DEVELOPMENT OF A MEASURING HEAD FOR ULTRASONIC IN-PLANE PAPER CONTROL

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ABSTRACT

This article presents a simple way to use bimorph ceramics in the construction of an 18 elements ultrasonic head. Impedance spectroscopy was used in transducer optimization and housing conception. High S/N ratios of the ultrasonic signals were obtained and several advantages can be appointed to the system. One is the less time consuming when performing the polar tensile stiffness plot. The other is the same order of accuracy obtained with this reduced data 22,5º-transducer system, instead of conventional 5º systems, using a convenient interpolation algorithm. Finally, analog multiplexing in both emitter and receiver stages reduces the need of supplementary circuitry.

INTRODUCTION

There is a growing interest for non-destructive techniques that allows the characterisation of various mechanical properties of paper. One of these techniques is based on ultrasonic velocity measurements due to its high dependence of the nature of the propagation media. Measuring the velocity of an ultrasonic pulse propagating in the plane of a paper sheet can determine properties of the sheet.

Several authors were interested in ultrasonic characterisation of paper from both theoretical and experimental point of view[1-9]. Some of this previous works investigated plate waves propagation in paper using contactless methods in attempt to obtain correlations with mechanical properties[1,2,7]. Other researchers like Baum and Habeger[3] and Kopkin[8] have developed on-line systems that can measure certain properties in a moving web. Off-line commercial equipment like that indicated in reference 4 is also available in the market.

Tensile stiffness index (TSI) is a measure of the elastic property of paper and could be estimated by

$$TSI = v^2 C \tag{1}$$

where v is ultrasonic velocity and C a dimensionless constant related to Poisson's ratio of the material, that is approximately 1 for paper. Tensile stiffness orientation (TSO) angle is defined by the orientation of the maximum of TSI plot and the machine direction. TSI has found increasing acceptance as a measure of the strength properties of paper. The strong correlation established in practice has allowed many mills to reduce traditional destructive testing because TSI can give the same results.

In our work was fully developed a prototype head and dedicated hardware and software that allows in-plane velocity and attenuation measurements and gives TSI and TSO. The head incorporates 16 transducers in a circumferential configuration (8 emitters and 8 receivers) for velocity evaluation and additionally 2 transducers to perform attenuation measurements in both machine direction (MD) and in cross direction (CD). Transducers were constructed using lead titanate zirconate piezoelectric ceramics. Both unimorph and bimorph configuration was studied and impedance analysis was used in transducer optimisation and housing conception. Experimental results reveal that in the reception stage high S/N ratio of ultrasonic signals, after propagation in standard paper sheets, can be obtained after convenient filtering. The main advantage of this system is the less time consuming for the same order of accuracy when compared with other conventional systems (2 transducers combined with a 5º rotation operation).

BIMORPHS AND UNIMORPHS

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[10]. The structure of piezoelectric bimorph and unimorph is quite simple. In figure 1 is schematically shown 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. The 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. The electric voltage is applied between the intermediate electrode and the top/bottom electrodes. Within the two piezoelectric layers, the polarity of 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 to this dimension 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.

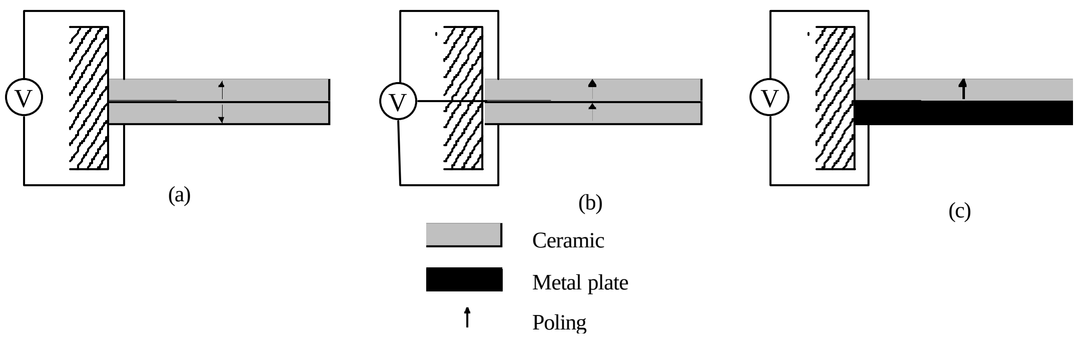


Figure 1 – Schematically configuration of bimorphs and unimorphs.

TRANSDUCERS DESIGN

Housing

In transducers conception were used ceramic multilayer bender (bimorph) manufactured by Ferroperm Piezoceramics. This ceramics[11] 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 3 external electrodes. This construction allows for high field strength of 3 MV/m resulting in large displacements even at low driving voltages. The selected material was lead titanate zirconate piezoelectric PZ29, due to its high strain with high dielectric constant and also low hysteresis and creep. The type of configuration used is of parallel type. The ceramics have a rectangular shape with dimensions of 21x7,8x1,8 mm (length/width/thickness). Transducer housing is made by two aluminium pieces that hold the ceramic and are tied by 4 screws. Unscrewing the screws can easily provide control of free length of the ceramic for test proposes.

<u>Resonant behaviour</u>

Theoretical fundamental natural bending resonant frequency of a cantilever comprising a PZT bimorph[12], as shown in figure 2 a), is given by

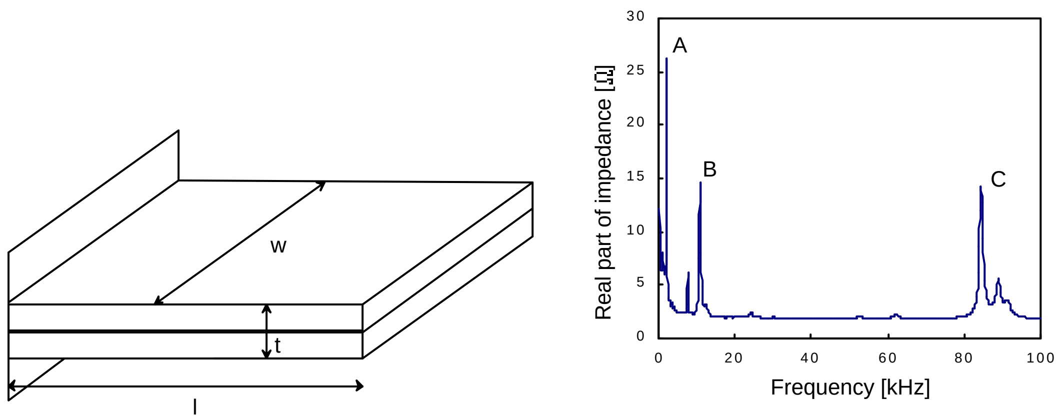
$$f_r = \frac{3.52\,t}{4\pi l^2}\sqrt{\frac{E}{3\rho}} \tag{2}$$

where t is the thickness, l the free length, E the Young's modulus and ρ the density. From (2) we can easily see that we can control the resonant frequency of the cantilever by controlling the free length of the ceramic.

Using a gain-phase analyser, typically frequency response of the cantilever for a free length of 16mm was obtained, and is shown in figure 2 b). The value of the most important resonance (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 the behaviour of the frequency response shows similar aspect.

In figure 3 a) is presented the ceramic behaviour with free length increasing. Theoretical and experimental agreement for fundamental mode (A) is again achieved for high values of the free length. Some discrepancies appear for low values of free length, probably due to imperfections on housing conception. The harmonic B only exist for values of l higher than 12mm and is behaviour is similar to the fundamental mode A. The harmonic C has a more or less constant value around 86kHz.

Real part of impedance is presented in figure 3 b). For all modes exist a growing behaviour with ceramic free length increasing.



a) b)

Figure 2 - a) Structure of a cantilevered bimorph actuator and b) frequency response of the cantilever with l=16mm.

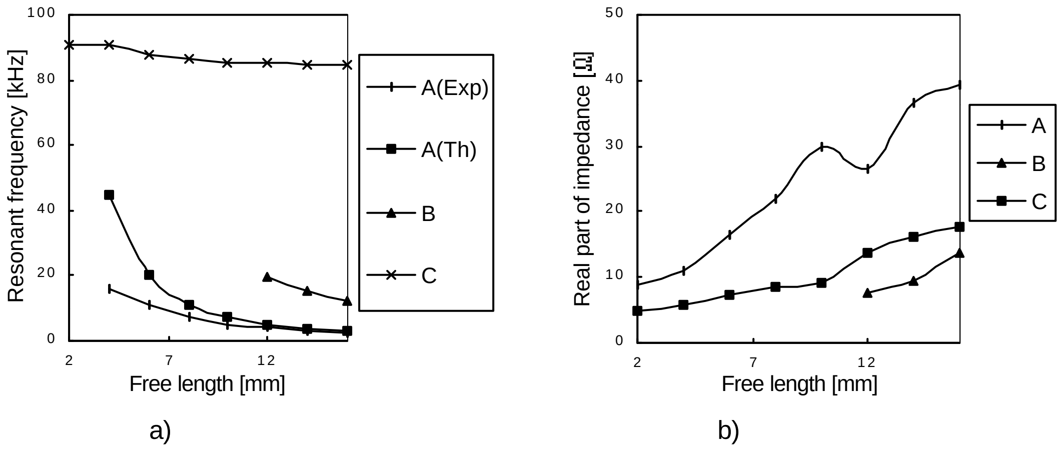


Figure 3 - a) Resonant frequency versus free length and b) real part of impedance versus free length for the three resonance modes.

<u>Frequency selection</u>

The next step and perhaps the most important in our work, is the working frequency selection. There are several factors that typically have to be taken into account:

1 - Use of a frequency above audio range to ensure a less noisy system;

2 - Selection of a resonant working frequency to response optimisation;

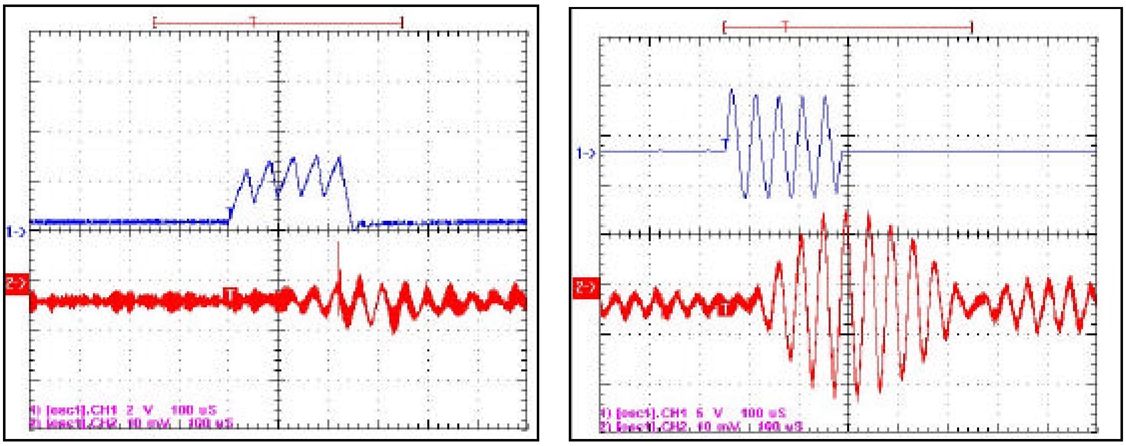
3 - Ensure a good S/N ratio of the collected signal for the selected frequency;

4 - As we are interested in velocity measurements, better accuracy in the detection of received signal can be achieved if high frequency is used.

Looking at figure 3 a) we can see that above 20kHz the only existent resonance corresponds to the curve C around 86kHz. For this frequency, requisites 1, 2 and 4 are fulfilled and we only need to ensure a good S/N ratio of the propagating signal. For this propose several kind of excitation modes were used. Experimental tests were done using two transducers, one as transmitter the other as receiver, in contact with common sheet of paper and 14cm apart. In the first set of experimental tests an excitation spike with 100V of amplitude and central frequency spectrum around 86kHz was used and it was verified that at the receiver any kind of signal was obtained. Sweeping this frequency downward to 20kHz similar results were obtained. We conclude that this kind of excitation is not adequate.

In the second set of experimental tests a tone-burst with 8V of amplitude was used as excitation signal. As we can see in figure 2 b), out of resonances, transducers real part of impedance is very low (about 3Ω) and a matching impedance circuit must be used. So, a push-pull circuit with low output impedance (1Ω) was connected between the output of the excitation circuit and the transducer to improve energy delivery. The influence of this matching circuit can be viewed in figure 4, where output signal before and after matching are presented. Like before, a sweeping frequency from 86 to 20 KHz was done and it was verified that only near 30kHz the collected signal presents a reasonable S/N ratio.

These experiments and practical considerations show, in opposition of our initial supposition, that the best working frequency is not at any of the resonant modes (factor 2). Looking at selection factors is obvious that factor 3 is the most important and should prevail in conjunction with the factor 1. For our proposes factor 4 is not relevant if a good algorithm is used for signal detection. So, a forced excitation is preferable to be used and the selected frequency was 21kHz because it offers a best comprise among all presented factors.



a) b)

Figure 4 – Impedance matching influence: a) without matching b) with matching. Top signals are at the emitter and bottom signals are at the receiver.

MEASURING HEAD

For velocity measurements propose, eight pairs of emitter/receiver transducers in a circumferential disposition compose the prototype of the measuring head. The distance between each pair of transducers is 14cm. 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 transducer, giving rise to some problems in signal detection. In figure 5 is shown a photograph of the measuring head, where we can see the transducers and the acoustic isolation performed by rubber.

The angular separation between adjacent transducers is 22,5º (360º/16). Analogue multiplexing is performed in both emitter and receiver stages. In emitter stage the goal is to reduce to only one excitation circuit for all emitters. In the receiver stage is to ensure the correct selection of each transducer and to avoid collected undesirable signals.

The overall system is PC controlled by means of an acquisition board and LabView based software. On-line velocity measurements are preformed and TSI plots are obtained using a third order polynomial interpolation algorithm over velocity values. In figure 6 are presented two typical TSI plots obtained with this system, one corresponds to a common writing paper sheet and other to a laboratorial non-standard fabrication process paper.

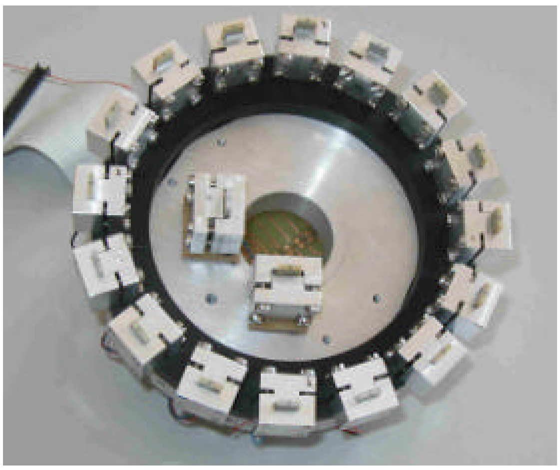


Figure 5 – Measuring head prototype.

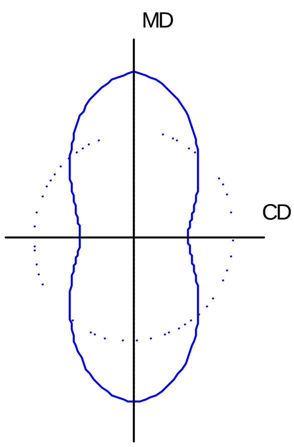


Figure 6 – TSI plots for common writing paper (-) and laboratorial paper (¨).

Two additionally transducers are strategically placed in MD and CD directions for attenuation measurements. The attenuation can be used for structural paper properties determination in complement of typical parameters like TSI and TSO.

CONCLUSIONS

The knowledge of TSI of the product being produced allows the papermaker to have a new way to optimise the process. This can be done measuring the velocity of an ultrasonic pulse propagating in the plane of paper sheet.

This work describes a new measuring head that allows strength and elastic in-plane properties evaluation of paper. Bimorphs widely used as actuators, were successfully integrated in the system and high S/N ratio of the ultrasonic signals propagating in paper was obtained for a working frequency of 21 kHz. The analog multiplexing used allows substantial reduction of circuitry components. The interpolation algorithm used in TSI plot overcomes the need of conventional 5º transducer system. Good accuracy, less time consuming and additional information can be obtained with this system.

ACKNOWLEDGMENTS

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