-of-plane motion of a concrete plate. Furthermore, they demonstrated how surface-breaking cracks on concrete slabs can be detected and imaged by studying wave attenuation (Zhu and Popovics, 2005). Measurements with air-coupled excitation and reception were performed on concrete by Piwakowski and Safinowski (2009) and Abraham *et al.* (2012). Non-contact evaluation of potential delamination of bridge decks (Kee *et al.*, 2012; Popovics *et al.*, 2014) and characterization of cracks in concrete (Kee *et al.*, 2011) have more recently been demonstrated. Ambrozinski *et al.* (2012) applied air-coupled transducers to perform single sided damage assessment of composite materials. Different incident angles were used in order to excite single wave modes depending on the type of damage examined.

Ryden *et al.* (2008) have developed a mobile data acquisition system, a prototype trolley where data can be collected while rolling the trolley forward. The trolley allows for rapid measurements over large areas and forms a starting point for the work in this thesis.

A widely used method for plate thickness determination and flaw detection is the Impact Echo (IE) method (Sansalone, 1997). It employs a high amplitude peak found in the frequency spectrum of the collected data, known as a thickness resonance frequency or IE-frequency. However, the method has mainly been limited to contact measurements due to low signal-to-noise ratio. Figure 3a shows three different receivers tested on a concrete plate, which has a thickness resonance frequency ~6 kHz, and their corresponding frequency spectrum are plotted in Figure 3b. It is clearly shown that only the accelerometer was able to identify a reasonable result in this case. In the data collected by the two different air-coupled receivers, the IE signal radiated into the air was overcome by ambient noise.


(a) (b)

**Figure 3. (a) Three different used receivers marked with black arrows and (b) their corresponding frequency spectrum.**

Holland and Chimenti (2003) have successfully generated and measured the S1 Lamb mode at zero group velocity, connected to the thickness resonance frequency, using air-coupled sensors. Zhu and Popovics (2007) performed air-coupled IE measurements by applying an enclosure, providing the microphone with sound insulation, screening ambient noise and the direct air wave from the impact. Dai *et al.* (2011) used a parabolic reflector to collect and amplify the airborne energy from the measured surface in order to enable air-coupled measurements.

# 3. Summary of papers

## Paper I: Non-contact surface wave testing of pavements: comparing a rolling microphone array with accelerometer measurements

Rolling non-contact measurements performed using an array of seven air-coupled microphones, are compared to conventional stationary accelerometer measurements. The compared results are limited to the Rayleigh wave velocity. All measurements are performed on the same concrete plate. It is shown that non-contact rolling measurements provide a fast and reliable alternative to the more time-consuming accelerometer measurements. However, the measurements are sensitive to unevenness of the measured surface. Measures to overcome this problem are discussed and demonstrated using both forward and backward rolling measurements. It is also shown that the rolling measurements have a very high repeatability.

## Paper II: Detecting the thickness mode frequency in a concrete plate using backward wave propagation

Impact Echo is an established method to determine the plate thickness by identifying the high amplitude peak in a measured frequency spectrum. It is a convenient method when an accelerometer is used as a receiver while microphones often give too low signal-to-noise ratio. An alternative method to estimate the thickness resonance frequency is presented in this paper. By studying complex dispersion curves it is shown that the resonance is caused by two counter-directional waves at the resonance frequency. It is demonstrated how the negative phase velocity wave can be measured in a narrow frequency range near the high amplitude resonance. The paper shows that the introduced method using backward wave propagation gives results close to the theoretically correct values. The differences are considered to be insignificant in the context of civil structure design.

# 4. Wave theory

## 4.1 Seismic waves

There are two different kinds of mechanical waves that can propagate through an infinite elastic solid material. The first type is the longitudinal wave, or the compression wave. The particles move in the propagation direction. The longitudinal wave is always the fastest wave why it is also often referred to as the primary wave or shortly P-wave. The second type of wave is the transversal wave, or shear wave. The transversal wave is slower than the longitudinal wave and it is also referred to as the secondary wave or shortly S-wave. P-waves and S-waves are together called body waves or bulk waves. The bulk wave velocities are directly related to the elastic constants of the material according to

$$V_P = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

$$V_S = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{2}$$

where $E$ is Young's modulus, $\nu$ is Poisson's ratio and $\rho$ is material density.

The presence of boundaries will cause other types of waves to be generated in the plate. A propagating wave along a free surface is called a surface wave. The surface wave is caused by interaction of bulk waves together with the boundary condition. Surface waves propagating in a homogeneous half space are generally Love waves or Rayleigh waves. Love waves have particle movement along the surface transverse to the propagation direction and Rayleigh waves have particle motion both in the propagation direction (like the P-wave) and in the out of plane direction (like the S-wave). The Rayleigh wave has a retrograde particle motion which reaches down one wavelength into the material (Graff, 1975) and the wave velocity is slightly lower than the shear wave velocity.

## 4.2 Lamb wave theory

In an infinite homogeneous medium only body waves can exist. In a rod or plate like structure, P- and S-waves are reflected between the free boundaries generating guided waves along the structure, the structure is a waveguide. A generic name for waves caused by the interaction of bulk waves propagating in a free plate, a plate with large dimensions compared to the thickness, is Lamb waves. Lamb waves carry information about the thickness and elastic properties of the plate material.

Lamb waves cause the plate to oscillate. Depending on the average particle movement with reference to the median plane of the plate, the oscillation is divided into two wave mode families. There are symmetric (also called longitudinal or extensional) and asymmetric (also called flexural or bending) wave modes, depicted in Figure 4.

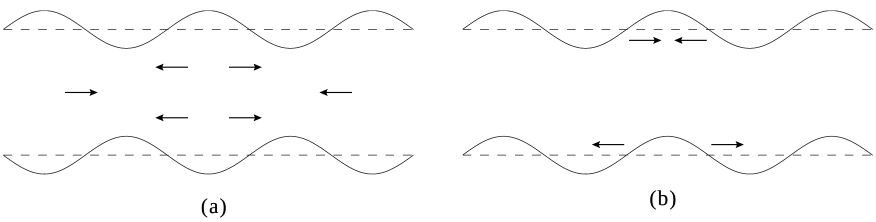



**Figure 4. Particle displacement of (a) symmetric and (b) asymmetric Lamb wave modes.**

Wave propagation in a free plate is only possible for certain frequency and phase velocity combinations. The phase velocity of Lamb waves varies with frequency, i.e. they are dispersive. Lamb (1917) derived the dispersion relation

$$\frac{\tan\left(\beta \frac{d}{2}\right)}{\tan\left(\alpha \frac{d}{2}\right)} + \left(\frac{4\alpha\beta k^2}{\left(k^2-\beta^2\right)^2}\right)^{\pm 1} = 0 \qquad (3)$$

where

$$\alpha^2 = \frac{\omega^2}{V_P^2} - k^2 \quad \text{and} \quad \beta^2 = \frac{\omega^2}{V_S^2} - k^2 \,.$$

The term $d$ in Equation 3 represents the plate thickness, $\omega$ is the angular frequency ($\omega = 2\pi f$, $f$ being frequency) and $k$ is the wave number ($k = \omega / c$, $c$ being the phase velocity). The ± sign in Equation 3 represents symmetric (+) and antisymmetric (-) type of wave propagation.

The velocity ratio $V_P$ / $V_S$ is related to the Poisson's ratio via

$$\frac{V_P}{V_S} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{4}$$

If the dispersion curves are normalized with respect to shear wave velocity and plate thickness, the curves only have to be calculated once for every new value on Poisson's ratio.

The dispersion equation (Equation 3) may look rather straight forward but there are no analytical solutions to it. It has to be solved numerically using a root searching function. An attractive way to find the roots is to set the frequency $f$ to a fix value while the wave number $k$ is varied (Achenbach, 1973). When $k$ is varied the roots will be revealed when the equation value goes towards zero. By performing the calculation for a wide range of frequencies, the solutions can be connected into dispersion curves for each wave mode respectively, see Figure 5. At low frequencies, only one root will be found for each Rayleigh-Lamb equation, corresponding to the fundamental S- and A-modes of vibration (called $S_0$ and $A_0$ respectively). With higher frequencies follow more roots corresponding to higher modes of vibration. If more than one root is found for a fix value of $f$, the root with the lowest phase velocity (highest wave number) corresponds to the fundamental mode.

Dispersion curves for the first three symmetrical and asymmetrical Lamb modes of a plate with a Poisson's ratio $\nu$=0.18, are shown in Figure 5. Note that the dispersion curves are normalized with respect to shear wave velocity and plate thickness so that they are valid for any plate thickness and shear wave velocity.

The solutions to the dispersion equation are generally complex. If only the propagating modes are considered, the imaginary parts can be neglected (Achenbach, 1998). However, to gain understanding about the thickness resonance frequency and how it can be determined, the complex dispersion curves are studied. The same basic principle is utilized where the frequency is set to a fix value in order to scan through a wide span of wave numbers in search of equation roots. Note that in this case the wave number consists of a real-valued part and an imaginary part that both have to be varied individually. The complex solutions can just like the purely real-valued be connected in order to create dispersion curves in the complex wave number domain.

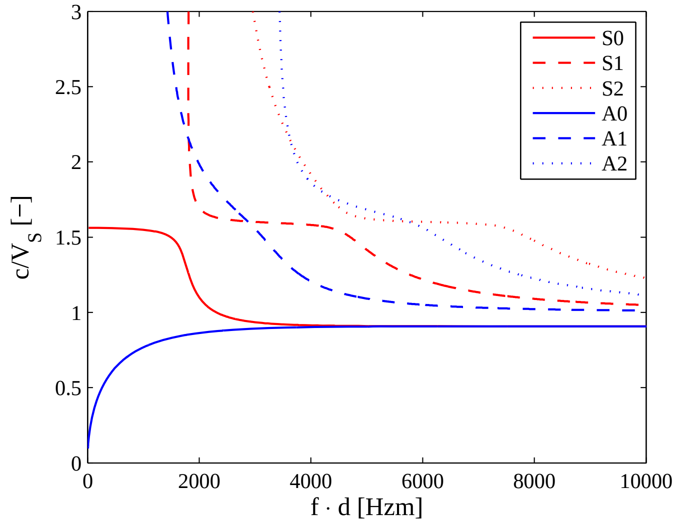



**Figure 5. Normalized dispersion curves for a plate with Poisson's ratio $\nu$ = 0.18. The dispersion curves are valid for any plate thickness and shear wave velocity.**

To gain understanding about complex dispersion curves, a consistent coordinate system first has to be identified. If a plate structure is considered in 1-D, an impact will cause wave propagation in both the positive and negative x-direction, see Figure 6. This implicates the use of Lamb modes with negative mode indices. Wave modes with negative indices mean that the waves are propagating in the negative direction (negative energy flux) according to the definition of positive and negative direction in Figure 6. The energy propagation can never change direction in a homogeneous plate with infinite lateral dimensions, it is therefore only the Lamb modes with positive indices that can be measured by the microphone depicted in Figure 6. The sign of the phase velocity is meanwhile given by wave number, positive wave numbers mean that the phase velocities are positive and vice versa. Mindlin (1960) explained that since the wave number in the Rayleigh-Lamb equation (Equation 3) only appears in the second power, the positive and negative roots must be equally correct, the dispersion curves are therefore mirrored around $k_r = 0$ and $k_i = 0$.

Each frequency is plotted in 3-D against the real part and the imaginary part of the wave number in Figure 7c. The projection of the complex dispersion curves on the plane $k_r = 0$ is plotted in (a), on the plane $k_i = 0$ in (b) and finally on the plane $f = 0$ in (d). The curves plotted

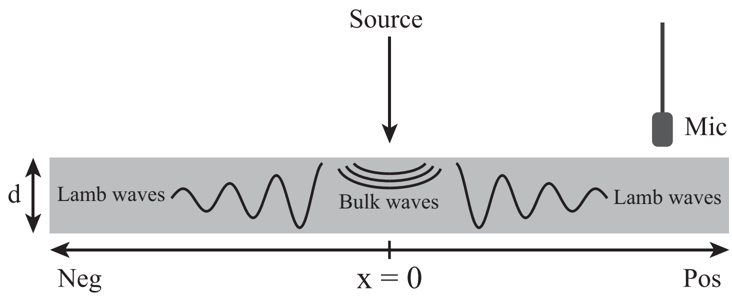



**Figure 6. A schematic picture of the measurement setup. A positive and negative direction is defined.**

are the first two higher symmetrical Lamb modes propagating in the positive ($S_1$ and $S_2$) and negative ($S_{-1}$ and $S_{-2}$) x-direction. The material properties used when plotting the dispersion curves in Figure 7 were $V_S = 2360$ m/s, $d = 0.3$ m and $\nu = 0.18$ and were chosen to match the measured concrete plate in Paper II.

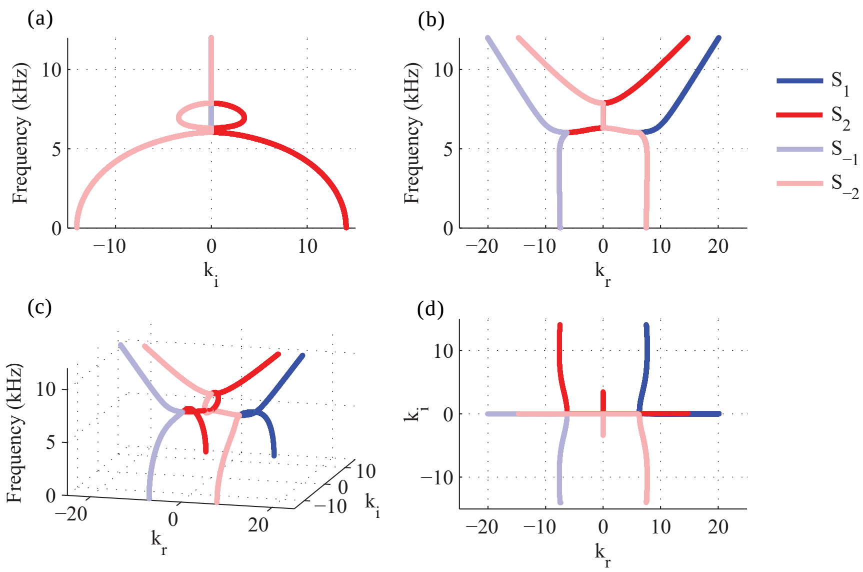



**Figure 7. Complex dispersion curves for a simulated plate with material parameters $V_S$ = 2360 m/s, $d$ = 0.3 m and $\nu$ = 0.18. The curves are plotted in 3-D in (c) and their projections on the plane $k_r$ = 0 in (a), $k_i$ = 0 in (b) and finally $f$ = 0 in (d).**

# 5. Seismic field measurements

The main purpose with this thesis is to perform non-contact surface wave testing using air-coupled microphones and to compare them to conventional accelerometer measurements. Non-contact measurements are here preferable in order to build a data acquisition system that is able to measure while moving. Non-contact measurements on civil structures have shown promising results but have not been compared to conventional accelerometer measurements (Ryden *et al.*, 2008).

Non-destructive seismic field measurements of pavements are today limited to stationary point testing. The use of contact receivers, such as accelerometers, to collect data is time consuming and therefore expensive. Furthermore, the accelerometer needs good attachment with the measured surface to assure good quality data. If the accelerometer is not properly attached to the surface, e.g. due to surface roughness, the risk of errors is predominant.

Non-contact receivers on the other hand have several advantages compared to accelerometers. With all needed equipment mounted on a vehicle, non-contact receivers enable rolling data acquisition almost continuously in a fraction of the time it would take using accelerometers. The problem of good attachment between accelerometer and measured material is also eliminated.

During the field measurements performed in this thesis, normal non-directional audio microphones were used as receivers. Seven microphones were mounted as an array on a prototype trolley (shown in Figure 8), built by Ryden *et al.* (2008) in order to perform measurements while rolling. It should be noted that a seven microphone system is rather small and may be expanded in the future to be able to collect better quality data. However, to test the system and find proper settings, a smaller and more convenient system is used. It is thus reasonable to expect a general improvement when the number of channels is increased. The microphones were connected to a data acquisition device (DAQ) via an amplifier. As an impact source a metal screw attached to a flexible metal strip was used. All equipment was power supplied by batteries. Data were collected and stored on a laptop. Results in this thesis are limited to the Rayleigh wave velocity and the thickness resonance frequency of the studied concrete plate.

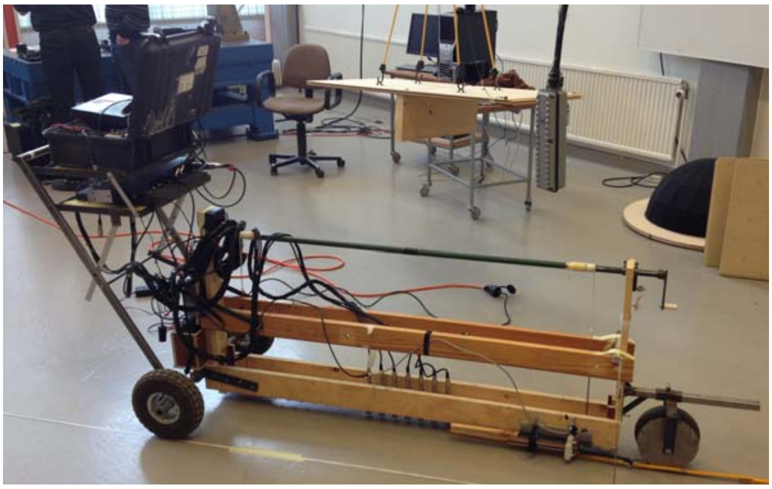


**Figure 8. Prototype trolley built by Ryden *et al.* (2008). The trolley enable air-coupled measurements performed while rolling.**

A multichannel data record can be created in different ways. In this thesis it was performed using two different methods. In Paper I the trolley mentioned above was employed to collect data on seven separate channels simultaneously while rolling. The system was triggered by exceeding a chosen voltage limit set for the first microphone in the receiver array. In Paper II a similar data record was created in stationary measurements using Multichannel Simulation with One Receiver (MSOR) (Ryden *et al.*, 2001). The rolling system from Paper I could not be used here due to the limited number of channels available. A larger system where more signals could be recorded simultaneously could be preferable but at once result in bulkier equipment.

The parameter evaluated in the second paper was the thickness resonance frequency. 80 signals were recorded in order to study the negative phase velocity span. By studying complex dispersion curves (shown in Figure 7) it can be concluded that at frequencies near the minimum frequency (cutoff frequency) of the $S_1$ mode, waves will occur with energy flux and phase velocity of opposite signs (Mindlin, 1960; Simonetti and Lowe, 2005). It is demonstrated how the MASW method can be used to calculate dispersion curves at negative phase velocities in order to detect the resonance waves.

# 6. Results and discussion

The non-contact measurements using air-coupled microphones in this thesis were performed in order to evaluate two parameters, Rayleigh wave velocity and thickness resonance frequency, and compare them to results from conventional accelerometer measurements.

## Paper I

The Rayleigh wave velocity was evaluated from data collected using an array of seven microphones mounted on a mobile trolley. The MASW method transforms the collected data into calculated dispersion curves that can be fitted to theoretical ones. The fundamental asymmetric dispersion curve $A_0$ is dominant in these images due to the large out of plane motion caused by this wave mode (Gibson and Popovics, 2005). Figure 9 shows good similarities between experimental dispersion curves collected using (a) an accelerometer and (b) microphones.

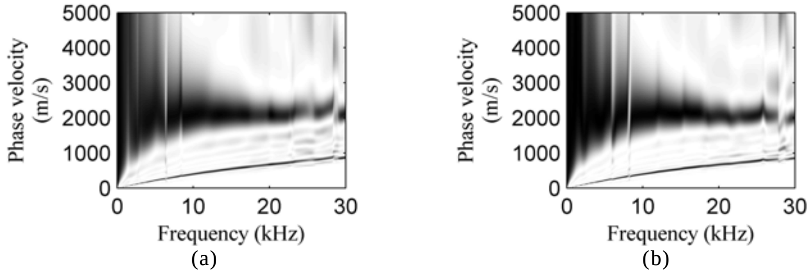



**Figure 9. Experimental dispersion curves from (a) accelerometer and (b) air-coupled microphones calculated using the MASW method.**

Data from the air-coupled microphone array were collected in 60 positions along a straight survey line. The same survey line was repeated five times to study repeatability. The mechanical impact was triggered automatically when rolling the trolley forward. The data from every measuring position were automatically and objectively evaluated in the same way in order to estimate a Rayleigh wave velocity.

Conventional accelerometer measurements were performed in twelve positions with equal increments along the survey line for comparison. An equivalent array was created by attaching an accelerometer in the impact point from the microphone setup and multiple impacts were instead applied in the microphone positions. Due to reciprocity, a signal from point A to point B is equal to a signal from B to A (in a linear system), comparable signals were achieved. The collected accelerometer data were processed the same way as the microphone data to receive comparable results.

The extracted result were in this study limited to the asymptotic trend of the non-dispersive end of the $A_0$ dispersion curve at high frequencies (see Figure 5) equal to the Rayleigh wave velocity. The evaluated Rayleigh wave velocity results along the survey line from microphone and accelerometer measurements are shown in Figure 10. The length of the microphone array is illustrated with horizontal markers in the lines from the microphone data sets.

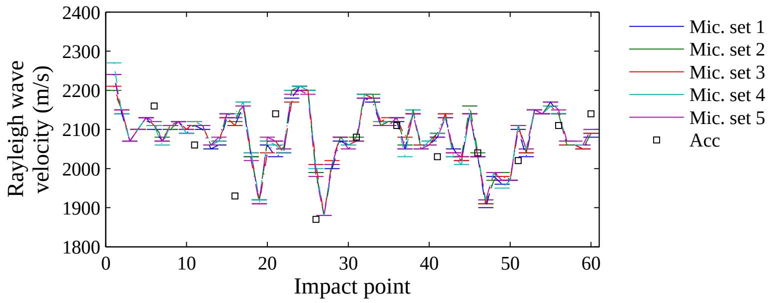



**Figure 10. Evaluated Rayleigh wave velocity along the survey line. The measurements are repeated five times to ensure high repeatability. The microphone array length at each position is illustrated with horizontal markers.**

Results from the investigated survey line revealed that the variation in evaluated Rayleigh wave velocity is small between the different measuring sets, i.e. the repeatability is high. However, the variation along the surface line was large. A part of the large velocity variation could be explained by local variability in the material. However, it was suspected that a large part of the variation along the survey line was due to small misalignments between the microphone array and the measured surface. A sensitivity analysis for the microphone array used in this study showed that even rather small misalignments could cause large errors. Measures to overcome the misalignment problem were discussed. It was shown that under certain circumstances the trolley could be turned around to collect data in the opposite direction in order to even out certain types of the misalignments. Evaluated Rayleigh wave velocities from the forward and backward rolling measurements are together with accelerometer results shown on a synchronized x-axis in Figure 11.

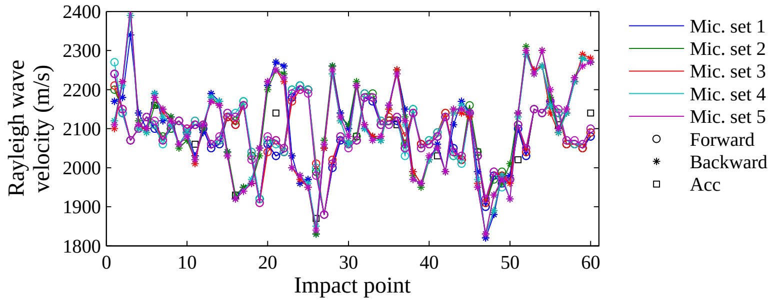



**Figure 11. Evaluated Rayleigh wave velocity from measurements performed in the forward and the backward direction. Accelerometer measurements are plotted for comparison.**

Figure 11 clearly shows that the accelerometers used as reference in most cases give results somewhere between the forward and backward rolling measurements. In Figure 12 the mean from all microphone measuring sets (five sets performed in the forward direction and five sets in the backward direction) is shown as a black line. The comparative accelerometer measurement results are plotted as red squares.

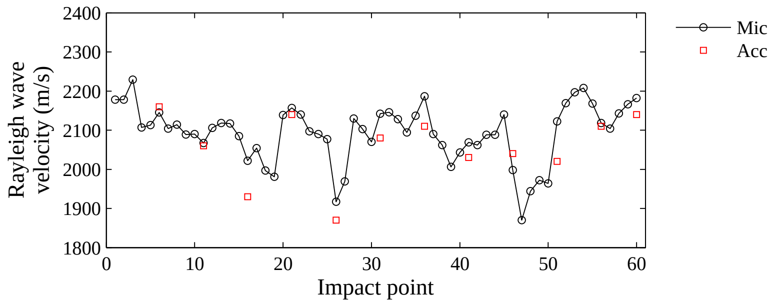



**Figure 12. Evaluated Rayleigh wave velocity averaged from forward and backward rolling measurements plotted in black. Accelerometer results are shown in red for comparison.**

The results from the microphone measurements after the "neutralizing" in Figure 12 are generally closer to the accelerometer reference measurements than after the first measurement performed in one direction. It can be concluded that the proposed method to even out the misalignments to some degree can improve the results. However, to consider errors caused by non-symmetric misalignments and surface roughness, further research is needed.

To examine the errors on a surface with realistic unevenness, a simulated surface for a high quality pavement (Andren, 2006; Bogsjö *et al.*, 2012) was created and is shown in Figure 13 (red line). A synthetic periodic wave with a constant frequency of 12 kHz was created by Equation 5, where $x$ is the array vector and $k$ is wave number with a reference phase velocity of 2200 m/s. 15 receivers with 0.05 m increments were simulated perfectly horizontal over the uneven surface. The surface unevenness was considered in the time-dependent term $\omega{\cdot}t$ by adding an individual time lag to each signal. The relative phase velocity error from the MASW method applied to the synthetic signal (from Equation 5) is plotted in Figure 13 (blue solid line). The same procedure was performed in the opposite direction (blue dashed line) to simulate rolling the trolley in the backward direction. The mean of the two simulations performed in opposite directions is very close (max 0.75%) to the reference velocity (zero relative error).

$$u(x,t) = A \cdot e^{i(k \cdot x - \omega \cdot t)} \tag{5}$$

In this case it is reasonable to expect that the errors are unrealistically large due to the assumption that the receiver array is always perfectly horizontal. In field measurements the trolley will be parallel to the surface in a slope which is longer than the distance between the wheels on the trolley. In this case the errors may be smaller than what is simulated in this study.

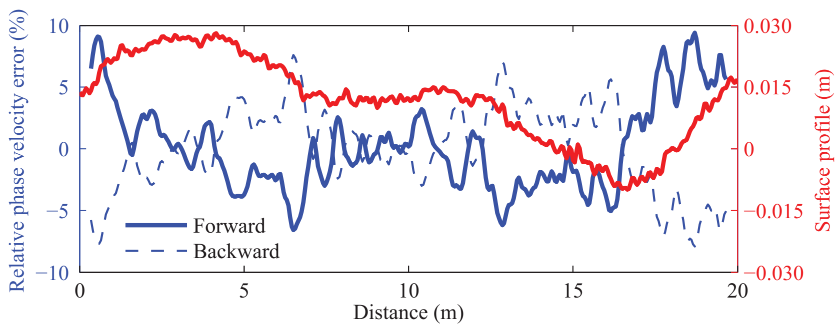



**Figure 13 : Relative phase velocity error (without unit) in calculated Rayleigh wave velocity for a synthetic periodic wave with a fix frequency of 12 kHz and a reference velocity of 2200 m/s.**

## Paper II

The evaluated parameter in the second paper is thickness resonance frequency. A commonly used technique to estimate plate thickness is the Impact Echo (IE) method (Sansalone, 1997) which is based on the measurement of this resonance frequency. However, IE is not a suitable method when air-coupled microphones are applied as receivers due to low signal-to-noise ratio. The resonance frequency is related to the minimum (cutoff) frequency of the $S_1$ Lamb mode. A simulation was performed using the software Comsol (Comsol, 2010) with the material parameters specified in Figure 7, chosen to represent the studied concrete plate as closely as possible. In this simulation the thickness resonance frequency was found to be 6014 Hz. Instead of using the conventional amplitude spectrum from a contact sensor, an alternative method is here proposed based on backward wave propagation. Negative phase velocities in a narrow frequency span close to the thickness resonance frequency can be theoretically predicted (Figure 7). The collected data was transformed from time to frequency domain and imaged as experimental dispersion curves using the MASW method. The wave amplitude values depicted as black in Figure 14b (where black is high amplitude and white is zero amplitude) were summed for each frequency over a chosen phase velocity range shown in the figures for each experimental setup. The summed amplitudes were normalized and plotted against frequency to find a peak which was taken as the resonance and compared to the theoretical value, see Figure 14c. Note that wavelengths shorter than half an increment between two receivers, or longer than twice the receiver array length, were sorted out and their amplitude set to zero to avoid spatial aliasing.

The measurements were performed in three sets. The first data set was collected using an accelerometer as receiver in order to have a contact measurement reference test. A schematic picture of the setup is shown in Figure 14a. 40 signals were collected with 0.05 m increments over a distance of 2.0 m from the source. Calculated amplitudes for the waves in the negative phase velocity range from -20 to -5 km/s are plotted in Figure 14b. The amplitudes from Figure 14b were summed over the shown phase velocity span for each frequency individually and plotted for a narrower frequency range in Figure 14c. A distinct peak marks the maximum backward wave amplitude at 6014 Hz.

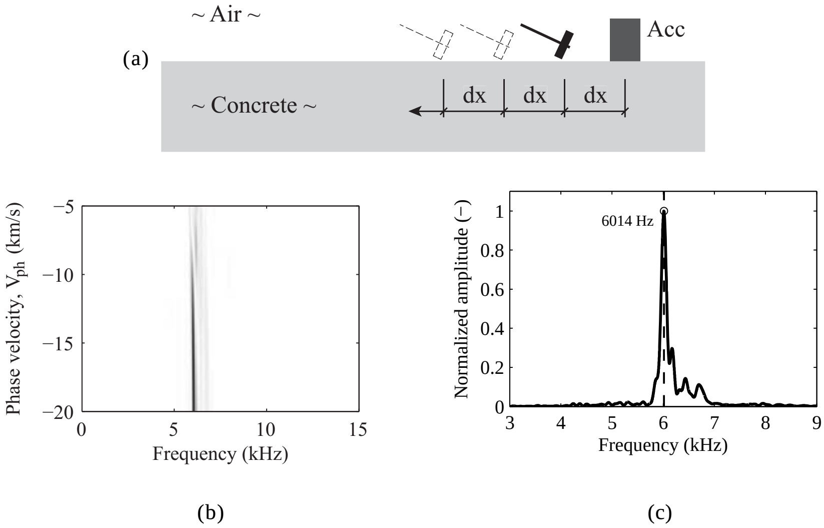
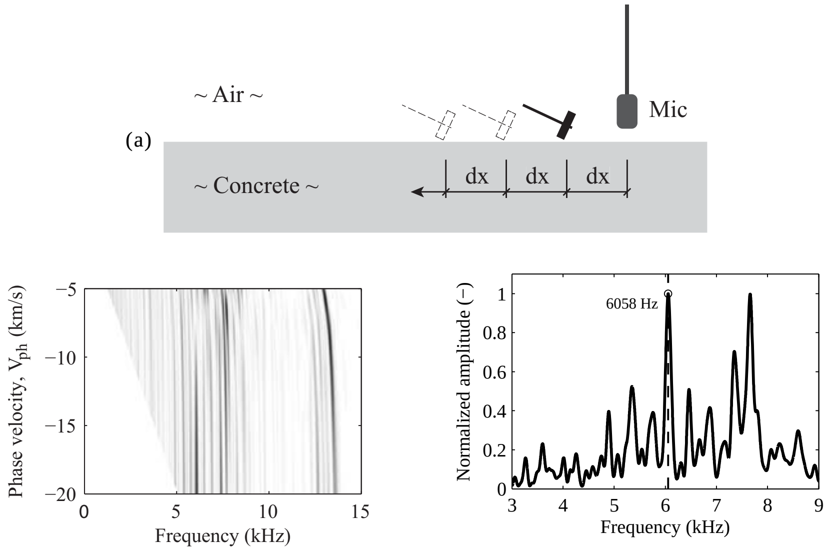



**Figure 14. (a) Schematic setup using accelerometer. (b) The amplitudes from the calculated dispersion curves for negative phase velocities were summed for each frequency and at last normalized and plotted in (c).**

The second data set was collected using an air-coupled microphone as receiver as shown in Figure 15a. The increments between the impact points were reduced to half, i.e. to 0.025 m, to avoid spatial aliasing of the direct acoustic wave in the air down to about 6 kHz. 80 signals over a distance of 2.0 m were collected in this set. The backward waves are less visible when using a microphone as receiver, see Figure 15b but the same peak as before can still be found when the wave amplitudes are summed for the negative velocities, Figure 15c.




(b) (c)

**Figure 15. (a) Schematic setup for the microphone case. (b) The amplitudes from the calculated dispersion curves for negative phase velocities were summed for each frequency and at last normalized and plotted in (c).**

The third data set was collected using the same air-coupled microphone as before as receiver. However, in this final set a small piece of soft foam acting as sound barrier was placed in front of the microphone to prevent the direct sound wave through the air to be recorded, shown in Figure 16a. The same settings and number of signals as the previous set were used here. The processed data are shown in Figure 16b and finally the summed amplitudes in Figure 16c. It is shown that even a small sound barrier in front of the microphone tend to improve the signal-to-noise ratio significantly.

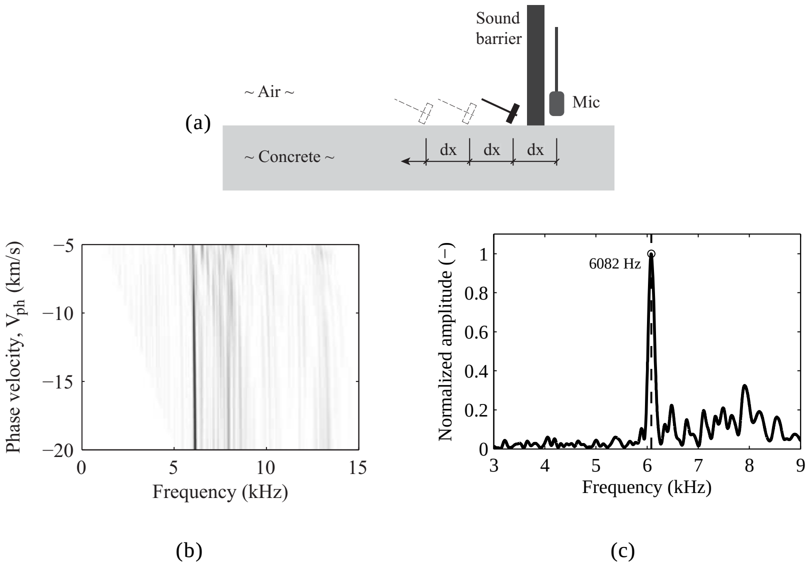



**Figure 16. (a) Schematic setup for the case using a microphone with a small sound barrier in front. (b) The amplitudes from the calculated dispersion curves for negative velocities were summed for each frequency and at last normalized and plotted in (c).**

The thickness resonance frequency was independently measured to 6014 Hz using the conventional IE amplitude spectrum measured. The material parameters used in the mentioned simulation also gave a $S_1$ mode minimum frequency of 6014 Hz. All three data sets in this thesis show waves with negative phase velocities at frequencies close to the expected resonance frequency. At most the difference between the estimated resonance frequency and the theoretical one is 1.1%, a difference that can be seen as insignificant in the context of calculating the plate thickness in civil structures. It can be concluded that the introduced method using backward wave propagation presented in this paper determines the thickness resonance frequency using both accelerometers and microphones.

# 7. Summary of findings

The work presented in this thesis has shown that it is possible to estimate the Rayleigh wave velocity with non-contact measurements using air-coupled microphones. The repeatability is very high when the same survey line is measured several times. However, the Rayleigh wave velocity variation along the survey line was found to vary surprisingly much. Even small misalignments between the air-coupled microphone array and the measured surface are enough to cause significantly large errors. It is demonstrated how measurements performed in opposite directions can help overcome these problems under certain circumstances.

It is also shown how conventional IE measurements using an air-coupled microphone as receiver can give unrealistic results due to low signal-to-noise ratio. An alternative method to determine the thickness resonance frequency based on backward wave propagation is introduced. It is demonstrated how an array of air-coupled microphones can be used to measure waves with negative phase velocities in a narrow frequency span near the thickness resonance frequency.

# 8. Future work

The results from rolling measurements presented in this thesis indicate that measurements using air-coupled microphones are sensitive to misalignments between the microphone array and the measured surface. Improvement in this field is needed in order to present reliable measurements. Lasers could be attached to the microphone array to measure the actual distance between the microphone array and the measured surface. Measured differences in distances along the array could then be taken into account in the data processing. An alternative can be to develop the “neutralizing” method used in this thesis. With dual impacts, one on each side of the microphone array, the neutralizing could be performed in every measuring position immediately and the trolley would not have to be rolled in both directions.

Estimation of the thickness resonance frequency using backward wave propagation showed to be successful. However, a data record of 80 signals over 2 m distance was created to receive good quality data. To perform rolling measurements where the thickness resonance frequency can be estimated, more channels placed closer together over a longer array length is probably needed to increase signal to noise ratio and avoid spatial aliasing of the direct air wave.

A key parameter to perform rapid and reliable non-contact measurements using air-coupled microphones seems to be the number of signals where more signals give higher resolution and better results. A non-contact source should also likely improve the overall functionality and quality of the measurement system. Future experiments could include alternative equipment (different receivers and impact sources) and different measurement setups in order to find a manageable, reliable and flexible data acquisition system

# 9. References

Abraham, O., Piwakowski, B., Villain, G. and Durand, O., 2012, *Non-contact, automated surface wave measurements for the mechanical characterization of concrete*, Construction and Building Materials, vol. 37, pp. 904-915.

Achenbach, J.D., 1973, *Wave propagation in elastic solid*, North-Holland Publishing Company, Amsterdam.

Achenbach, J.D., 1998, *Lamb waves as thickness vibrations superimposed on a membrane carrier wave*, Journal of the Acoustical Society of America, vol. 103 (5), pp. 2283-2286.

Ambrozinski, L., Piwakowski, B., Stepinski, T. and Uhl, T., 2012, *Application of air-coupled ultrasonic transducers for damage assessment of composite panels*, 6th European Workshop on Structural Health Monitoring, Tu.3.E.1, Dresden, Germany.

Andren, P., 2006, *Power spectral density approximations of longitudinal road profiles*, International Journal of Vehicle Design, vol. 40 (1-3), pp. 2-14.

Bogsjö, K., Podgórsgi, K. and Rychlik, I., 2012, *Models for road surface roughness*, Vehicle System Dynamics, vol. 50 (5), pp. 725-747.

Castaings, M. and Cawley, P., 1996, *The generation, propagation, and detection of Lamb waves in plates using air-coupled ultrasonic transducers*, Journal of the Acoustical Society of America, vol. 100 (5), pp. 3070-3077.

Comsol Multiphysics, User's Guide, Version 3.5 by – COMSOL AB 2010, http://www.comsol.com

Dai, X., Zhu, J. and Tsai, Y.T., 2011, *Use of parabolic reflector to amplify in-air signals generated during impact-echo testing*, Journal of the Acoustical Society of America, Express Letters, vol. 130 (4), pp. 167-172.

Ganji, V., Gucunski, N. and Nazarian, S., 1998, *Automated inversion procedure for spectral analysis of surface waves*, Journal of Geotechnical and Geoenvironmental Engineering, vol. 124 (8), pp. 757-770.

Gibson, A. and Popovics, J.S., 2005, *Lamb wave basis for Impact-Echo method analysis*, Journal of Engineering Mechanics, vol. 131 (4), pp. 438-443.

Graff, K.E., 1975, *Wave motion in elastic solids*, Oxford University Press, London.

Haskell, N.A., 1953, *The dispersion of surface waves on multilayered media*, Bulletin of the Seismological Society of America, vol 53 (1), pp. 17-34.

Heisey, J.S., Stokoe II, K.H. and Meyer, A.H., 1982, *Moduli of pavement systems from spectral analysis of surface waves*, Transportation Research Record, vol. 852, pp. 22-31.

Heukelom, W. and Foster, C.R., 1960, *Dynamic testing of pavements*, Journal of the Soil Mechanics and Foundations division, Vol. 86 (SM1), Part 1, pp. 1-28.

Holland, S.D. and Chimenti, D.E., 2003, *Air-coupled acoustic imaging with zero group velocity*, Applied Physics Letters, vol. 83 (13), pp. 2704-2706.

Jones, R., 1955, *A vibration method for measuring the thickness of concrete road slabs in situ*, Magazine of Concrete Research, vol. 7 (20), pp. 97-102.

Kee, S.-H., Fernández-Gómez, E. and Zhu, J., 2011, *Evaluating surface-breaking cracks in concrete using air-coupled sensors*, ACI Materials Journal, vol. 108 (5), pp. 558-565.

Kee, S.-H., Oh, T., Popovics, J.S., Arndt, R.W. and Zhu, J., 2012, *Nondestructive bridge deck testing with air-coupled impact-echo and infrared thermography*, Journal of Bridge Engineering, vol. 17 (6), pp. 928-*939.*

*Lamb, H., 1917, On waves in elastic an plate*, Proceedings A, The Royal Society, vol. 93 (648), pp. 114-128.

Luukkala, M., Heikkila, P. and Surakka, J. 1971, *The wave resonance – a contactless test method*, Ultrasonics, vol 9 (4), pp. 201-208.

Mindlin, R.D., 1960, *Waves and vibrations in isotropic elastic plates*, Proceedings of the first symposium on naval structural mechanics, pp. 199-232.

Nazarian, S., Stokoe I, H.K. and Hudson, W.R, 1983, *Use of the spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems*, Transportation Research Record 930, pp. 38-45.

Nazarian, S., Stokoe I, H.K., Briggs, R.C. and Rogers, R., 1987, *Determination of pavement layer thicknesses and moduli by the SASW method*, Transportation Research Record 1196, pp. 133-150.

Nazarian, S., Yuan, D. and Tandon, V., 1999, *Structural field testing of flexible pavement layers with seismic methods for quality control*, Journal of the Transportation Reseach Board, vol. 1654, pp. 50-60.

Park, C.B., Miller, R.D. and Xia, J., 1999, *Multichannel analysis of surface waves*, Geophysics, vol. 64 (3), pp. 800-808.

Pickett, G., 1945, *Dynamic testing of pavements*, Journal of the American Concrete Institute, vol. 16 (5), pp. 473-489.

Piwakowski, B. and Safinowski, P., 2009, *Non-destructive non-contact air-coupled concrete evaluation by an ultrasound automated device*, 7th International Symposium on Non Destructive Testing in Civil Engineering, June 30th – July 3rd, Nantes, France.

Popovics, J.S., Ham, S., Ghasr, M.T. and Zoughi, R., 2014, *Comparison of synthetic aperture radar and impact-echo imaging for detecting delamination in concrete*, 40th Annual Review of Progress in Quantitative Nondestructive Evaluation, AIP Conference Proceedings 1581, pp. 866-871.

Rix, G.J., Stokoe II, K.H. and Roesset, J.M., 1991, *Experimental study of factors affecting the Spectral Analysis of Surface Waves method*, Research report 1123-5, Center for Transportation Research, The University of Texas at Austin.

Ryden, N., Ulriksen, P., Park, C.B., Miller, R.D., Xia, J. and Ivanov, J, 2001, *High frequency MASW for non-destructive testing of pavements-accelerometer approach*, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2001), Environmental and Engineering Geophysical Society, Annual Meeting, Denver, Colorado.

Ryden, N. and Park, C.B., 2006, *Fast simulated annealing inversion of surface waves on pavements using phase velocity spectra*, Geophysics, vol. 71 (4), pp. R49-R58.

Ryden, N., Lowe, M.J.S. and Cawley, P., 2008, *Noncontact surface* wave scanning of *pavements using a rolling microphone array*, CP975, Review of Quantitative Nondestructive Evaluation Vol. 27, ed. by D.O. Thompson and D.E. Chimenti, AIP Conference Proceedings, pp. 1328-1332.

Sansalone, M., 1997, *Impact Echo: The complete story*, ACI Structural Journal, vol. 94 (6), pp. 777-786.

Simonetti, F. and Lowe, M.J.S., 2005, *On the meaning of Lamb mode nonpropagating branches*, Journal of the Acoustical Society of America, vol. 118 (1), pp. 186-192.

Stokoe II, H.K., Wright, S.G., Bay, J.A. and Roesset, J.M., 1994, *Characterization of geotechnical sites by SASW method,* ISSMFE Technical Committee #10, ed. by R.D. Woods, Oxford & IBH Publ., pp. 15-25.

Thompson, W.T., 1950, *Transmission of elastic waves through a stratified solid medium*, Journal of Applied Physics, vol 21, pp. 89-93.

Trafikverket, 2011, *TRVKB 10 Bitumenbundna lager*, Swedish Transport Administration.

Van der Poel, C., 1951, *Dynamic testing of Road Constructions*, Journal of Applied Chemistry, vol. 1 (7), pp. 281-290.

Yuan, D., Nazarian, S., Chen, D. and McDaniel, M., 1999, *Use of seismic methods in monitoring pavement deterioration during accelerated pavement testing with TxMLS*, International Conference on Accelerated Pavement Testing, Reno, Nevada.

Zhu, J. and Popovics, J.S., 2002, *Non-contact detection of surface waves in concrete using an air-coupled sensor*, CP615, Review of Quantitative Nondestructive Evaluation Vol. 21, ed. by D.O. Thompson and D.E. Chimenti, AIP Conference Proceedings, pp. 1261-1268.

Zhu, J. and Popovics, J.S., 2005, *Non-contact imaging for surface-opening cracks in concrete with air-coupled sensors*, Materials and Structures, vol 38 (9), pp. 801-806.

Zhu, J. and Popovics, J.S., 2007, *Imaging concrete structures using air-coupled impact-echo*, Journal of Engineering Mechanics, American Society of Civil Engineers, vol. 133 (6), pp. 628-640.