PAPER CHARACTERIZATION BY MEASUREMENT OF THICKNESS AND PLATE RESONANCES USING AIR-COUPLED ULTRASOUND.

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Abstract. – Measurements of different types of paper (surface density from 80 gr/m^2 to 300 gr/ m^2) using air-coupled, wide frequency band ultrasound and analysis in the frequency domain is presented. Working frequency range is 0.6-2.2 MHz. At normal incidence, thickness resonances in the paper samples are excited and sensed. From the analysis in the frequency domain of such resonances density, longitudinal velocity and attenuation of sound waves in the paper samples are obtained. At oblique incidence Lamb waves are observed by use of Cremer's coincidence rule. Velocity of different Lamb modes is measured.

I. INTRODUCTION.

Resonance techniques using air-coupled ultrasonic waves applied to the characterisation of paper are well-known. Thickness resonances and Lamb modes in paper have been used in the past to characterise different kind of paper materials. [1]-[3] Nevertheless, most of published data are in the frequency range 0.1-0.3 MHz; more recently this has been extended up to 1MHz using capacitive air-coupled transducers, but only for thickness resonances. [4]. Because of this frequency limitation, measurements are restricted to thick paper samples (0.75-0.25 mm) and cardboards, and to Lamb modes in the low frequency limit: A0 and S0, although many times, S0 is only observed.

This work present measurement of paper thickness resonances at normal incidence and Lamb modes at oblique incidence generated by the phase matching method or Cremer's coincidence rule in the frequency range 0.5-2.5 MHz. [5], [6]

Measurements for both thickness resonances and Lamb modes are obtained from through-paper transmission at normal and oblique incidence of wideband airborne ultrasonic pulses and analysis in the frequency domain by Fourier transform.

Measurements are performed for a large set of paper samples having thicknesses from 0.1 mm – 0.25 mm (surface density from 80 gr/m2 to 300 gr/m2), different quality (from recicled paper to high quality writing paper). Specially designed broadband air-coupled piezoelectric transducers for these frequency range are used.

II. EXPERIMENTAL SET-UP.

An scheme of the experimental set-up is shown in Fig. 1. Two pairs of specially designed air-coupled piezoelectric transducers were used. Center frequency is 0.9 MHz for one pair and 1.7 MHz for the other. Active elements are 1-3 piezocomposite disks made by the dice and filling technique (PZ-26, Ferroperm and Araldite-D), 2 mm thick for the 0.9 MHz transducers and 1 mm thick for the 1.7 MHz transducers. Matching to the air is achieved by a stack of two quarter wavelength matching layers. First layer is made of Araldite-D, for the outter layer a porous polymer film is used, properties are in Table I. Working frequency range is 0.6-1.2 MHz for one pair and 1.2-2.2 MHz for the other. Active area diameter is 25 mm.

Table I. Properties of the outter matching layer.

Impedance (Mrayl)	Attenuation @ f_r (Np/m)	$\lambda/4$ frequency (f_r) (MHz)
0.24	220	1.1
0.38	800	1.6

Coefficient of sound transmission for each paper sample was measured at normal and oblique incidence. At normal incidence distance between transducers and sample is adjusted so that difraction effects can be neglected. Ratio of the modulus of the FFT of the received signal with the sample in between the transducers to the modulus of the FFT of the received signal without sample provides the transfer function for that sample. See Ref. [7] for more details bout the experimental technique.

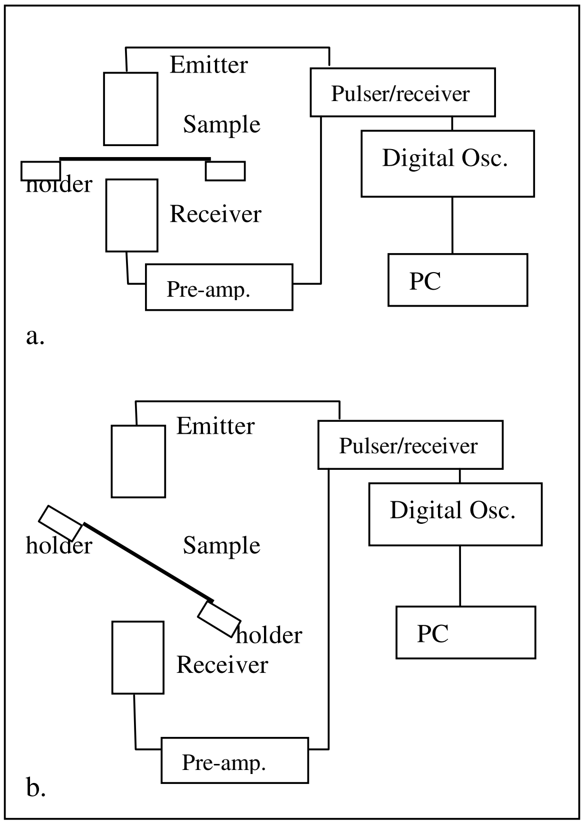

Figure 1. Experimental set-up: a. Normal incidence, b. Oblique incidence.

III. CHARACTERIZATION.

Normal incidence: thickness resonances.

Coefficient of sound trasnmission through a plate at normal incidence is given by:

$$T = \frac{4}{2 + 2\cos^2 \tilde{k}_l t + \dfrac{Z_2^4 + Z_1^4}{Z_2^2 Z_1^2} \sin^2 \tilde{k}_l t} \qquad (1)$$

where Z is the acoustic impedance (1: for the air, 2: for the paper sample), t is the thickness and $\tilde{k}_l$ is the complex wave vector for longitudinal wave propagation in the plate. It is complex because of the introduction of the attenuation by the viscoelastic correspondence principle [8].

From Eq. 1, thickness resonances are located at:

$$f_r = \frac{v}{2l} n, \quad n = 1, 2 \ldots \qquad (2)$$

where l is the thickness of the sample, n the order of the resonance, and v the velocity of longitudinal waves. Depending on the velocity, the thickness, and the working frequency range one or more thickness resonances can be observed.

Figure 2 and 3 show the amplitude of the transfer function for 160 gr/m^2 and 150 gr/m^2 paper samples respectively, theoretically calculated values from Eq. (1) are also shown. A first approach for the velocity is obtained from Eq. (2) and the measurement of the frequency location of the maximum. Fitting theoretically calculated curve to experimental data provides velocity, density and attenuation in the sample. A highly attenuated resonance is observed, a good agreement between measured and calculated values is observed.

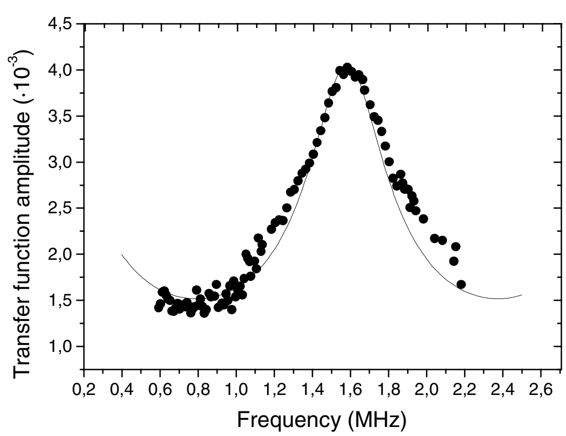

Figure 2. Transfer function amplitude vs. frequency for a 160 gr/m^2 paper sample at normal incidence. Dots: measurements, Solid line: calculated (v =665 m/s, ρ = 755 kg/m^3, α = 1860 Np/m)

Table II sumarized the obtained results for the different paper samples at normal incidence. Surface density is provided by manufacturers. As mentioned above most of the samples exhibit the first thickness resonance above 1 MHz. For the thicker samples, 2nd and 3rd order resonances are observed.

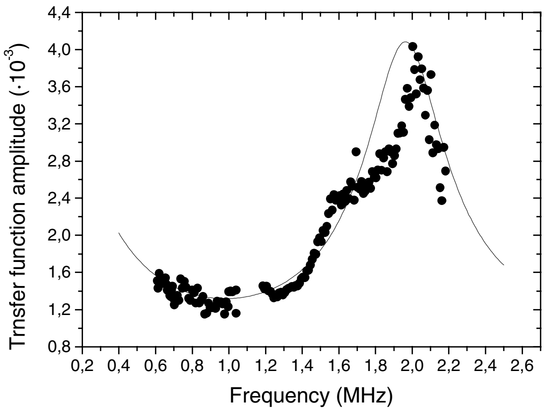

Figure 3. Transfer function amplitude vs. frequency for a 150 gr/m^2 paper sample at normal incidence. Dots: measurements, Solid line: calculated (v =550 m/s, ρ = 1071 kg/m^3, α = 2380 Np/m)

Table II.
Paper samples properties and measured magnitudes from normal incidence measurements.

Sample	Thick. (µm)	Impedance (Mrayl)	Resonance (MHz)	Velocity ±2 (m/s)
80 gr/m^2	105	0.43	(~ 2.7)	567
130 gr/m^2	170	0.43	1.57 (1st)	534
150 gr/m^2	140	0.67	2.00 (1st)	560
160 gr/m^2	210	0.59	1.59 (1st)	668
200 gr/m^2	260	0.41	1.02 (1st)	528
			2.03 (2nd)	528
300 gr/m^2	500	0.36	~0.59 (1st)	594
		0.29	0.96 (2nd)	480
		0.29	1.43 (3rd)	477
Recycled (100 gr/m^2)	110	0.26	1.35 (1st)	297
Cardboard (240 gr/m^2)	205	0.41	0.85 (1st)	349
		0.37	1.55 (2nd)	318

Oblique incidence: Plate waves.

At oblique incidence, maximum transmission is obtained at angles that verify the Cremer's rule:

$$v_L = \frac{v_{air}}{\sin\theta} \qquad (3)$$

where v_L is the velocity of a Lamb wave in the sample, v_{air} is the velocity of sound in the air and θ is the angle of incidence of the acoustic beam on the surface of the sample.

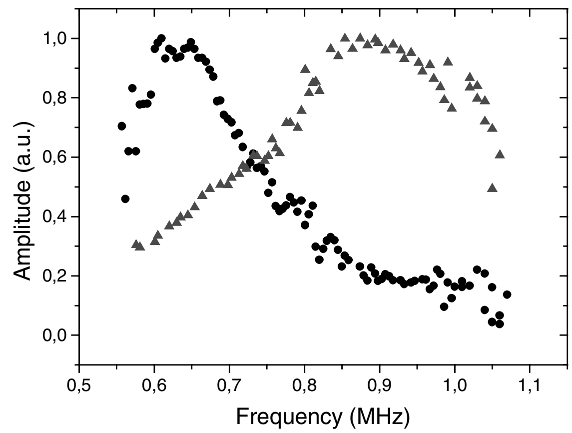

Figure 4. Measured transfer function vs frequency for 150 gr/m^2 sample, oblique incidence:. ▲: 36º, ●: 39º.

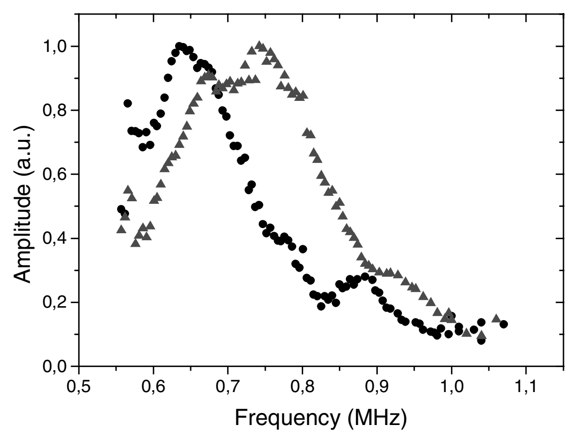

Figure 5. Measured transfer function vs frequency, oblique incidence.
▲: 80 gr/m^2, 47º, ●: 160 gr/m^2, 46º

Figure 4 shows the measured transfer function vs frequency for the 150 gr/m^2 sample at two different angles. Figure 5 shows the measured transfer function vs frequency for the 80 gr/m^2 and the 160 gr/m^2 samples at oblique incidence. Observed maxima are attributed to the generation of Lamb waves by the phase matching mechanism. Velocity of Lamb waves is calculated from Eq. (3)

Table III summarized the obtained results. Most of the observed plate resonances are associated to the S0, S1 and A1 modes. The A0 mode does not appear because the velocity of this mode is apparently lower than that of air. [2].

Table III.
Measured properties at oblique incidence.

Sample	Angle (degree)	Maximum at (MHz)	Velocity ±2 (m/s)
80 gr/m^2	47	0.73	466
	44	0.99	487
130 gr/m^2	34	1.31	610
	42	0.65	511
150 gr/m^2	39	0.63	540
	36	0.9	578
160 gr/m^2	46	0.65	476
		0.88	
200 gr/m^2	47	0.64	466
300 gr/m^2	31	0.69	655
	39	0.67	540
cardboard	31	0.95	655

IV. CONCLUSIONS.

Thickness and plate resonances have been observed in paper samples using air-coupled and wide band piezoelectric transducers in the frequency range 0.6-2.2 MHz. Compared with previous works this one is carried out using higher frequencies so that thinner samples can be studied. For thicker samples second and even third order thickness resonances can be observed. In this case it is possible to determine the variation of acoustic properties with frequency.

Different paper samples having different density, thickness, stiffness, texture and quality have been studied. Both measurements permit one to determine velocity of longitudinal and Lamb waves and hence to determine the elastic constants specially for orthotropic materials like paper.

ACKNOWLEDGMENTS: This work has been funded by CICYT project DPI2001-2156-CO2-02.

V. REFERENCES

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