RADIATION OF SURFACE WAVES INTO CONCRETE BY MEANS OF A WEDGE TRANSDUCER: DESIGN AND OPTIMIZATION

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Abstract: Spectral Analysis of Surface Waves (SASW) has been used for two decades to determine the stiffness profile of soils. The application of this technique is currently evaluated for inspecting subsurface damage in concrete structures in the 100 kHz frequency range. Accurate measurements of phase velocity and attenuation require an appropriate source to efficiently generate wideband Rayleigh waves. This paper presents the design and testing procedure of a variable angle wedge transducer. The performance of this transducer is evaluated in terms of the peak amplitude and frequency of the transmitted signal, and it is compared with the performance of the fixed angle wedge transducer used so far. In mortar, the new design is slightly more efficient than the previous one. In other materials (steel and Plexiglas), it allows to generate Rayleigh waves, whereas the fixed angle transducer is completely inefficient. The newly designed transducer can thus be considered as a suitable source of Rayleigh waves for a wide range of materials. Further optimisation requires the wave path in the wedge to be minimized.

Introduction: This paper presents the design and evaluation of a variable angle wedge transducer. This transducer is intended to be used to investigate subsurface defects in the concrete cover of civil structures. The testing technique is the Spectral Analysis of Surface Waves, or SASW (Krstulovic-Opara et al., 1996). It consists in transmitting pulsed Rayleigh waves along the surface of the structure and, by picking up the signals received at several locations, to evaluate the phase velocity dispersion. As the penetration depth of the Rayleigh wave is proportional to the wavelength, this measurement provides results related to the elasticity and damage profile as a function of depth. As deterioration of concrete is due to penetration of chemical agents (moisture, CO_2, nitrates, sulfates,…) through the cover, such information is of major importance to predict the long-term durability of the structure.

The implementation of the SASW technique in heterogeneous materials, like concrete, requires efficient generation and reception of Rayleigh waves. In our application, the subsurface area to be investigated is a few centimeters deep, so a frequency range from 150 to 700 kHz approximately is required to achieve sufficient spatial resolution. Several excitation sources can be used: impact sources, point-contact, comb and wedge (or angle beam) transducers (Viktorov, 1967). Impact sources, such as the impact hammer (Cho and Lin, 2001), are not repetitive and limited to a lower frequency range. In addition, the level of spurious signals associated with the generation of volume wave is high. Dry point contact piezoelectric transducers have been recently designed (Shevaldykin et al., 2003), but their frequency range is still below 200 kHz. Comb transducers are efficient sources of Rayleigh waves, but they are restricted to narrowband applications. Finally, the wedge method is the most widely employed for Rayleigh wave excitation, and it complies with the requirements of our specific application: wide bandwidth, high frequency range and high sensitivity. The principle of the wedge method is to convert the volume wave (longitudinal or shear) in the wedge into a Rayleigh wave in the tested sample, by causing total reflection of volume waves. According to Snell-Descartes laws of geometrical acoustics (Kinsler and Frey,1982), the angle of refraction of a plane wave incident with angle θ_l from the wedge material is given as:

$$sin\theta_2=\frac{c_{2\,L,T}}{c_{1\,L,T}}sin\theta_1 \quad (1)$$

where $c_{1\,L,T}$ and $c_{2\,L,T}$ are the longitudinal or shear wave velocities, respectively in the wedge and in the sample. Total reflection of both longitudinal and shear waves is achieved as angle θ_2 equals 90°, thus for :

$$sin\theta_1=sin\theta_{1C}=\frac{c_{1\,L,T}}{c_{2\,T}} \quad (2)$$

Eq.2 expresses the critical angle, allowing Rayleigh waves to be generated into the sample. This angle exists if $c_{1\,L,T} < c_{2,T}$. As the shear velocity in concrete is around 2000 m/s, a low velocity material is required for the wedge. In a recent study (Piwakowski et al., 2003), several transducer/wedge material combinations were investigated. The best combination, in terms of efficiency, bandwidth and frequency range, was obtained using a commercial longitudinal wave transducer (Panametrics V191: diameter 1,125', 0,5 MHz central frequency) coupled with a Teflon wedge. Teflon has a longitudinal velocity (1350 m/s) lower than $c_{2,T}$. In addition, it can be easily machine-finished and has outstanding mechanical properties. The angle of the wedge was calculated for $c_{2,T}$ equal to 2000 m/s, which yields an angle of 42°. However, this angle may not be appropriate for all kinds of concrete, e.g. with high density of gravels ($c_{2,T}$ > 2000 m/s) or highly deteriorated ($c_{2,T}$ < 2000 m/s). Therefore, further optimization of Rayleigh wave generation requires designing a new wedge transducer with variable angle.

The following section describes the geometry of this new transducer. Two solutions, referred as small and large base transducers, will be explored. Then, the signal generated by the new transducer is compared with the one generated by the previous design (with fixed angle). The tested sample is made of mortar, but other materials with higher or lower velocity (steel and Plexiglas) are also considered. The signal level and central frequency is also presented as a function of the wedge angle. The paper finally concludes on the possibility and pertinence of adopting the newly designed transducer for concrete testing.

Results: The geometry of the variable angle wedge transducer is presented in figure 1. It is simply made of two complementary parts: a rotating part and a fixed part. The rotating part is a half cylinder; a thin circular hole is made on its flat side to receive the active element of the ultrasonic transducer. The fixed part, later referred as the "base", has a bottom side laid on the inspected sample and a curved side in contact with the rotating part.

The transducer, the cylinder and the base are fastened to each other with a steel strap. All interfaces (transducer/cylinder, cylinder/base and base/sample) are covered with a coupling gel to ensure transmission of the ultrasonic wave. According to Viktorov (1967), the optimum excitation is obtained when the projection of the wedge bottom onto its sloping face coincides with the transducer diameter. It the dimension of the base is too small, the emitted beam bounces against the side edges of the wedge; if it is too large, the converted Rayleigh wave is attenuated as it radiates as a leaky wave back into the wedge. In our case, Viktorov's criterion is impossible to fulfil for all angle values. Therefore, two dimensions have been considered for the base: a smaller one, where the criterion is fulfilled only for the angle computed for the fixed wedge (42°); and a larger one, where the projection of the wedge bottom onto the sloping face is always larger than the transducer diameter, for angles corresponding to 1700 m/s < $c_{2,T}$ < 2100 m/s.

The experimental setup used to evaluate the newly designed wedge transducer is shown in figure 2. The electrical excitation of the emitter is generated by means of a high-frequency pulser-receiver (Panametrics 5055PR). To eliminate the influence of variable coupling between the receiver and the sample, an air-coupled transducer (mBAT-1 by Microacoustic Instruments) is used to pick up the transmitted signal at different locations along the sample. The tilting of the receiver is adjusted to the critical angle between the sample material and air, so as to maximize the amplitude of the received signal for the Rayleigh wave. To avoid near-field effects, the minimum emitter/receiver distance is set beyond the value of the Fresnel distance, i.e. $z_f=D^2/\lambda_R$ where D is the length of the wedge base and λ_R the wavelength of the Rayleigh wave in the sample at the central frequency of the transmitter. The received signal is amplified first, through a low noise charge amplifier (Q-Amp by Microacoustic Instruments) and second, through the 60dB amplifier of the 5055PR. It is further acquired on a digital oscilloscope (Tektronix TDS 3012B), averaged 256 times and transmitted to a PC through the GPIB.

The tested sample is a slab of mortar with dimensions 300×150 mm and 50 mm thickness. The mortar is made of 11% water, 22% cement and 67% sand with grain diameter less than 5 mm. The wedge transducer has also been evaluated on other materials: a block of Plexiglas (100 mm thick) and a plate of steel (400 mm thick). Thickness values are chosen significantly larger than the Rayleigh wavelength to avoid propagation of Lamb modes.

Figure 3, 4 and 5 compares the received signals and their spectra, using the variable angle wedge (short and large base) and the fixed angle wedge, for the three tested materials. Since the path in the fixed angle wedge is the shortest, the time delay is always smaller for this wedge. The highest received peak amplitude is obtained with the short base wedge for the mortar and steel samples, and with the long base wedge for the Plexiglas sample. Figure 6.a shows the peak amplitude S_{max} of the received signal as a function of the wedge angle, for the short base wedge and the mortar sample. In a similar way, Figure 6.b presents the variation of frequency F_{max}. We observe that the maxima of S_{max} and F_{max} are located at the same angle (40°).

Discussion: The selected criteria for determining the optimal transducer design are the peak amplitude S_{max} and frequency F_{max}. Maximum values of these indexes are achieved when the wave attenuation in the wedge is minimized. In mortar, the short base wedge gives a slightly better result than the fixed wedge, although the value of F_{max} is slightly lower. In this case, the new design doesn't provide a significant improvement. However, the test was made on a material for which the angle of the fixed wedge is already nearly optimal. Further tests should be made on a cement-based material with a significantly higher (e.g. concrete with gravel) or lower velocity (e.g. mortar with a higher water/cement ratio or with surface damage).

In contrast, tests on other materials (steel and Plexiglas) show that the variable wedge transducer can generate Rayleigh waves in cases where the angle of the fixed wedge is not suitable. The short base design gives better results, except on materials with velocity lower than in mortar (< 2000 m/s). In this case, the critical angle is higher than 42° and part of the ultrasonic beam is reflected on the side edge of the wedge. The long base wedge gives then better results.

As for frequency F_{max}, we observed that the value for the fixed angle wedge is slightly higher than for the variable angle wedge. This is because the wave path is a little shorter in the fixed angle wedge, so signal attenuation is lower and the downward spectral shift is slightly reduced. For all tested designs, frequency F_{max} is significantly lower than the original 0,5 MHz transducer central frequency: around 200 kHz in mortar and Plexiglas, around 300 kHz in steel. This relatively low value in steel, a quasi lossless material, suggests that this frequency shift is partly due to wave attenuation in Teflon. In addition, the spectrum presents a second peak around 450 kHz. One possible explanation is that the high acoustic impedance mismatch between Teflon and steel causes multiple reflections of the original longitudinal wave into the wedge.

Conclusions: A variable angle wedge transducer was designed and tested. This transducer is intended to efficiently generate Rayleigh waves in the 100 kHz frequency range, and will be used to evaluate subsurface damage in concrete structures. Its performances were compared with those of a previous design, namely a fixed angle wedge transducer. The experimental setup includes the wedge transducer as transmitter and an air-coupled transducer as receiver. The criteria chosen for comparison between designs are the peak amplitude and the frequency of the spectral peak of the received signal. The new design was found only slightly better in the case of mortar. Nevertheless, it was able to generate Rayleigh waves in other materials, such as steel and concrete, whereas the fixed angle wedge transducer was not. The long base design gives better results in materials with velocity lower than 2000 m/s, and the short base design in other cases. The obtained results suggest further tests and optimization. Firstly, various cement-based materials with Rayleigh wave velocity differing from the reference value of 2000 m/s will be tested to evaluate the advantage of the new design over the previous one. Secondly, it appears that using Teflon as the wedge material causes a significant downward shift of the central frequency. However, readily available materials with less attenuation would not have a velocity low enough to allow generation of Rayleigh waves. Therefore, further optimisation of the variable wedge transducer will consist in reducing as much as possible the wave path in the wedge.

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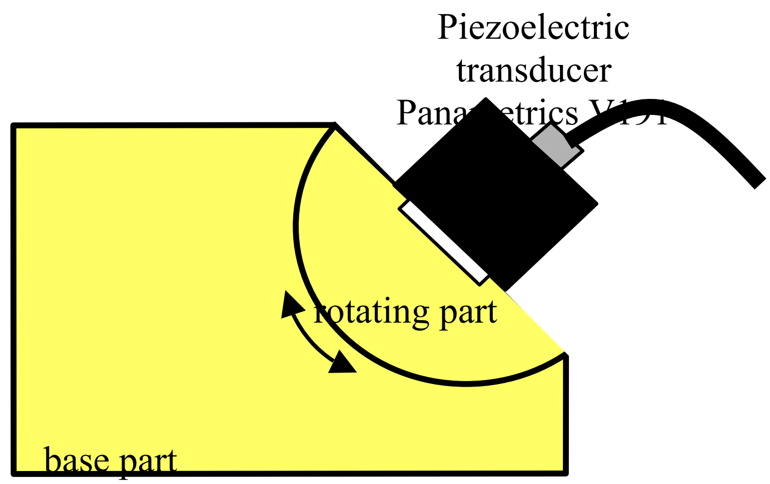

Figure 1 : sketch of the variable angle wedge transducer

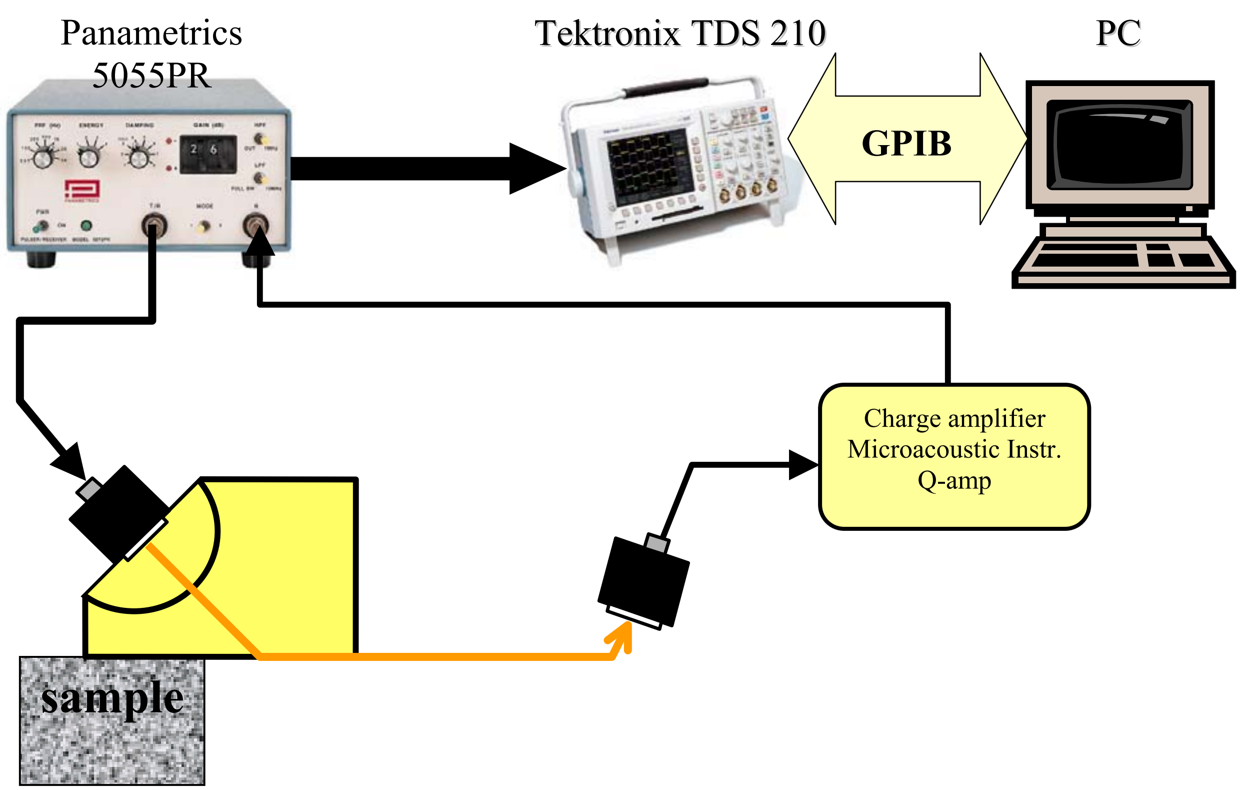

Figure 2 :experimental setup used for evaluating the variable angle wedge transducer

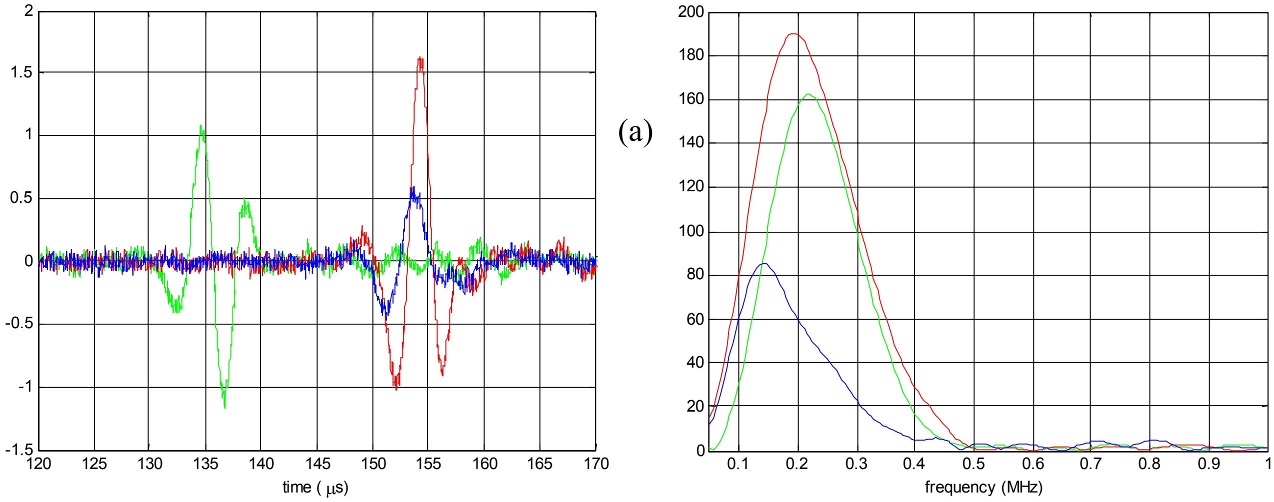

Figure 3 :signals generated in mortar (a) time waveforms (b) spectra
red: short base wedge – blue: large base wedge - green: fixed angle wedge

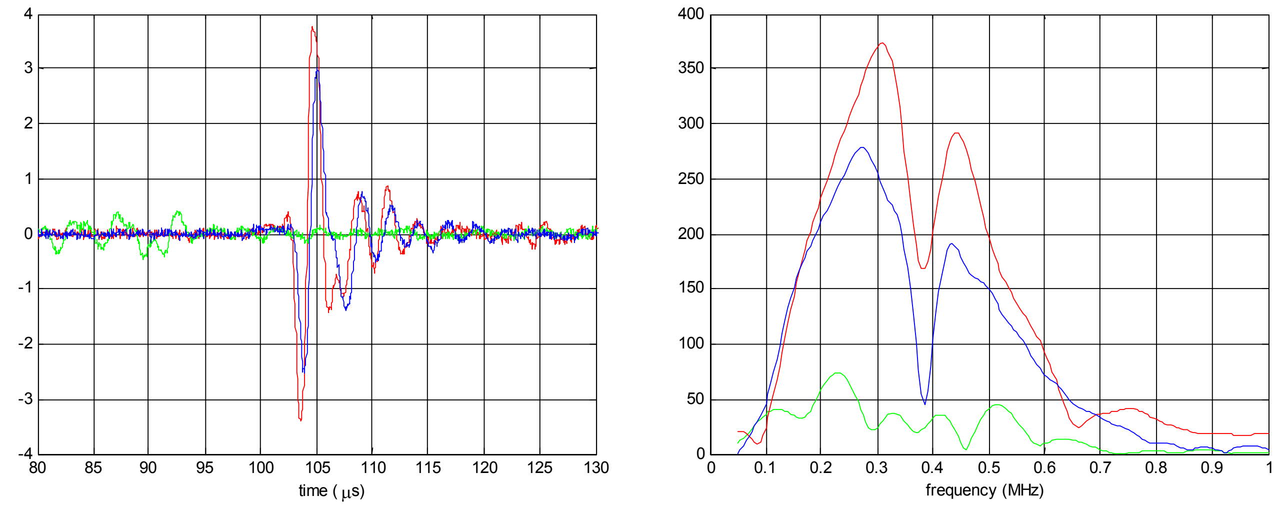

Figure 4 :signals generated in steel (a) time waveforms (b) spectra
red: short base wedge – blue: lar

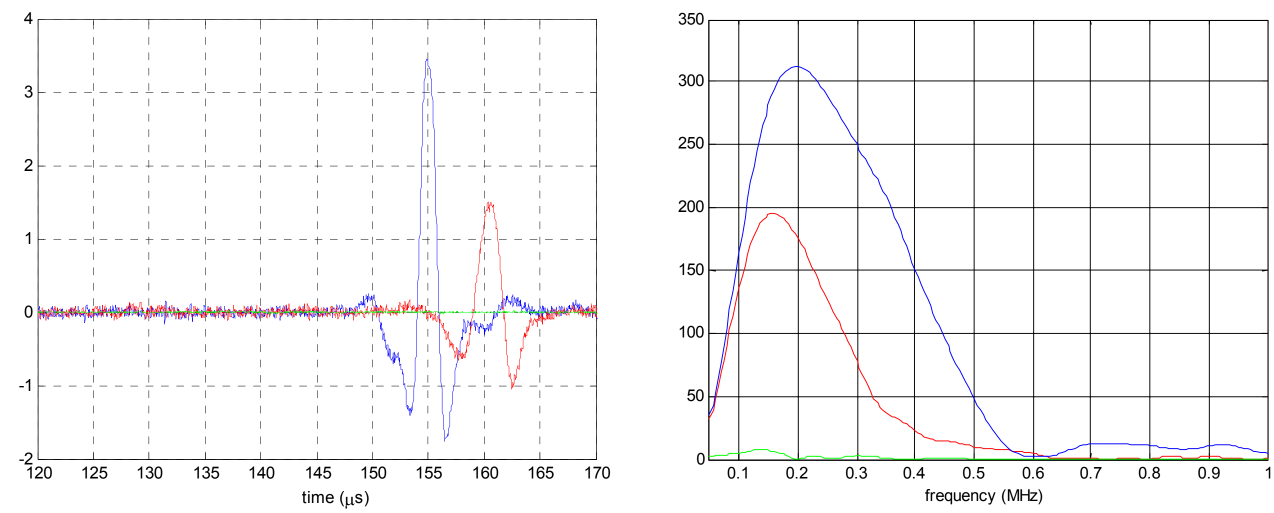

Figure 5 :signals generated in Plexiglas (a) time waveforms (b) spectra
red: short base wedge – blue: large base wedge - green: fixed angle wedge

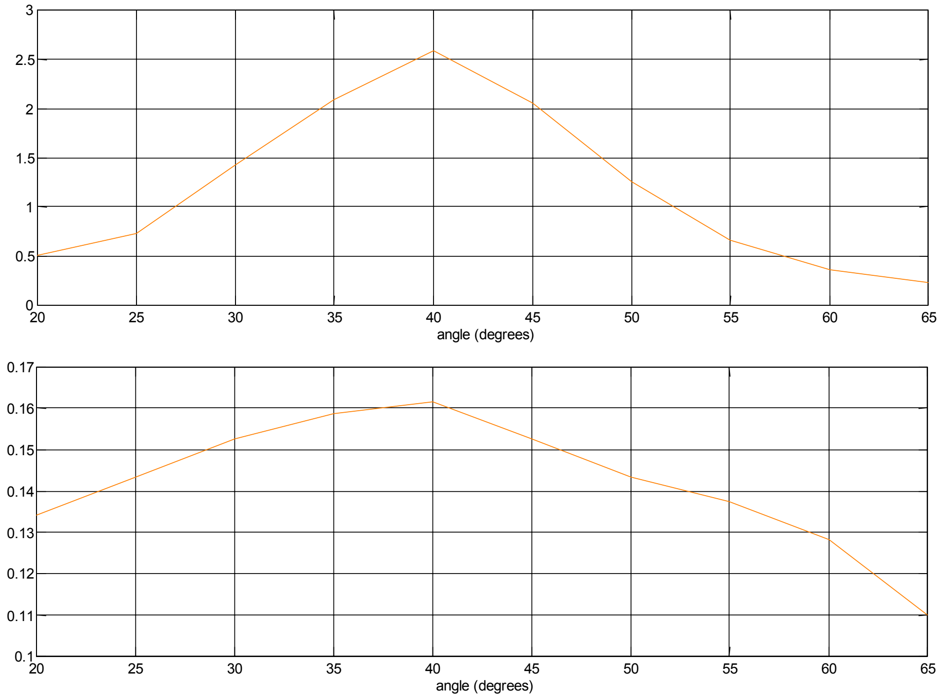

Figure 6 : performance indexes as a function of tilting angle for the short base transducer in mortar
(a) peak amplitude S_{max} in Volts (b) frequency of spectral peak F_{max} in MHz