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New opportunities for NDE with air-coupled ultrasound

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Abstract

The area of NDE-applications of air-coupled ultrasound is expanded substantially for a weakly focused acoustic wave incident obliquely on a plate-like sample at an angle of 'resonance' transmission. Such a focused slanted transmission mode (FSTM) combines the benefits of plate wave excitation with a high spatial resolution and enables to characterise local elastic properties of a material. It was shown that the in-plain elastic anisotropy could be obtained by measurement of the 'resonance' transmission angle of the FSTM-output signal as a function of the azimuth angle. A striking contrast enhancement was demonstrated for the FSTM-C-scan imaging of cracked defects and delaminations. Non-contact FSTM-measurements of local variations of flexural wave velocity were used to detect fine structural changes and damage induced in polymer and composite materials during tensile tests.

Keywords: NDE; Air-coupled ultrasound; Nonlinear analysis; Fracture mechanics

1. Introduction

Air-coupled ultrasound (ACU) is a challenging non-contact alternative to conventional immersion and dry-contact methods of acoustic NDE. The ACU configuration usually involves ultrasonic waves incident normally to the sample surface (normal transmission mode (NTM)) so that only longitudinal waves are excited in the sample and deliver information on material properties. In addition, the energy transmission coefficient for the NTM is extremely small due to a severe impedance mismatch on the boundaries of the sample. To increase acoustic transmission, one can use an oblique incidence of the acoustic wave at an angle of 'resonance' transmission [1]:

$$\sin \theta_0 = v_{air}/v_p, \quad (1)$$

which is caused by plate mode generation in the sample. This brings two attractive opportunities for material characterisation: firstly, one can determine the phase velocity v_p of the plate modes and thus monitor variations in local stiffness of a sample. Secondly, the plate modes can be scattered by cracked defects more efficiently than longitudinal waves thereby providing a higher sensitivity of NDE and better contrast of acoustic imaging of flaws.

However, the technique is critically dependent on the two factors: (a) precise measurements of the angles of incidence and (b) a requirement of an incident plane wave that inevitably stipulates for the use of wide-aperture transducers [2]. The latter deteriorates the spatial resolution and prevents the development of the scanning FSTM-versions for ACU NDE systems.

In this paper, we use a weakly focused acoustic beam to enhance a spatial resolution of the technique and to provide high-contrast acoustic imaging of various flaws. The FSTM-configuration is also applied to the measurements of variations in local material stiffness associated with in-plain elastic anisotropy as well as damage induced by nonlinear tensile deformations.

2. FSTM methodology

2.1. Experimental set-up

In our experiment (Fig. 1), commercially available piezoelectric 1–3 composite material transducers were used to transmit and receive a focused ultrasound beam (fundamental frequency 450 kHz, diameter of the transducers 18 mm, full angular transducer aperture $2\gamma_0 \cong 20°$,

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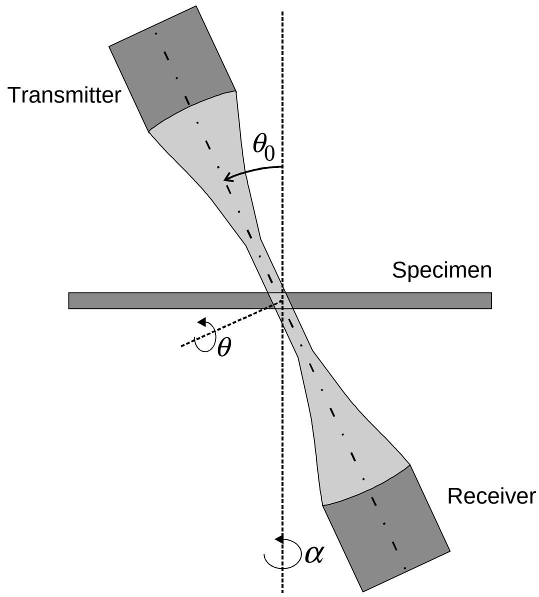

Fig. 1. Experimental configuration of the ACU-FSTM.

focus distance $\cong$40 mm, and focus spot diameter $\cong$2 mm). A 15-cycle burst of $\approx$1400 V amplitude was applied to the transducer to generate the acoustic wave; the two-step amplification of the receiver provided $\cong$120 dB total dynamic range of the PC-operated system. After 8 bit-A/D-conversion at 12.5 MHz sampling frequency the transmitted pulse can be observed and measured at the PC-display. A scan of the angle of incidence (θ) was implemented by a sample rotation using a line-scan of the PC-operated scanning table. Such angular B-scans usually demonstrated $\cong$20 dB rise in the transmitted wave amplitude under the 'resonance' phase matching conditions (1) for the zero-order anti-symmetrical a_0-mode. This mode was used in experiments with an accuracy of θ_0 measurements $\cong$0.5°.

2.2. Focused ACU transducers

In a confocal focused acoustic beam configuration (Fig. 1), the half-intensity focal range in axial direction extends over the length [3]:

$$\Delta z = 0.45\lambda/(1 - \cos \gamma_0), \quad (2)$$

where γ_0 is half the angular aperture of the transducer; λ is the wavelength in air.

On the other hand, γ_0 determines the focus spot size (in radial direction) obtained with the spherically focused transducer [3]:

$$w = 0.61\lambda/\sin \gamma_0. \quad (3)$$

In our case with $\gamma_0 \approx 10°$ one obtains: $\Delta z \approx 30\lambda$, while $w \approx 3.5\lambda$. Therefore, in the focus area a small aperture (w) acoustic field is supported over a certain distance (Δz). The field is thus similar to the near-field zone of a piston transducer, i.e. can be considered as a plane wave. For $\lambda \approx 0.75$ mm (450 kHz—ultrasonic wave in air), one obtains: $w \approx 2.6$ mm and $\Delta z \approx 2.3$ cm. We conclude, therefore, that the focused ultrasonic beams of a moderate angular aperture ($\gamma_0 \approx 5$–15°) combine a high lateral resolution with a plane-wave collimation in the focus area. Under these conditions, Eq. (1) is applicable to the focused beam with a high accuracy of the plate velocity determination from (1).

2.3. Plate waves in FSTM

Physically, the 'resonance' transmission is achieved when the incident wave on the front surface excites a plate mode, which re-radiates acoustic energy from the rear side of the sample. Such a model, obviously, assumes a good acoustic coupling between the two sample surfaces which occurs for acoustically thin plates, i.e. for $k_t d \leq 1$ (k_t is the wave number for shear waves; d is the thickness of the plate). As a result, the maximum transmission gain due to the FSTM is expected for symmetrical and/or anti-symmetrical zero-order modes (s_0 and a_0). The efficiency of either mode to be generated also depends on its polarisation: the air coupling can only be implemented for the modes where the displacement is normal to the sample surface. Symmetrical plate deformation of the s_0-wave is accompanied mainly by the in-plane particle displacements and thus can be hardly excited in the FSTM. The anti-symmetrical (flexural) plate deformation observed for the a_0-wave causes mostly out-of-plane displacements and for this reason dominates in the FSTM. Since its velocity $v_{a_0} \to 0$ for $k_t d \ll 1$, the application of the FSTM to thin specimens requires the higher frequency ACU to provide $v_{a_0} \geq v_{air}$ in (1).

For thicker samples ($k_t d \gg 1$), both waves are localized near the plate surface and their velocities are approaching to the surface wave velocity [4]. For $k_t d \sim (5$–$10)$, the superposition of the zero-order modes can be considered as a surface acoustic wave. This impedes acoustic excitation of the opposite side of the plate and prevents sound transmission through thick specimens. To apply the FSTM for thick specimens, the low-frequency ACU is required to reduce $k_t d$ down to the optimal range $k_t d \leq 1$.

3. FSTM-measurements of local elastic anisotropy

Anisotropy is usually associated with crystalline materials where it is caused by specific arrangements of atoms in a lattice. In the majority of engineering materials (polycrystalline alloys, polymers, composites, etc.), the elastic anisotropy manifests in meso- and macro-scale structures due to internal stresses, texture, molecular and fibre orientation. The latter is usually derived from the measurements of bulk (longitudinal and shear) acoustic wave velocities along various directions in the material. The FSTM provides an opportunity for the in-plane elastic