Strojniški vestnik - Journal of Mechanical Engineering 56(2010)9, 557-564
UDC 544.57:539.3

Paper received: 22.08.2009
Paper accepted: 04.03.2010

Air-Coupled Lamb and Rayleigh Waves for Remote NDE of Defects and Material Elastic Properties

Igor Solodov* - Daniel Döring - Gerd Busse
Institute for Polymer Technology, NDE Group (IKT-ZfP), Germany

Conventional air-coupled ultrasound (ACU) is a well-established tool for acoustic NDT and material characterization. Its major shortcoming is concerned with a week penetration into solid materials due to a severe impedance mismatch at the air-solid interface. A dramatic rise in acoustic coupling is obtained by using acoustic mode conversion into plate and surface waves in slanted configurations. In our experiments, an increase of the ultrasound amplitude by up to one order of magnitude was observed in various materials (metals, wood, concrete, composite) under phase matching conditions. On this basis, fully air-coupled configurations are developed and applied for non-contact NDT. The methods based on this principle enable precise measurements of fibre directions and quantification of in-plane anisotropy in composites and natural materials, elastic depth profiling, drying of coatings, advanced imaging of cracked defects and delaminations.

Keywords: air-coupled ultrasonic testing, Lamb and Rayleigh waves, material characterization, elastic anisotropy, elastic depth profiling, process monitoring, NDT imaging

0 INTRODUCTION

Air-coupled ultrasound has become a routine tool for non-destructive testing and material characterization [1]. The conventional through-transmission or normal transmission mode (NTM) is based on conversion of the incident ACU into longitudinal acoustic waves which propagate through the bulk of material and interact with defects. A modified configuration of the focused slanted transmission mode (FSTM) [2] employs the ACU conversion into plate acoustic waves (PAWs, also known as "Lamb waves") which are found to be highly sensitive to surface-breaking cracked defects and delaminations as well as applicable to evaluation of specimen properties like thickness, stiffness and in-plane anisotropy. The interaction of the PAW with a thin liquid or solid layer on the plate substrate can be used for real-time monitoring of elastic properties of films and coatings, for example of drying of paint.

The PAW amplitude excited depends strongly on the angle of incidence: the resonance PAW generation at the optimal angle enhances substantially the signal-to-noise ratio of the ACU-NDT systems. The inverse PAW-ACU conversion results in the radiation of a pair of ultrasonic waves leaking into air at the same (optimal) angles from both surfaces of the specimen. The wave radiated on the excitation side is used in the focused slanted reflection mode (FSRM) in which both sending and receiving transducer are positioned on the same side of the object under inspection. Despite some scale distortion due to an elongated probing area, this mode enables flexible single-sided scanning of large specimens.

The single-sided configuration provides an opportunity to expand the family of the ACU-NDT methods based on the mode conversion to include surface acoustic waves (SAWs, also "Rayleigh waves"). These waves propagate within a thin surface layer (~ one wavelength) of solids, thus being useful for selective testing of this area for its elastic properties and defects. Since SAWs exhibit no dispersion in homogenous semi-infinite solids, any change in phase velocity as a function of frequency is either an indication of inhomogeneity (surface hardening, inhomogeneous porosity, etc.) or a violation of the "thick-against-the-wavelength" condition for the substrate (e.g. sub-surface voids and delaminations).

The use of PAWs and SAWs in NDT&E is not a new development, but existing solutions for the excitation/detection normally require contact configurations (wedge transducers, phased arrays), which are also limited to rather fast materials (SAW velocity > 1500 m/s). Other

*Corr. Author's Address: Institute for Polymer Technology, NDE Group (IKT-ZfP), University of Stuttgart, Pfaffenwaldring 32, D-70569 Stuttgart, Germany, igor.solodov@ikt.uni-stuttgart.de

techniques are based on materials with special properties (conducting (EMAT) or piezo-electric (interdigital transducers)) that confines substantially the area of guided wave applications in NDT.

Much greater flexibility is obtained with the air-coupled FSRM-methodology which does not require particular material qualities, contact or couplant for the transducers, and extends the range of materials for evaluation down to those with SAW velocity as low as ~ 400 m/s. The new materials inspected with SAW in this paper include technical and natural fibre composites, plastics and metals. For the NDT application, a scanning FSRM system was developed and applied to a wide range of materials.

1 METHODOLOGY

1.1 Principle: Phase-Matched Coupling

An efficient mode conversion (air-coupled ultrasound into transversal bulk waves, PAWs, SAWs, etc.) can only occur if the projection of ***k***-vector for each of the waves on the plane of incidence takes on the same value.

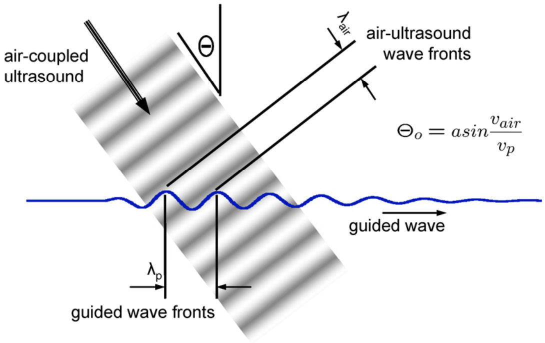


Fig. 1. *Schematic representation of the coincidence rule for phase-matched coupling*

In the case of a guided wave to be exited, this can be regarded as a coincidence of the wave fronts at the surface (see Fig. 1) [3] which takes place for particular (resonance) angle of incidence Θ_o:

$$\sin\Theta_o = \frac{v_{air}}{v_{guided}}. \quad (1)$$

This relation shows that the value of the resonance angle can be used to measure the guided wave velocity which carries information on the elastic material parameters. The SAW velocity is dominated by the ratio of sheer modulus G and mass density ρ with minor contribution of Poisson's ratio μ. An approximate expression for the Rayleigh wave velocity has the form [4]:

$$v_{SAW} = \frac{0.87 + 1.12\mu}{1+\mu}\sqrt{\frac{G}{\rho}} \quad (2)$$

The PAW family includes a number of different modes which are all dispersive in the frequency-thickness product. For low frequencies / thin plates, the lowest-order antisymmetric mode, which is of the highest importance for ACU testing, the velocity dispersion can be approximated using a flexural-wave approach [4]:

$$v_{a_o} = \sqrt[4]{\frac{E}{3\rho(1-\mu^2)}}\sqrt{\frac{\omega D}{2}} \quad (3)$$

In many cases, the contribution of Poisson's ratio in the denominator is neglected so that Eq. (1) can be used for deriving the value of the material Young's modulus.

1.2 Application: Focused Slanted Transmission Mode (FSTM)

The primary method to apply the mode conversion is based on the slanted transmission using two air-coupled transducers in a co-axial setup (Fig. 2a). This is a suitable configuration for a rotation around the measurement point in the specimen to adjust the incidence angle to obtain maximum transmitted wave amplitude (Fig. 2b). If the specimen is also rotated in the azimuth plane, such an adjustment made for each value of the azimuth angle (Fig. 2c) enables to quantify and map the in-plane stiffness anisotropy on the basis of Eq. (1).

1.3 Application: Focused Slanted Reflection Mode (FSRM)

A propagating plate wave radiates air-coupled ultrasound from both sides of the specimen, so that this signal can also be detected on the excitation side. As the specular reflection is normally much stronger than the re-radiated signal, a beam shield of absorbent material positioned close to the specimen surface is used

(Fig. 3). For longer propagation paths, the signals can also be separated in time domain: the PAW velocity is usually in the range of 600 to 2000 m/s as compared to the 340 m/s for ultrasound in air. The single-sided configuration also provides a remote access to the Rayleigh wave which does not penetrate into the bulk of a thick specimen and thus can *only* be excited and detected in the single-sided setup.

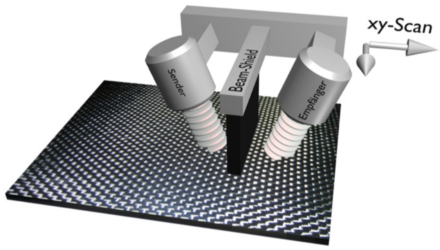


Fig. 3. *Setup for FSRM scanning*

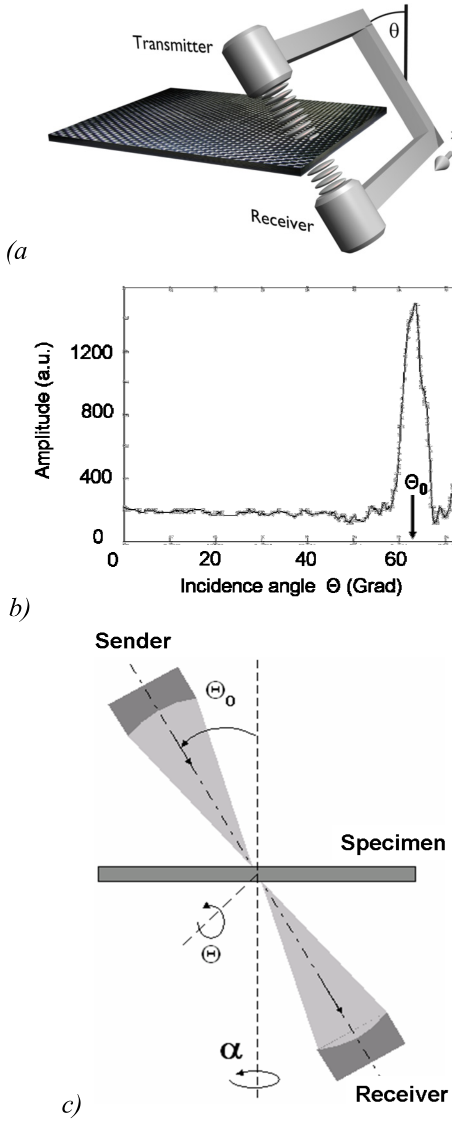


Fig. 2. *a) FSTM co-axial configuration, b) transmitted amplitude as a function of incidence angle in paper, c) bi-axial rotation for mapping in-plane stiffness anisotropy*

1.4 Application: Air-Coupled Differential Time of Flight (DTOF)

The accuracy of guided wave velocity measurements can be significantly increased by tracing the wave along the specimen surface. When the receiver in the FSRM configuration is shifted parallel to the surface in the direction of wave propagation, only the guided wave path changes (Fig. 4a).

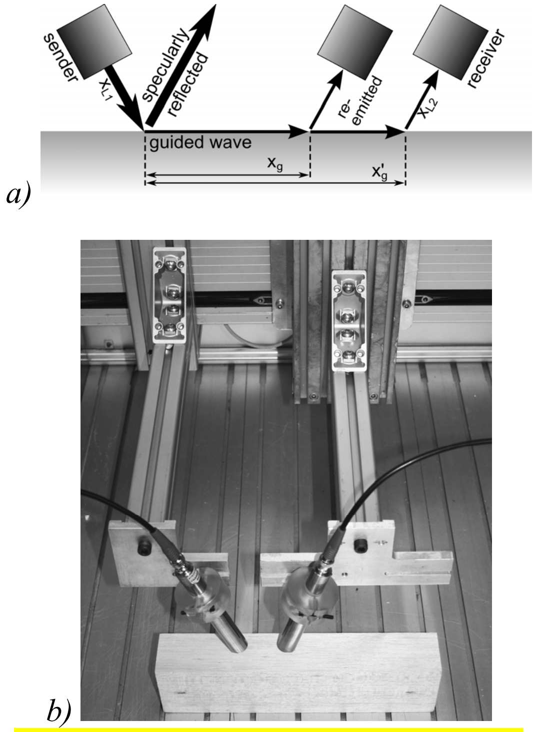


Fig. 4. *A scheme a) and laboratory setup, b) for air-coupled time-of-flight measurements*

Thus, the measurement of the relative phase difference $\Delta\varphi$ in the received signal and the change in propagation path Δx is sufficient for a precise calculation of the guided wave phase velocity at the frequency f:

$$v_{ph} = 2\pi f \frac{\Delta x}{\Delta \varphi}. \quad (4)$$

In the experiment, the phase shift is determined from the recorded A-scans by using a discrete Fourier transformation. This enables to recover the value confidently even from data with a low signal-to-noise-ratio.

2 MEASUREMENTS AND RESULTS

All experiments used commercial air-coupled ultrasonic testing equipment with piezo-composite transducers and a 3-axis stepped scanning table. High-voltage (200 V) square wave bursts were used for excitation of air-coupled ultrasound in the frequency range of 200 to 450 kHz. The higher harmonic components of the input signal were filtered out due to a low bandwidth of the transducers (~ 10 %) so that the ultrasonic signal was monochromatic.

2.1 FSTM for Non-Destructive Air-Coupled Ultrasonic Imaging

Surface breaking tight cracks are known to be a rather difficult NDT subject for bulk-wave ultrasonics. This is confirmed by the air-coupled NTM image presented in Fig. 5 (left): the contrast of the image produced by a longitudinal wave propagating parallel to the crack faces is measured to be only ~2%. On the contrary, the flexural wave in the FSTM mode (Fig. 5, right) is scattered by the crack much stronger resulting in much higher contrast (~ 80%) and signal-to-noise ratio of the image.

2.2 Experimental Study of Slanted-Mode Wave Conversion Efficiencies

The mode conversion in slanted configuration is expected to enhance the ultrasound penetration into solid materials due to the resonance excitation of PAW/SAW. To measure the efficiency of mode conversion, the output signal in the FSTM/FSRM configuration was compared with the amplitude of the ACU transmitted directly between the transmitter and receiver. For ACU-PAW conversion, the additional losses strongly depend on the value of Θ_o (Table 1).

The data of the table confirm that mode conversion provides a substantial enhancement in elastic coupling compared with conventional NTM. The gain obtained increases along with the values of Θ_o, which indicates a contribution of space resonance.

In fact, the length of the excitation area (in wave-lengths) changes as $(W/\lambda_{air})tg\theta_0$ and rises sharply for large values of Θ_o. The measurements of ACU-SAW mode conversion were carried out in the FSRM configuration at 390 kHz and a SAW propagation distance of ~6 cm.

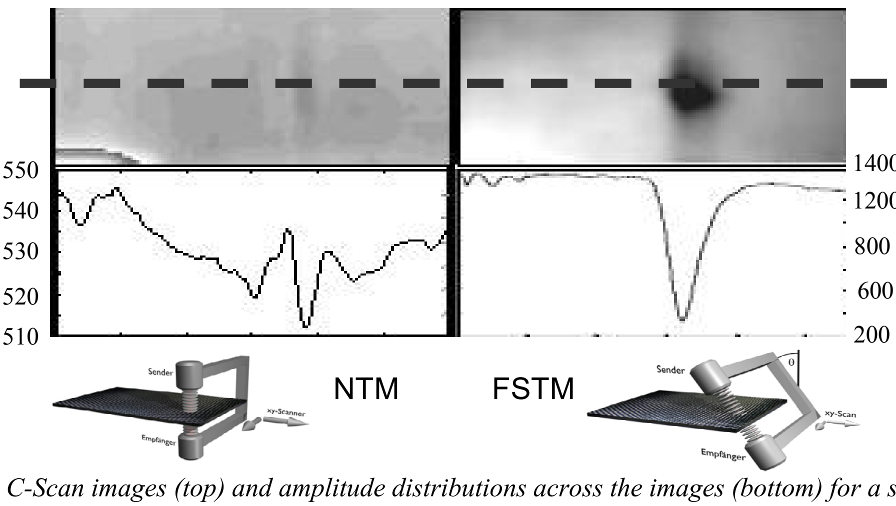


Fig. 5. *C-Scan images (top) and amplitude distributions across the images (bottom) for a surface breaking crack in polycarbonate measured in normal and slanted transmissions*

Table 1. *Experimental results of ACU-PAW mode conversion (frequency 450 kHz)*

Material	Thickness [mm]	Resonance Angle θ_0 [degrees]	PAW velocity v_{a_0} [m/s]	Conversion losses (NTM) [dB]	Conversion losses (FSTM) [dB]	Gain (NTM- FSTM) [dB]
Paper I (A4)	0.1	52±1	430±10	44	20.5	23.5
Paper II	0.17	48±1	460±10	47	28.5	18.5
Al-foil	0.1	32±1	640±20	53.5	38.5	15
Polystyrene	1.1	21±1	950±60	64.5	53	11.5
Wood (spruce, L/LT)	0.65	19±1	1040±60	53	43	10

Table 2. *Experimental results of ACU-SAW mode conversion*

Material	θ_0 [degrees]	v_{SAW} [m/s]	Conversion losses (FSRM) [dB]	SAW acoustic impedance (Mrayl)
Fir (L/LT)	17±0.5	1160±30	37	0.9
PMMA	16±0.5	1230±40	40	1.5
Graphite	14±0.5	1400±50	45	2.1
Concrete	9±0.5	2200±100	61	5.3
Aluminum	7±0.5	2800±200	54	7.8
Copper	10±0.5	2000±100	59	18.8
Steel	6.5±0.5	3000±200	63	23.4

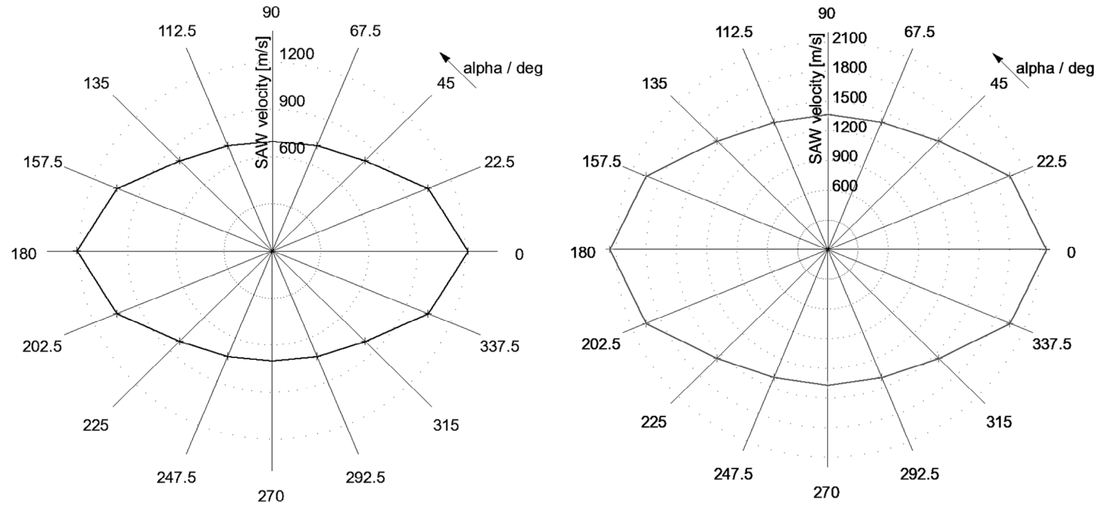


Fig. 6. *SAW velocity anisotropy a) in the RL-plane of beech, b) in unidirectional CFRP*

Thus, a few dB of dissipation should be subtracted from the values of conversion losses given in Table 2.

All values of Θ_o are smaller in this case, so that impact of the length of the excitation area is insignificant. Instead, a good correlation between conversion losses and the value of acoustic impedance of materials for SAW is observed. The only deviation in the case of concrete is apparently due to higher propagation losses (due to scattering in multi-scale inhomogeneities) in this material.

Table 3. *SAW velocities measured by DTOF at 200 kHz*

Material	Orientation α	v_{SAW} [m/s]
CFRP	0°(in fibre)	2160±20
	22.5°	1950±20
	45°	1550±10
	67.5°	1395±10
	90° (across)	1369±7
Wood (Beech, RL- cut)	0° (L)	1216±15
	22.5°	1048±15
	45°	815±12
	67.5°	727±12
	90° (R)	697±12

2.3 Experimental Study of SAW Anisotropy

Using the DTOF methodology, the SAW velocity was measured in a natural (wood) and an engineering material (unidirectional CFRP laminate) with a high elastic anisotropy as a function of propagation direction (azimuth angle α) relative to the fibres.

The degree of the velocity anisotropy becomes more apparent when the measured data is plotted in a polar diagram (see Fig. 6). In both cases it reflects the reinforcement characteristics induced by the fibres with an almost two-fold increase in velocity which implies approximately four-fold increment in material stiffness.

2.4 Air-Coupled Single-Sided Imaging for Non-Destructive Testing

A number of light-weight aerospace components comprise sandwich-type structures consisting of light (and relatively weak) core materials (foam, honeycomb, balsa wood) which join adhesively the high-strength CFRP liners. The adhesion of the honeycomb to the liners is critical, as it is the only factor that prevents them from buckling under compressive load. The FSRM with a plate wave propagating in the CFRP liner provides a technique for remote testing of adhesion to the core.

Two specimens containing artificial delaminations between the CFRP liners and two types of honeycomb structures were fabricated and tested with air-coupled ultrasound. The FSRM scans (Fig. 7) clearly show the delamination-simulating inserts as well as some core cells filled with epoxy resin. All defects in the image are stretched in the scanning (horizontal) direction due to initial distance between the transducers (~5 cm) characteristic for the FSRM setup.

2.5 Non-Destructive Testing with Air-Coupled SAW

Natural sandstone is a material in which a macro-scale elastic anisotropy is hardly expected. Nevertheless, it might be produced by the sedimentation process involved in the formation of the stone, with either deposition of layers of different properties or a dominant orientation of non-symmetrical individual particles.

The direction of increased stiffness is found to be parallel to the sediment layers (0° in Fig. 8, sometimes visible as colour pattern), resulting in a SAW velocity increase by 10% compared to the weak (90°) direction (Table 4).

A change in SAW frequency increases the penetration depth of the wave, but does not significantly change the SAW velocity on a freshly-cut surface (Table 4).

If the surface is infiltrated with a silica-based resin to improve the properties−mainly to harden it against pollution corrosion−the SAW velocity is increased by 20 to 30%, depending on frequency and propagation direction.

Table 4. *DTOF measurements of SAW velocities of variegated sandstone as a function of propagation direction and surface treatment*

Side	Orientation	v_{SAW} at 200 kHz [m/s]	v_{SAW} at 200 kHz [m/s]
Freshly cut	0°	1850±20	1820±30
	90°	1670±20	1690±30
Hardened	0°	2240±10	2400±40
	90°	2220±10	2300±40

From Table 4 it is also evident that the infiltration process mostly cancels the cause of the elastic anisotropy of the sedimentation structure, which suggests that the small amount of additional substance equalizes the contact between the individual grains. In addition, a closer comparison of the velocities at 200 and 400 kHz shows a somewhat higher value for the shorter wavelength (λ_{400} ~ 6 mm). This can be considered as an estimate of the hardened layer thickness; the 200 kHz wave penetrates deeper (λ_{200} ~ 12 mm) and in the bulk of the material that results in a slower SAW velocity. By using a wider range of probing frequencies, a non-contact elastic depth profiling should be possible.

2.6. Remote Process Monitoring: Drying of Paint

The SAW/PAW velocity and dissipation also depend on stiffness and viscosity of coatings.

As a result, the FSTM- and FSRM- output signals are sensitive to changes in the physical state of films and coatings (hardening, polymerization, drying, etc.). Both amplitude and phase of air-coupled SAW/PAW can be used for real time non-contact monitoring of such processes on-site in an industrial environment. An example of SAW application for the monitoring of paint drying is illustrated in Figure 9. It shows that drying of identical paints develops differently for concrete and PMMA substrates. In concrete, the reaction proceeds more intensively (higher values of phase derivative in Fig. 9, b) and faster (drying time ~4500 s against ~8000 s in PMMA) because the paint solvent not only evaporates, but also diffuses into the porous cementitious material.

3 CONCLUSIONS

The slanted mode methodologies with mode conversion to plate and surface waves were shown to enhance significantly the efficiency of penetration of air-coupled ultrasonic waves in solid materials as compared to the established normal transmission mode.

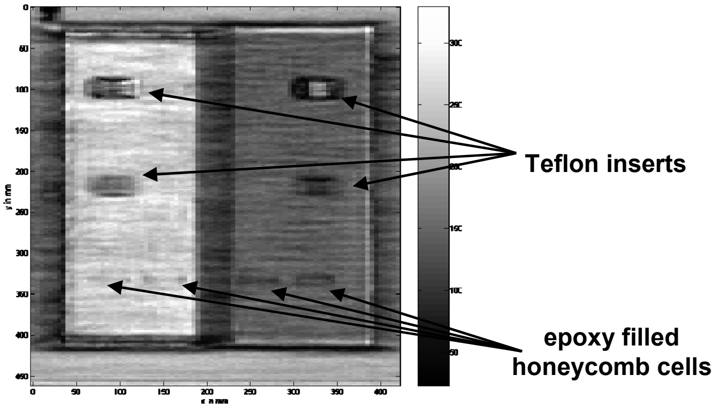


Fig. 7. *PAW FSRM C-scan (200 kHz) of a carbon-composite specimen with aluminium (left) and Nomex (right) honeycomb core; teflon foils between core and CFRP liner and resin-filled core cells simulate production defects; specimen provided by FACC, Austria*

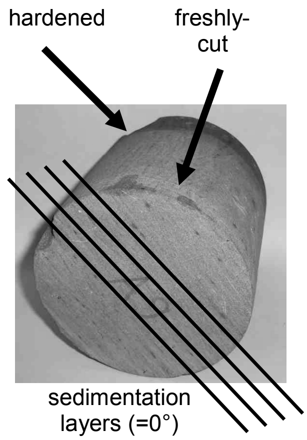
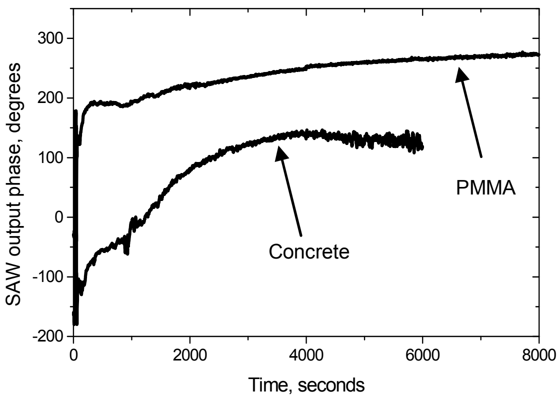
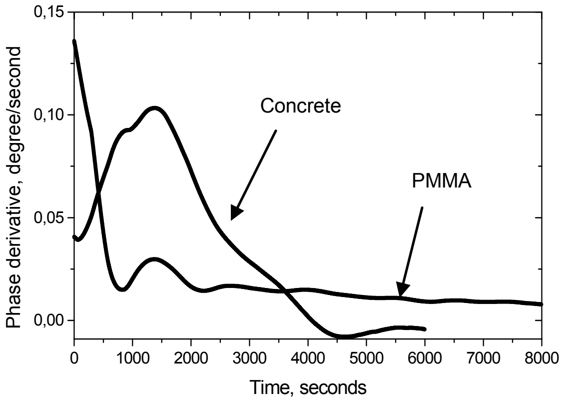


Fig. 8. *Sedimentation in natural stone*



a)



b)

Fig. 9. *Air-coupled SAW monitoring of drying paint: a) output phase; b) and its derivative variations in time*

The use of air-coupled flexural waves improves the detection of surface-breaking cracks while a single-sided non-contact configuration enables to image critical delamination-type flaws in sandwich compounds.

Differential time-of-flight measurement of guided wave velocities is a sensitive instrument for an evaluation of elastic anisotropy and depth-resolved profiling.

Non-contact excitation/detection of air-coupled guided waves is a basis for remote and non-invasive monitoring of fluid-solid phase transitions (drying, hardening, etc.) applicable in an industrial environment.

4 REFERENCES

[1] Rogovsky, A.J. (1991). Development and application of ultra-sonic dry-contact and air-contact C-scan systems for non-destructive evaluation of aerospace components. *Material Evaluation*, vol. 50, p. 1491-1497.

[2] Solodov, I., Stößel, R., Busse, G. (2004). Material characterization and NDE using focused slanted transmission mode of air-coupled ultrasound. *Research in Non-Destructive Evaluation*, vol. 15, p. 1-21.

[3] Cremer, L. (1947). Über die Analogie zwischen Einfallswinkel und Frequenzproblemen. *Arch. Elektr. Übertragung*, vol. 1, no. 28.

[4] Victorov, I.A. (1967). *Rayleigh and lamb waves. Physical theory and applications*. Plenum Press, New York.