ANALYSIS OF ULTRASONIC SENSING SYSTEMS

The design of a rolling wheel transducer is described. It will enable the Young's modulus of paper in the cross machine direction, and the horizontal shear modulus in the machine making direction to be measured. Measurement of other moduli may also be possible. The design is suitable for continuous monitoring of these moduli on a paper making machine.

1. Introduction

Amcor is a Melbourne based producer of pulp and paper products with an annual operating budget of over $3 billion. It is one of the largest such companies in the world. Amcor is a major producer of paperboard, heavy paper, and carton stock for use in packaging and containers. A knowledge of the elastic mechanical properties of these products is essential for the efficient design of containers and packaging that will not fail in handling and storage situations.

Paper is a fibre composite material, with pronounced orthotropic anisotropy due to preferential alignment of the fibres in the manufacturing process machine direction. The orthotropic elastic mechanical behaviour of the paper is determined by nine elastic constants. Amcor proposes to measure these constants on-line using an ultrasonic device located between the point where the finished product leaves the mill and the point where it is rolled onto the final roll for shipment. The successful implementation of such a device will lead to better quality control and the possibility of a feedback loop to control the production process.

Russell Allan of Amcor originally brought this problem to MISG 1994. The use of ultrasonic measurements was initially proposed by researchers at the Institute of Paper Chemistry in the USA and references to this work can be found in the MISG 1994 report. The work in the USA seemed to have had only limited success, and the 1994 project was to understand the transmission of ultrasonic waves in paper, and to seek the means of improvement on the experience in the USA. Most of the MISG 1994 report is devoted to an explanation of ultrasonic wave propagation in orthotropic plates and how measurement of the propagation speed of these waves can be used to determine the elastic properties of the paper.

Since then Russell Allan has developed an improved signal processing system to measure the wave propagation velocities using a continuous FM signal system. The task for the MISG95 project team was to analyse the most efficient means of exciting and detecting the ultrasonic waves that would give maximum information about the elastic constants.

As a result of our deliberations a design concept was proposed for a transducer to transmit and receive continuous waves in the paper sheet. Amcor will proceed with the implementation of this device at the mill.

2. Wave propagation in orthotropic plates

Although paper is an inhomogeneous material consisting of wood fibres in a continuous matrix of bonding material, it is assumed throughout this report that the wave length of the waves generated is not only very much longer than the dimensions of the individual wood fibres, but also longer than the thickness of the paper. Thus, the ultrasonic measurements will reflect average 'smeared out' values of the elastic constants for the composite paper sheet. However because of the preferred orientation of the fibres in the machine direction account must still be taken of the orthotropy of the sheet. That is, wave propagation velocities will be different for waves in the machine direction from waves in the cross machine direction.

In an unbounded elastic medium two distinct types of wave are possible:

1. Dilatational waves or volumetric strain waves.
2. Shear waves where the particle motion is perpendicular to the wave propagation direction. These waves cause no volumetric strain or dilatation.

In a bounded elastic medium such as a vibrating plate these two types of waves undergo repeated reflections at the plate surfaces. At certain angles of reflection the waves interfere constructively to produce guided waves that propagate in directions parallel to the plate surfaces. This complicated interaction of the shear and dilatational waves gives rise to three generic modes of propagating plate waves:

1. S or symmetrical waves in which the particle motion (at low frequencies) is predominantly in the direction of propagation and parallel to plate surfaces, as illustrated in figure 1. The particle motion is symmetric with respect to the plate middle surface. The symmetric particle motion perpendicular to the plate surfaces is mainly due to Poisson expansion and contraction.
2. SH or horizontal shear waves. The particle motion is parallel to the plate surfaces and perpendicular to the direction of wave propagation.

3. A or asymmetric waves. The predominant particle motion is perpendicular to the plate surfaces and is asymmetric with respect to the plate middle surface. At low frequencies these waves produce the largest out-of-plane displacements.

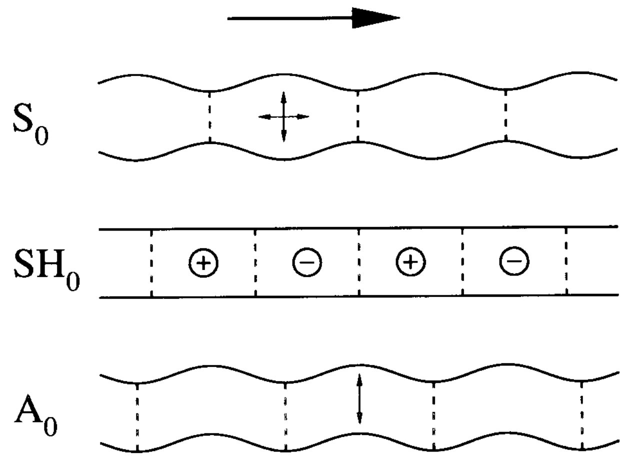

Figure 1: Schematic diagram of plate deformation caused by *symmetrical longitudinal* (S) waves, *horizontal shear* (SH) waves, and *asymmetrical longitudinal* (A) waves.

Each of these modes of wave propagation has a distinctive frequency-dependent velocity of propagation and each generic mode can propagate in a fundamental or higher order mode of propagation. The higher order modes correspond to more nodal lines (parallel to the plate surfaces) in the particle displacement functions across the plate thickness.

All the waves except the fundamental SH_0 mode waves suffer *geometrical dispersion* and typical *phase velocity* vs *frequency* dispersion curves for waves propagating in the machine direction are shown in figure 2. Because paper is orthotropic the wave velocities are different in the cross-machine direction. The dispersion curves for waves in the cross-machine direction are similar to those shown in figure 2. Further details can be found in the MISG 1994 report and in the paper by Mann, Baum, and Habeger (1979).

3. What modes should be used?

The initial plan was to use measurements of features of the dispersion curves for the fundamental modes of propagation S_0, SH_0 and A_0 in order to estimate

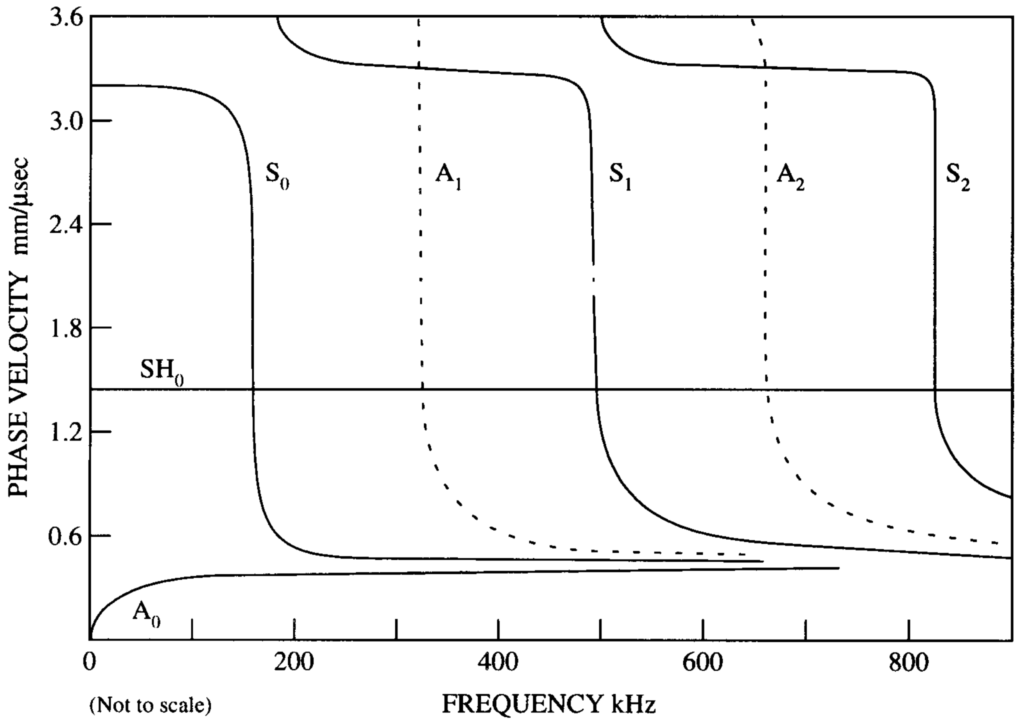

Figure 2: Phase velocity versus frequency curves for waves in the machine direction for an orthotropic plate. After figure 3 of Mann, Baum, and Habeger (1979).

the elastic constants of the paper. It was planned to use frequencies in the neighbourhood of 170 kHz where the S_0 dispersion curve suffers a sharp drop due to the fact that the Young's modulus in the direction perpendicular to the plane of the paper is much less than in the other two directions.

The problem was to design a transducer that will transmit most of its energy into the paper in the desired mode. The transducer must be in direct contact with the paper and the use of couplant gels to promote efficient transmission of the excitation energy into the paper is not practical. Further to prevent wear at the transducer/paper contact surface it is desirable to have a transducer in the form of a wheel that rolls on the paper, which travels with a velocity 10 m/s in the machine direction. This velocity is much lower than the velocities of the ultrasonic waves.

The A_0 mode

The waves in this mode are also called bending or flexural waves, particularly at low frequencies. In the static case, the paper is supported between the rollers of the paper making machine by tension rather than the bending stiffness of the paper. Comparison of the transverse wave equation for a tensioned string and the one dimensional bending wave equation for the paper showed that tension will only be important at very low frequencies.

Initially it was hoped to use a contact transducer that would impart a motion perpendicular to the plane of the paper to generate these waves, because at low frequencies their propagation velocity depends directly on the bending stiffness of the paper. However, a measurement of the bending stiffness of the paper is not as useful or necessary as the measurement of the Young's moduli in the machine and cross direction and the in-plane shear modulus. This is because it is not possible to determine accurately what value of thickness should be used to determine the Young's modulus from the bending stiffness. The Young's moduli are needed to compute the bending stiffness of the 'composite' plates (corrugated cardboard box material) that are made up from the paper sheet product produced by the mill.

For these reasons it was decided to abandon any attempt to make measurements in the A_0 mode

The S_0 and SH_0 modes

The dispersion curve for the S_0 mode has three very distinctive features. A region of high constant phase velocity for frequencies below (approximately) 170 kHz, a region of low fairly constant phase velocity for frequencies above (approximately) 300 kHz, and a very rapid transition between these two regions at approximately 170 kHz in the example given in figure 2. The values of these two velocities in the so called plateau regions and the value of the frequency at which the transition takes place depend critically on the machine direction and cross machine direction Young's moduli E_{md} and E_{cd} respectively. Finally, the measurement of the constant velocity of the non-dispersive SH_0 mode velocity gives a direct measure of the in-plane shear modulus G. In the next section a design concept for a transducer system to measure these features of the S_0 and SH_0 dispersion curves is described.

4. Transducer design

The main particle motion of S_0 and SH_0 waves is parallel to the plane of the paper. Thus to excite and detect these waves it is necessary to design a transducer which produces and responds to motion in the plane of the paper. Thus, obvious designs which produce and respond to motion perpendicular to the plane of the paper were ruled out. The high speed of the paper and the need to avoid wear on the paper and the transducer required a rolling wheel design. Overseas attempts at noncontact transducers failed because the airborne coupling varied wildly because of fluctuating air currents around the high speed paper making machinery.

High powered ultrasonic transducers are operated at a resonant frequency. In this case it was desirable to have the transducer operate between 20 and 250 kHz. This need for a broadband transducer meant that the resonances of the transducer should be above 250 kHz if possible and that the transducer should be as close to critically damped as possible. To keep the resonant frequencies high the transducer should be as small as possible. However the smallness of the diameter of the wheel is limited by the maximum rotation speed of the wheel's bearings. Although larger than desired, a wheel diameter of 50 mm was chosen because it produces a rotation speed of about 4000 rpm for a paper speed of 10 m/s. Although this is well within high speed bearing limits of 10,000 to 12,000 rpm, it allows for anticipated future increases in the speed of paper machines. In order not to cut the paper, the thickness of the contact part of the wheel was chosen to be 3 mm with a smooth rounded contact surface.

The piezo-electric material was chosen to be PVDF film because it is easy to cut and glue into the required shape and has a relatively low mechanical quality factor of 10. The first thickness resonance occurs when the total thickness of the layers of film is equal to half a wavelength. The speed of sound perpendicular to the plane of the PVDF film is 2200 m/s. The total thickness of the layers of PVDF film was chosen to be 5 mm, since this gives a first thickness resonance of 220 kHz. Both aluminium and steel have quasi-longitudinal wave speeds of about 5100 m/s. Thus a 3 mm disc of these materials would have a first thickness resonance of 850 kHz. If we ignore the mass of the PVDF film, the mass-spring combination of the 3 mm metal plate mass and the 5 mm PVDF spring has a resonance frequency of 35 kHz for aluminium and 21 kHz for steel.

In order to have bearings on both sides of the metal disk and piezo-electric assembly, it is necessary to make the metal disk and piezo-electric disk into annular rings so that the bearing shaft can pass through them without impeding their lateral motion. This also has the advantage of raising the planar resonant frequencies from those of the disks. An annular thickness in the radial direction of 5 mm for the PVDF film assembly would make the radial resonant frequency the same as the thickness resonant frequency, namely 220 kHz. Because the metal disk has to stop the PVDF film from touching the paper, it needs to have a greater annular thickness in the radial direction, say 8 mm. This gives a radial resonant frequency of 320 kHz for aluminium or steel.

The annular metal and PVDF film assembly needs to be mounted on a metal plate attached perpendicularly to the axis of the bearing shaft. The side of this plate opposite the assembly should be shaped as an exponential horn to transfer vibration to the bearing shaft. Calculations performed at MISG 1995 showed that this exponential horn should have a minimum length of 33 mm. The exponential horn will reduce the effect of resonances in the support plate.

The piezo-electric strain constants of a material can be expressed in units of m/V. Thus the higher the voltage applied, the larger the motion produced. When stacking piezo-electric elements, the effective voltage across the stack can be increased by alternating the polarisation directions of the elements and alternating the electrode connections between the two voltage source terminals. This applies the whole voltage of the source across each piezoelectric element and keeps each element expanding and contracting at the same time. Of course it happens at the expense of having to drive a larger capacitive load.

The piezo-electric strain constants can also be expressed in units of C/N. Stacking and wiring the elements as described in the previous paragraph increases the charge output of the transducer for a given applied force. This is desirable if a charge amplifier is being used to detect the output. If a voltage amplifier is used, the higher capacitance reduces the noise level and reduces the effect of shunt capacitance in the cables and amplifier. The output voltage is given by the charge divided by the total capacitance (if the shunt resistance is high enough at the given frequency). Thus it is possible to obtain a higher voltage output by not alternating the polarisation directions of the film layers and measuring across the whole stack. However because the increased voltage is obtained because of the smaller capacitance, the noise will increase and the effect of shunt capacitance will be greater. Thus a higher signal to noise ratio will probably not be obtained. The final choice of the stacking and wiring configuration depends mainly on the requirements of the electronics.

The PVDF piezo-electric film is available in thicknesses of 9, 16, 28, 52, 110, 220 and 800 micrometres. Twenty layers of the 0.22 mm thick film together with the conducting glue used to bond the layers together should give a thickness of about the required 5 mm.

The design described drives the metal contact annular plate from only one side. It was suggested by Joseph Ha at MISG 1995 that the plate be driven by "push-pull" by duplicating the PVDF piezo-electric film assembly and exponential horn backing plate on the other side of the plate and driving it 180 degrees out of phase. This seems to be a good idea since it would give more rotational stiffness to the plate support and increase the sensitivity of the transducer. A disadvantage might be extra unwanted resonances.

It is proposed that three of these wheel transducers would be used on a paper machine. There would be one transmitter and two receivers. One of the receivers would be in the cross machine direction from the transmitter and would detect the S_0 wave from the transmitter. The other receiver would be in the machine making direction from the transmitter and detect the SH_0 wave from the transmitter.

While it is difficult, if not impossible, to design a transducer that will excite and respond equally for all wave types, it is probably impossible to design one that will not excite slightly all wave types. This is because of the tensor nature of the piezo-electric coupling constants and Poisson expansion and contraction. Thus it is possible that the transducer will produce and detect useable amounts of the other wave types in each direction.

5. Conclusion

A rolling wheel transducer has been designed. It will enable the measurement of the Young's modulus in the cross machine direction and the measurement of the horizontal shear modulus in the machine making direction. Measurement of other moduli may also be possible. The design is suitable for continuous monitoring on a paper making machine.

Acknowledgments

This project was presented by Russell Allan of Amcor and coordinated jointly by John Davy and Barrie Fraser. Other participants whose efforts in particular should be aknowledged were Joseph Ha, Jill Ogilvy and Bernie Wendlandt.

References

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