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Ultrasonic system for in-plane paper characterisation

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An ultrasonic system that enables the measurement of paper properties like anisotropy or filler content is fully described in this paper. The system is composed of a measuring head that integrates 16 ultrasonic bimorph circumferentially disposed transducers. The hardware responsible for the emission and the reception tasks is PC controlled by means of an acquisition board and by specifically developed software. The experimental results obtained present a very good agreement with others obtained by classic methods, namely destructive tests, and allow evaluation of paper properties such as tensile stiffness index, tensile stiffness orientation angle, anisotropy and filler content, with good accuracy.

1. Introduction

In the last two decades there has been a growing interest in non-destructive techniques that allow the determination of mechanical properties of paper. One of these techniques is based on ultrasonic methods. In the literature it is possible to find several works that analyse this subject from both a theoretical and an experimental point of view[1-9]. Some of these previous studies investigated plate wave's propagation in paper, in an attempt to obtain correlations with mechanical properties using contactless methods due to the impossibility of using traditional contact techniques[1,2,7]. Other researchers have developed on-line systems that can measure certain properties in a moving web[3,8-10]. Ultrasonic analysis is a very interesting technique because it is fast, non-destructive and is very sensitive to the cellulose-fibre-based structure of the paper.

In this paper a computer-controlled, fully-automated ultrasonic-based system composed of a measuring head and peripheral hardware was conceived. The system performs ultrasonic velocity measurements in the plane of the paper sheet which can be used to establish the tensile stiffness index (*TSI*). This parameter has an increased acceptance as a measure of paper strength properties[2]. Once *TSI* for the different orientations is known, the tensile stiffness orientation angle (*TSO*), defined by the orientation of the maximum of the *TSI* plot and the paper machine direction, can be evaluated.

Another important factor in the paper industry is the use of mineral fillers that are applied for economic reasons, because fillers impart to paper specific properties. Bulk, air permeability, porosity, light scattering, stiffness, gloss and printability are some of the paper properties that are dependent on mineral fillers and on filler level[10]. Paper strength is reduced by filler incorporation, due to the reduction in bonded area of cellulose fibres. Mineral fillers have very different elastic properties from cellulose fibre, so the overall elastic property of the paper with fillers is different from a paper that has only cellulose fibres. Due to the good linear correlation between the mineral filler content in paper and ultrasonic velocities, the prediction of the elastic properties variation can be achieved.

2. Background

The measurement of ultrasonic velocities is a powerful technique for non-destructive analysis of the mechanical properties of materials. Typically, the propagation velocity of a plane wave through a material is equal to the square root of the Young's modulus divided by the mass density. So, the Young's modulus can be obtained from velocity measurements. In our case we are interested in the analysis of planar materials. These are defined as plates that have lateral dimensions larger than the wavelength of in-plane bulk waves and whose thickness is small compared to the wavelength of out-of-plane bulk waves[11]. Paper can be considered as a planar material and the model of a composite layered medium is commonly assumed to be an orthotropic material[12]. The symmetry axes are along the so-called machine direction (*MD*), cross-direction (*CD*) and thickness direction. These designations are related to the paper-making process: *MD* is the direction along which the paper web is running in a paper-making machine and *CD* is perpendicular to the *MD*. Because paper is mainly composed of cellulose fibres with a thin structure, the movement during the paper-making process gives rise to a predominant alignment of fibre with *MD* and, consequently, to anisotropy in the paper structure. A *SEM* (Scanning Electronic Microscopy) image of paper is shown in Figure 1.

Guided wave theory applied to obtain the dispersion equations for an orthotropic material like paper is more complex than for an isotropic material. Nevertheless, in the low frequency regime, the fundamental S0 mode can be considered as independent of the frequency and its velocity is given by[2]:

$$V_{S0}^2 = \frac{E}{\rho(1-\upsilon_{xy}\upsilon_{yx})} \quad \text{.................................(1)}$$

where E is the Young's modulus, ρ the density and υ_{xy} and υ_{yx} the Poisson's ratios in the plane of the paper. In practice, as $\upsilon_{xy}\upsilon_{yx}$ is much less than unit one, the Eq. (1) can be approximated to:

$$V_{S0}^2 = \frac{E}{\rho} \quad \text{...(2)}$$

The Young's modulus normalised with respect to density, which is coincident with the square of the S0 mode velocity, is

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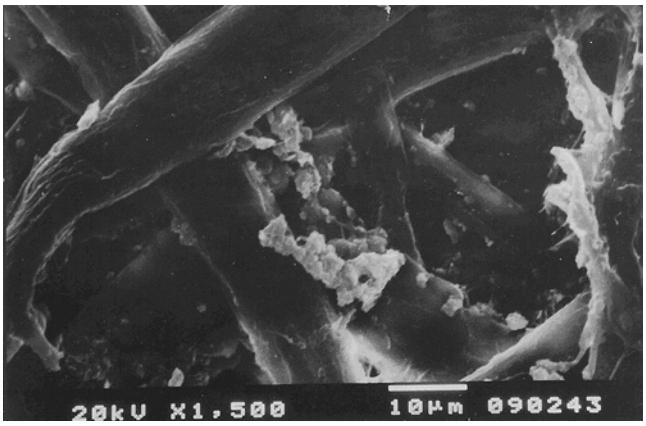

Figure 1. Microstructure of paper

called *TSI* and is commonly accepted as a good estimative of paper strength[5-7]:

$$TSI = V_{S0}^2 \text{ ....(3)}$$

Another fundamental task in paper-making is the anisotropy monitoring, because this parameter is usually related to the process. Typically, the propagation velocity is maximum for *MD* and minimum for *CD* due to fibre orientation. This property is related to the variation of the compressibility degree of fibres with direction. So, by measuring the velocities in different directions along the paper plane it is possible to evaluate the fibre orientation and consequently the anisotropy. This set of measurements is known as the *TSI* plot and is represented in Figure 2. Several types of information can be taken from this plot. One of the most important parameters is the *TSO* angle, which should be as low as possible for the optimisation of the paper-making process, in other words the maximum value of *TSI* should be coincident with *MD*. For copy and laser printer papers a maximum *TSO* angle deviation of +/- 3° is recommended and +/- 5° is recommended for other paper grades. For higher values, some problems like twist and curl in copiers or stack lean could arise. Another parameter usually analysed is TSI_{MD}. The variation between minimum and maximum values must be between 5-10% if good runnability in the paper machine is to be achieved[13].

In paper-making, fillers are the second most important raw material, after fibres. They are called *fillers* because they fill up paper pores between fibres, yielding a whiter and denser paper. In Figure 1 it is possible to see fillers (white particles) incorporated in the fibre structure of paper. The most common types of fillers are minerals like kaolin, talc, ground and precipitated calcium carbonate, chalk and mica[14]. The trend is to increase the level of fillers in paper, reducing costs and, at the same time, contributing to less demand on fibres, which is beneficial for the sustainability of forests. Fillers are also applied in order to improve paper quality in terms of bulk, air permeability, porosity, light scattering, stiffness, gloss and printability. The knowledge of all types of fillers, their characteristics and potential ability in the paper-making process is of major importance for the papermaker[15].

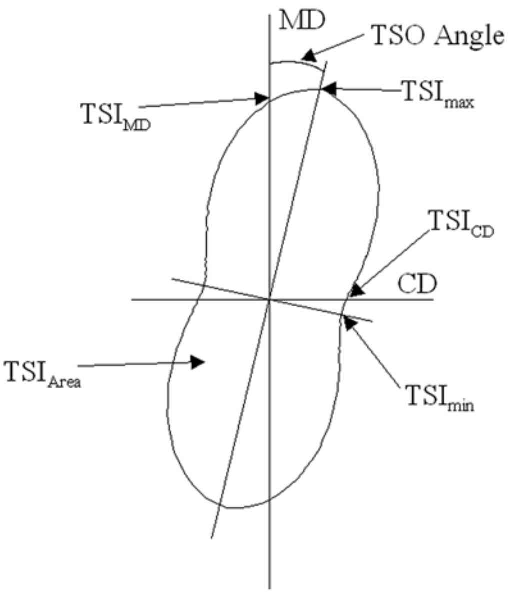

Figure 2. TSI plot

3. Ultrasonic measurement system

3.1 Transducers design and characterisation

Ultrasonic through-transmission and pulse-echo techniques are widely used for inspection of materials. In a typical application the transducers are electrically pulsed and coupled to the test object. In paper, traditionall coupling techniques cannot be used so other types of transducers must be developed to overcome this problem. Piezoelectric bending actuators, such as bimorphs and unimorphs, have been used widely in many applications including position controlling, vibration damping, noise control, acoustic sensing, etc. The structure of piezoelectric bimorph and unimorph is quite simple. Figure 3 is a schematic of the possible arrangements. Two types of connection are often used in bimorphs. One is the series or antiparallel connection (a), in which two piezoelectric sheets with opposite polarisation direction are bonded together. An electrical voltage is applied across the total thickness. The other is parallel connection (b), in which the two piezoelectric layers have the same polarisation directions. An electric voltage is applied between the intermediate electrode and the top/bottom electrodes. Within the two piezoelectric layers, the polarity of the driving voltage is opposite. In both cases, one plate expands while the other contracts. The result is a bending deflection. In unimorph (c), one piezoelectric layer and one elastic layer are bonded together. When the piezoelectric layer is driven to expand or contract, the elastic layer resists this dimensional change, leading to bending deformation. Any bimorph can work like a unimorph if no electrical voltage is applied to one of the layers. Piezoelectric bimorphs are very useful because the motion of the tip can be considerable when compared with other piezoelectric actuators.

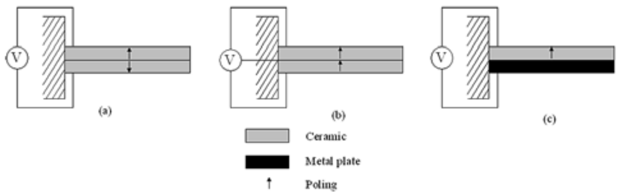

Figure 3. Schematic configuration of bimorphs and unimorphs

The transducers were conceived from ceramic multilayer bender (bimorph) Pz29 manufactured by Ferroperm Piezoceramics. These ceramics[16] are built up from very thin layers of piezoelectric material and built-in internal electrodes. Internal electrodes extend to the rear end of the component and are connected to a set of three external electrodes. This construction allows for high field strength of 3 MV/m, resulting in large displacements even at low driving voltages. The configuration used is of parallel type. The ceramics have a rectangular shape with dimensions of 21 × 7.8 × 1.8 mm (length/width/thickness). The transducer housing is made by two aluminium pieces that hold the ceramic and are tied by four screws. Unscrewing the screws can easily provide control of free length of the ceramic for test proposes. The coupling is done by direct contact between the ceramic and the paper sheet. A photograph of the transducer is shown in Figure 4.

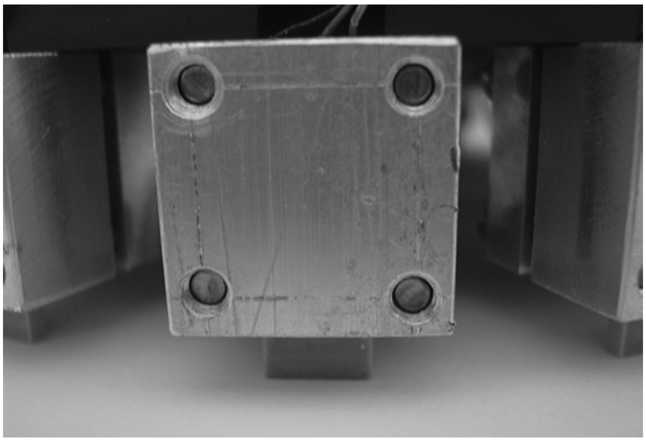

Figure 4. Transducer direct coupled with paper

The theoretical fundamental resonant frequency of a cantilever comprising a bimorph[17] is given by:

$$f_r = \frac{3.52t}{4\pi l^2}\sqrt{\frac{E}{3\rho}} \quad ....(4)$$

where t is the thickness, l the free length, E the Young's modulus and ρ the density. From Eq. (4) we can easily see that we can control the resonant frequency of the cantilever by controlling the free length of the ceramic.

The frequency response of the transducer with 16 mm of free length was obtained using a gain-phase analyser, and is presented in Figure 5. The fundamental resonance mode (A) agrees well with theory and additionally two other peaks are present due to high-order harmonic resonances (B and C). Several experimental tests were done with different ceramics and housings and its frequency response behaviour shows similar aspect.

The analysis of the fundamental resonance mode with the variation of the free length of the ceramic is of great importance for transducers characterisation. Figure 6 presents the ceramic behaviour for variations of l between 4 and 16 mm. Theoretical and experimental agreement for fundamental mode is achieved for high values of the free length. Some discrepancies appear for low values of free length, probably due to imperfections on housing conception and because in these cases the clamping length increases above typical values, which should be around 3-5 mm[16].

The next step of the present research work was the selection of the working frequency, which must ensure a good S/N ratio of the collected signals and must lie above audio range to guarantee a less noisy system. Experimental tests were done using two transducers, one as transmitter and the other as receiver, in contact with common

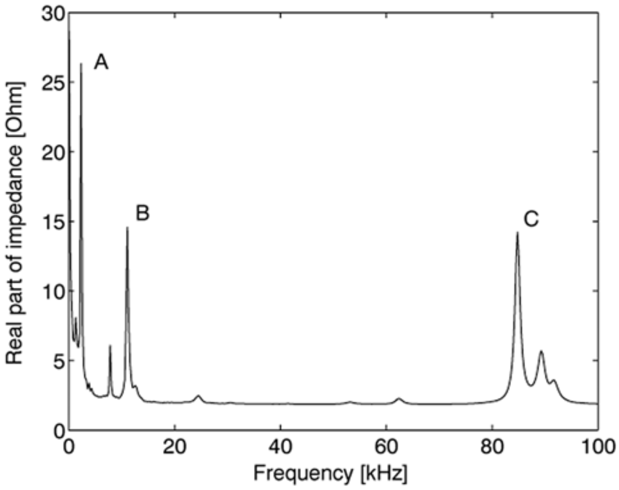

Figure 5. Frequency response (l=16 mm)

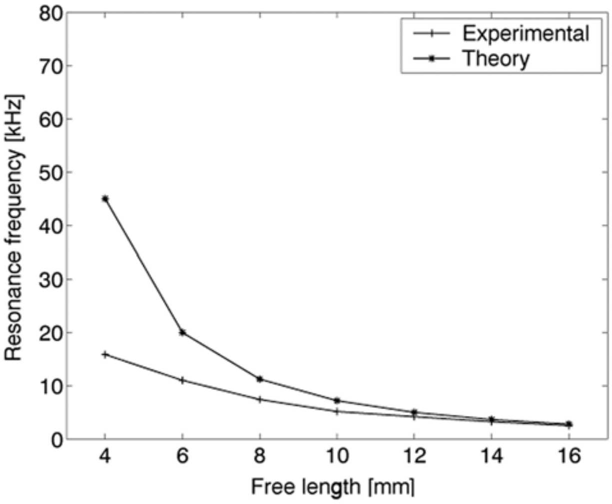

Figure 6. Resonance frequency *versus* free length

sheet of paper and 14 cm apart. First, an excitation spike with 100 V of amplitude was used. Controlling the central frequency of the spike spectrum, a sweeping from 86 kHz downward to 20 kHz was done to analyse the behaviour of the signal at the receiver. It was verified that at the receiver any kind of signal was detected, so this kind of excitation is not adequate. In the second set of experimental tests a tone-burst with 8V of amplitude was used as the excitation signal. From Figure 5, when out of resonance, the real part of the transducer's impedance is very low (about 3 Ω) and a matching impedance circuit must be used. So, a push-pull circuit with low output impedance (1 Ω) was connected between the output of the excitation circuit and the transducer to improve energy delivery. For central frequency burst excitation of 21 kHz and a free length of the ceramic of 5 mm, an S/N ratio of around 32 dB was obtained in the receiver, which indicates that this type of excitation could be used in this system with good results.

3.2 Measuring head

For velocity measurements, eight pairs of emitter/receiver transducers in a circumferential disposition compose the measuring head that is shown in Figure 7. The distance between each pair of transducers is 14 cm. An aluminium disc is used as support of the entire system. Experimental tests reveal that acoustic isolation must be done between disc and transducers housing, otherwise undesirable signals propagated through the disc body arrive at receiving transducers, giving rise to some problems in signal detection. This isolation is performed by a rubber disc. The angular separation between adjacent transducers is 22.5º (360º/16).

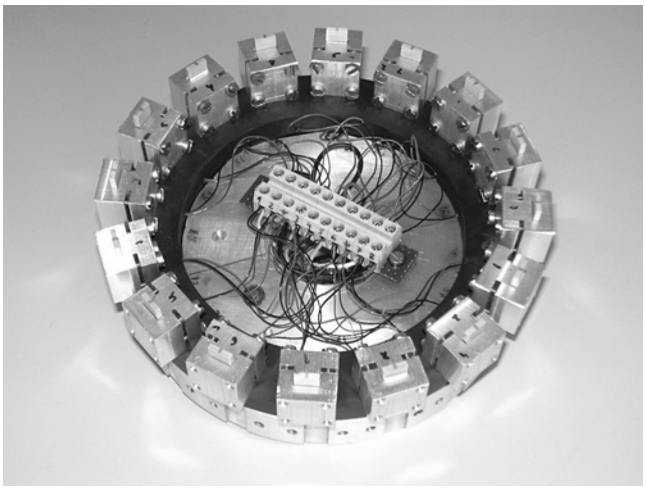

Figure 7. Measuring head

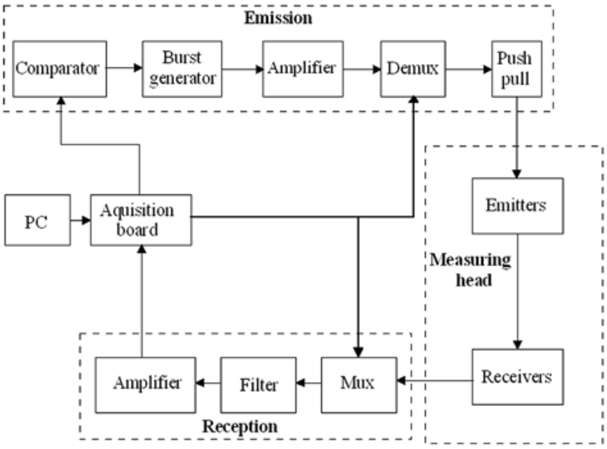

Figure 8. Schematic diagram of the system

3.3 Controlling hardware and software

The schematic diagram of the controlling system is represented in Figure 8. Analogue multiplexing is performed in the emitter stage in order to reduce to one excitation circuit for all emitters and in the receiver stage in order to ensure the correct selection of each transducer and to avoid collected undesirable signals. The emitter stage contains a comparator to elevate the control signal level (0-5 V) that comes from the acquisition board, because the burst generator needs higher level voltages (+/- 12 V). After amplification, demultiplexing is carried out using three digital outputs of the acquisition board. Finally, before the excitation of the emitters, the signals pass through a push-pull stage that performs impedance matching. After the propagation in paper the signals are collected by the receivers and a multiplexing operation is carried out. To improve the S/N ratio and minimise measurement errors, hardware/digital filtering, amplification and averaging of the received signals was used. Besides the low S/N ratio, it was also verified that the central frequency of the received signals lies around 12-13 kHz, which is lower than the frequency of the excitation signals (21 kHz). This is in agreement with Eq. 4 for the free length used (*l*=5 mm). The variation between 12 and 13 kHz is related to the construction parameters of the transducers, such as the little differences in the free length of the ceramics or in the housing pressure. To solve this problem, a wide-band hardware filter with central frequency coincident with the average frequency of all the receivers, together with digital filtering, was used. To find the central frequency of the digital filter for each receiver, a previous acquisition is done and the resonance frequency is evaluated. This frequency is used as central frequency of the digital filter. Experimental tests show that averaging three signals for each receiver gives a good compromise between accuracy and measurement time.

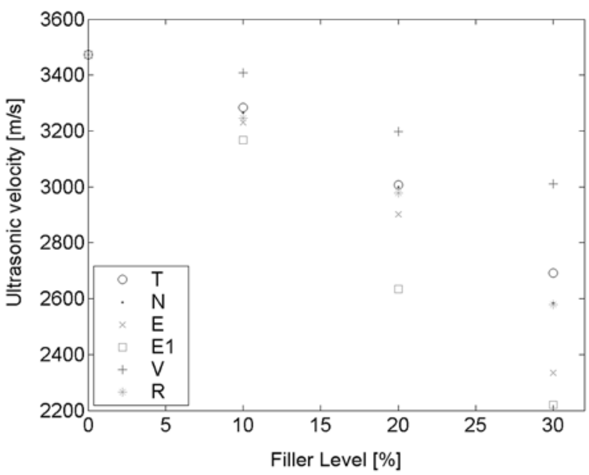

Figure 9. Ultrasonic velocity *versus* filler level

Accurate signal detection by the receivers and consequently velocity evaluation are the critical parameters of the system. This is done by measuring the noise level of the receiving signal and adding a security level of 5 mV. Above this new level, the first spike of the signal is considered and after, using zero detection algorithm, the beginning of the signal is determined. This measured time is not the real propagation time, because there are some delays associated with the hardware, so the system needs to be calibrated using some papers with known velocities. Finally, the *TSI* plot is obtained by interpolating our data using a third order Fourier series fitting over the square of velocities values.

The sampling rate of the acquisition board used is 1.25 MS/s (Megasamples/s), corresponding to a time resolution of 0.8 μs and a maximum error of 1% for the propagation times involved. This error and the approximation introduced by the interpolating process give rise to an average accuracy of the system of approximately 3%.

4. Results

The influence of filler content level in ultrasonic velocity propagation was analysed in paper sheets with six different fillers. Three represent non-aggregated fillers: talc (T), kaolin (V) and GCC (ground calcium carbonate) (N). The other three represent PCC (precipitated calcium carbonates) (E, E_1 with scalenohedral habit and R with rhombohedral habit) aggregated fillers. The paper sheets were produced in the lab with a grammage of 80 g/m^2 with eucalyptus bleached pulp 35ºSR. Four filler content levels were

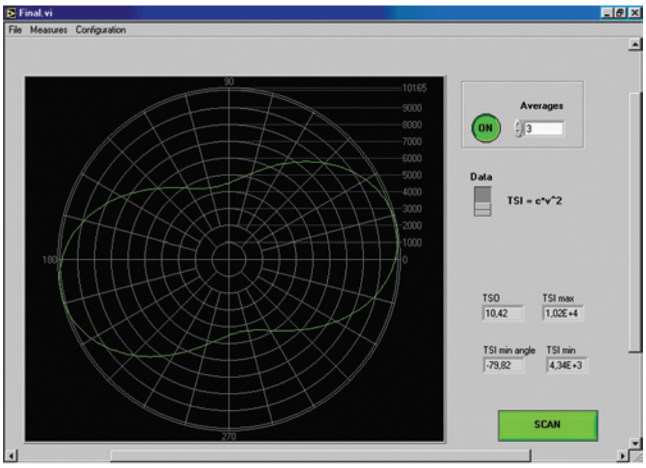

Figure 10. *TSI* plot obtained for commercial paper

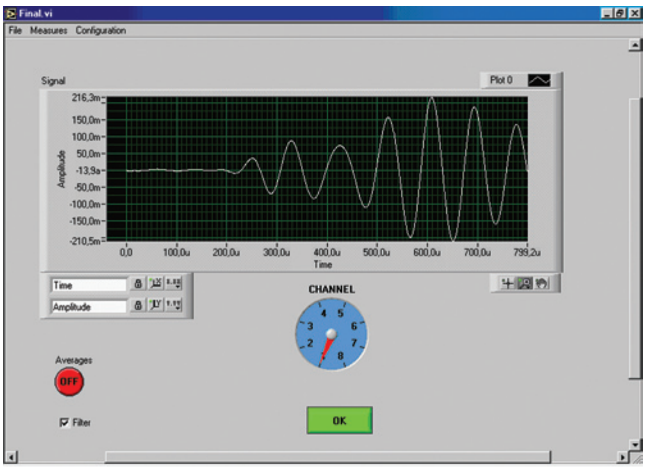

Figure 11. Typical signal at the receivers

chosen: 0%, 10%, 20% and 30% for paper sheets production. A pilot paper machine, a vertical former, run at RAIZ (Instituto de Investigação da Floresta e Papel), in Eixo-Aveiro (Portugal) was used.

For each paper sheet the propagation velocity was as shown in Figure 9. There is a good linear correlation between velocity and filler level for all the samples. The average of square correlation coefficient is 0.97 $R_T^2 = 0.99$, $R_N^2 = 0.98$, $R_E^2 = 0.94$, $R_{EI}^2 = 0.99$, $R_V^2 = 0.96$, $R_R^2 = 0.96$) which allows us to conclude that the measurement of the ultrasonic velocity can predict the elastic properties variation due to filler content in paper.

Minerals with lamellar particles (kaolinite particles show a strong platy aspect) (T, V and N) are responsible for denser paper sheets, while precipitated calcium carbonate particles with scalenohedral shape (E and E_1) give a bulkier and porous sheet. These facts are responsible for the difference in terms of ultrasonic velocity especially for 20% and 30% filler levels. Fillers with rhombohedral particles (R) show an intermediate behaviour in terms of sheet density and sheet bulk between lamellar and scalenohedral fillers.

In Figure 10 one of the graphical interfaces of the system is shown. In this example, the *TSI* plot for a commercial paper is presented, where *MD* is intentionally deviated from the alignment of the measuring head to show clearly the *TSO* angle. In the lower right-hand corner the TSI_{max} and TSI_{min} and the respective *TSO* angles are visible. In the upper right-hand corner the user has the possibility to select the plot variable (*TSI* or velocities) and also if the plot is performed with or without averaging.

Other parameters like acquisition board configuration or visualisation of time domain signals are also available from this interface. In Figure 11 a typical aspect of a collected signal at one receiver is shown.

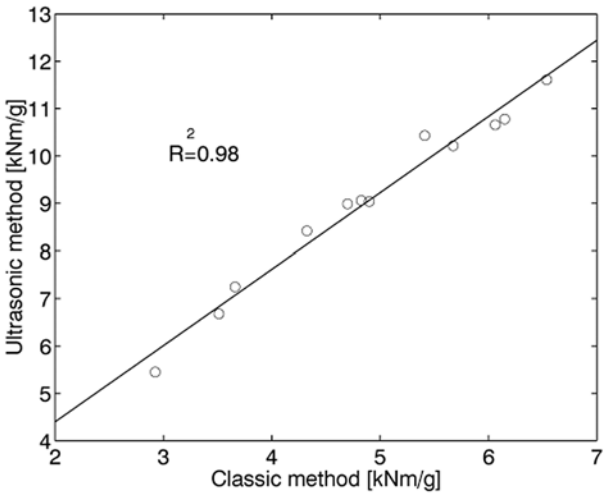

Figure 12. Stiffness obtained with classic and ultrasonic methods

Finally, in order to validate strength properties of paper by measuring ultrasonic velocities based in Eq. (3), a classic tensile stiffness method was used. In the classic method the stiffness is measured in the elastic region of the force *vs* strain curve (load and elongation of paper sheet is sufficiently small for the sheet to recover completely when removing the load). Tensile stiffness relates to the elastic properties of paper sheets because it refers to the resistance of the paper when it is deformed by an external load that acts parallel to the plane of the sheet. The results obtained using both methods are presented in Figure 12. The correlation is very high, 0.98.

5. Conclusions

This paper presents a full description of an ultrasonic non-destructive system that enables measurement of paper properties such as fibre anisotropy or filler content.

Transducer design, measuring head conception as well the controlling hardware and software have been described. The bimorphs ceramics were successfully used as a way to solve the coupling problems with paper. Analogue multiplexing allows substantial reduction of circuitry components and, in conjunction with hardware and software filtering, gives rise to reasonable S/N ratio at the receivers. The interpolation algorithm used in *TSI* plot seems to be efficient because it gives an average accuracy of 3%.

With this system it is possible to obtain good accuracy in less time when compared with other conventional systems like those that use two transducers in association with a rotation platform.

Experimental results proved the validity of the ultrasonic method when strength properties are important and the system can be applied with success in filler content determination and fibre anisotropy prediction.

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