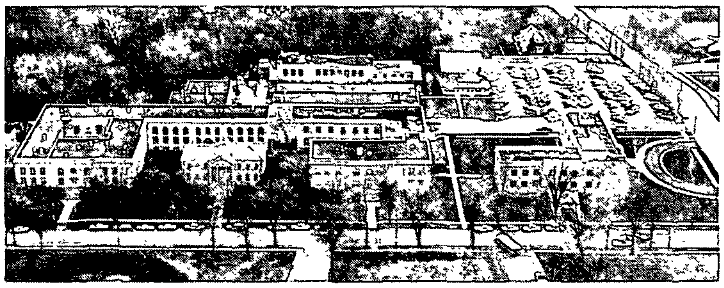

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AUTOMATIC DETERMINATION OF ULTRASOUND VELOCITIES IN PLANAR MATERIALS

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Abstract

A computer-controlled, fully-automated instrument which measures ultrasound velocities in planar materials is presented. By finding two longitudinal and two transverse velocities, it can completely characterize the in-plane elastic properties of an orthotropic sheet. Even though it is specifically designed to analyze paper and paperboard samples, other sheet materials can also be tested.

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Introduction

Paper and paperboard are orthotropic sheets whose mechanical properties are subject to paper machine process changes and variations in the furnished pulp. In-plane mechanical integrity (usually determined by strength testing) is important to end-use performance, and strength measurements are often used for quality control and to guide adjustments in manufacture. Even though failure testing is contrived to emulate the critical conditions which the final product must withstand, there are serious drawbacks to the standard practice of assigning strength tests as the indicators of mechanical quality. First of all, it is not feasible to test strength during manufacture; therefore, quality checks can be made only after samples are cut from a finished reel. For some grades, it requires about thirty minutes or more to make a reel of paper which weighs tens of tons and is worth tens of thousands of dollars. Since samples are only taken from the end of the reel, a very small portion of the product is characterized. Fifteen minutes can elapse before tests are completed and results are reported. Large quantities of product, which may be either substandard or needlessly over-built, are produced before any feedback is received. In addition, paper is non-homogeneous, and its strength properties have large variations. The number of tests performed in the allotted time is far too small to assign a reasonable level of confidence to the test average. This situation is greatly compounded if the papermaker needs to determine variations in strength profiles across the machine. Here is a clear case of too little testing coming too late, which can only be remedied with a computer-controlled, on-line measurement.

Before the principles of computer directed quality assurance and process control can be effectively utilized in the manufacture of paper, the standards for mechanical performance must be shifted from the traditional failure criteria to other standards which can be applied nondestructively, rapidly, and on-line. The most fundamental and straightforward method to nondestructively assess mechanical behavior is to look at the relationships between stress and strain at small strains. The elastic parameters are the common representation of mechanical behavior in this linear regime, where on-line testing must be done. Therefore, elastic parameters are the natural choice to replace failure criteria as the standards for mechanical integrity during manufacture. Fortunately, this will not mean that the concept of strength prediction must be abandoned. In many cases paper strength is highly correlated to elastic parameters. This is particularly true for the less complex measurements, such as tensile strength[1] and compressive strength[2], in which elastic behavior is an important aspect of the failure mechanism. In fact, the prediction of strength from continuous, on-line elastic measurements may well be a better predictor of the strength properties of the entire reel than a few direct tests on sample from the reel end.

An effective way to determine elastic parameters of paper is to find the phase velocity of mechanical plate waves.[3,4,5] This technique is nondestructive, rapid, and has been demonstrated on-line.[6] As this technology is applied at the paper machine, a great need will arise for laboratory instruments which also measure ultrasonic velocities. These devices will provide the basis for on-line testing by allowing papermakers to understand the performance of their product in terms of elastic parameters. Aside from supporting on-line instrumentation, ultrasonic laboratory testing is important in its own right. It yields rapid, repeatable mechanical information without damaging the sample. It provides a complete set of in-plane elastic parameters including shear modulus and Poisson ratios, which are difficult to obtain in other ways.

The purpose of this paper is to describe an instrument which makes extensive laboratory testing feasible. It is fully automated and systematically determines the four independent in-plane elastic parameters of a sheet. It does the large number of repetitions necessary on inhomogeneous samples without being labor intensive. It is computer controlled, making it versatile and easily adapted to special needs.

Background

The measurement of ultrasound velocities is a powerful technique for nondestructive analysis of the mechanical properties of polymeric and other materials. Often, the phase velocity of plane wave propagation of sound through a material is equal to the square root of an elastic stiffness divided by the mass density. Therefore, the value of a mass specific elastic stiffness can be obtained from velocity calculations. Of particular interest here are planar materials. These are defined as plates whose lateral dimensions are large compared to the wavelength of bulk sound waves propagating in-plane and whose thickness is small compared to the wavelength of out-of-plane bulk waves. If the lateral dimensions of a sheet are much greater than the thickness, it is usually possible to find a frequency range in which the plate can be approximated as a planar material. Because of asymmetry in fabrication, the mechanical properties of paper (and many other polymeric sheets) are different along the direction of manufacture (the MD) than perpendicular to the direction of manufacture (the CD). Often, these sheets have orthotropic symmetry. That is, there are two orthogonal principal directions (the MD and CD) and the material has reflectional symmetry about planes determined by a principal axis and the sheet normal. If the frequency is low enough to consider the plate to be planar, symmetric plate waves are nondispersive.[7] The motions constituting these disturbances have a small out-of-plane component, but they are mainly along the direction of propagation when traveling in a principal direction. Such modes will be called longitudinal. The velocity of a longitudinal wave in a principal direction is the square root of a planar stiffness divided by the density, i.e., in the MD, $V_{Lmd}^2 = C_{11}'/\rho$, and in the CD, $V_{Lcd}^2 = C_{22}'/\rho$. A planar stiffness is defined as the small strain limit of the ratio of the normal stress to the normal strain when there is no out-of-plane stress and no strain in the other principal direction. Transverse plane waves also propagate along the principal axes of the plate. Their motion has no out-of-plane component and is entirely along the principal axis perpendicular to the propagation direction. These modes are nondispersive at all frequencies, and the velocity squared in both principal directions is the shear stiffness, C_{66}, divided by density.[7] If desired, engineering elastic parameters can be calculated from planar stiffnesses.

Since the longitudinal and transverse modes in planar materials are nondispersive, time-of-flight velocity measurements can be used to characterize the elastic properties of the material. An orthotropic planar material has four independent elastic parameters, and four independent velocities must be measured to completely define the elastic behavior of the planar material. Three of these are the longitudinal in the MD, longitudinal in the CD, and transverse in the MD or CD. These comprise all the modes along principal axes. The fourth velocity measurement cannot be along the MD or CD. Plane waves which are not in a principal direction have in-plane components along and perpendicular to the propagation direction. If the sheet is not overly anisotropic, there is a plane wave, the quasitransverse mode, that displaces nearly perpendicular to the direction of propagation at all angles to the MD. Its velocity at 45 degrees to the MD can be the fourth measurement. However, there is a complication and this selection needs justification. Even though off-axes normal modes in orthotropic materials are nondispersive (phase velocity and group velocity are equal and frequency independent), the time-of-flight velocity measured between point sources does not equal the phase velocity.[8] Roughly, this is because the path of least delay is not along the straight line from transmitter to receiver. There can be significant differences between the time of flight velocity and the plane wave phase velocity for quasilongitudinal waves. This is because quasilongitudinal phase velocity can vary rapidly with angle in highly anisotropic sheets. Fortunately, quasitransverse velocities change only a few percent between MD and CD. Thus, assuming that the measured velocity is related to elastic properties by the phase velocity equation leads to only small errors. The relationships between the engineering elastic parameters and the phase velocities are[3]

$$G/\rho = V_S^2 \tag{1}$$

$$\nu_{12} = \Big(\Big\{[2V_S^2(45°) - 1/2(V_{Lmd}^2 + V_{Lcd}^2) - V_S^2]^2 - [1/2(V_{Lmd}^2 - V_{Lcd}^2)]^2\Big\}^{1/2} - V_S^2\Big) / V_{Lmd}^2, \tag{2}$$

$$\nu_{21} = \nu_{12}\, V_{Lmd}^2 / V_{Lcd}^2, \tag{3}$$

$$E_{md}/\rho = V_{Lmd}^2 / (1-\nu_{12}\nu_{21}), \tag{4}$$

and $$E_{cd}/\rho = V_{Lcd}^2 / (1-\nu_{12}\nu_{21}). \tag{5}$$

Here, V_{Lmd} and V_{Lcd} are longitudinal velocities in the MD and CD, V_S and $V_S(45)$ are the transverse velocities in the principal directions and at 45°, respectively, ν's are Poisson ratios, E's are Young's moduli, and G is the shear modulus.

General description

This section provides an overview of the operation of the instrument. The specific details, organized by function (acoustic, mechanical, electronic, and programming), are discussed later.

The purpose of the instrument is to find the time-of-flight velocities of transverse and longitudinal plate waves in sheets. Fig. 1 is a schematic diagram of the apparatus, and Fig. 2 is a photograph of the system. Ceramic piezoelectric transducers placed on the surface of the sheet are used to couple mechanical energy into and out of the sample. A sinusoidal voltage pulse is applied to one transducer, the transmitter, which oscillates and sets up wave motion in the sample. A second transducer, the receiver, responds as the disturbance reaches it a short time later. The receiver signal is amplified, digitized, and transferred to a computer, which displays it as a function of time on a CRT. The computer analyzes the signal and adjusts the gain of the amplifier so that the full range of the A/D is used without saturation. This transmitter pulse and receiver signal analysis sequence is repeated for the number of times selected by the operator. Each receiver pulse is superimposed on the original CRT display. Under computer control, the transducers are lifted off the sheet, their separation distance is increased, and they are lowered back on to the sample. The signal analysis routine is repeated and the "far" signals are also superimposed and displayed on the CRT but below the "near" signals. The computer averages both the near and far sequences and replaces them with averaged signals. The computer then cross-correlates the two signals and finds the time shift which has a maximum in the cross-correlation function. The time-of-flight velocity is calculated by dividing the difference in transducer separations by this time shift.

The transducers are then lifted and returned to the near separation, completing one velocity measurement.

(Fig. 1 and 2 here)

The transducers oscillate in the plane of the sample, and it is possible to detect transverse or longitudinal waves by aligning the direction of oscillation perpendicular to or parallel with the transducer separations. The computer can initiate a rotation of the transducers by 90 degrees to alternate the mode of propagation detected. The computer can also translate the carriage holding the transducers laterally across the sheet. By moving the carriage, the sheet can be tested at a number of locations, and average values and variances can be calculated. Finally, the sample is attached to a rotating base driven by a stepping motor. The computer activates the stepping motor, permitting wave propagation velocities along different sheet axes to be measured. In all, the computer can (1) raise and lower the transducers, (2) choose between two transducer separations, (3) move the transducer carriage over the sample, (4) rotate the sample holder, and (5) rotate the transducers by 90 degrees.

The most common test determines the four independent in-plane elastic parameters. Before testing begins, the operator selects the number of received signals to be averaged and the number of locations, N, on the sheet, over which each velocity is to be averaged. A sample is cut with its edges parallel to the principal axes and placed in the rotating sample holder. When the operator initiates testing, the instrument first determines the machine- and cross-machine directions in the sample. It does this by orienting the transducers to study longitudinal motions and by making a velocity measurement in both principal directions. The direction with the largest velocity is designated as the MD, while the other is the CD. The MD longitudinal velocities are now measured at N/2 translations of the carriage. The sample then rotates 180 degrees and another N/2 MD longitudinal tests are conducted on the other half of the sample. The N velocities are averaged and standard deviations are calculated. The sample then rotates 90 degrees and the CD longitudinal motion is analyzed in a like manner. Next, the transducers are rotated about their vertical axes for transverse wave propagation. Transverse velocity measurements are made N/4 times at each 90° increment from the MD. The average velocity and standard deviation of the shear mode in the principal directions are calculated. This measurement series is repeated for transverse waves at orientations 45° to the principal axes.

The four average velocities and their standard deviations and the average velocities squared and their standard deviations are printed out. The squared velocities of the first three modes are planar stiffnesses divided by density. These mass specific elastic parameters are appropriate for irregular materials like paper, whose thickness (and therefore density) are hard to define. However, if the operator chooses, a value for density is entered, and the engineering elastic parameters are calculated. The report generated afer testing a typical sample is presented in Fig. 3.

(Fig. 3 here)

Acoustics

The purpose of the acoustic portion of the apparatus is to generate and receive plate waves which have phase velocities that are directly related to mass specific elastic parameters. If the frequency is low enough so that the out-of-plane wavelengths are long compared to the sample thickness, the plate waves are nondispersive. In a nondispersive frequency range, the time-of-flight velocity equals the phase velocity, and time-of-flight measurements can determine elastic parameters. Since wavelengths are shorter and time resolution is better at high frequencies, the resonant frequency of the transducer should be as high as possible without generating dispersive waves in the sample. The upper frequency limit is determined by the sample thickness and velocity of the out-of-plane dilatational mode. Since this velocity in paper is very low (~ 0.3 km/sec) and paper board samples can be up to 0.5 cm thick, the upper frequency limit is about 100kHz.[4] In addition, the attenuation of sound in paper increases rapidly with frequency, and pulses with good signal to noise ratio are hard to obtain over 100kHz. For these reasons, 60kHz has been chosen as the resonant frequency of the transducers in this apparatus. The wavelengths of the longitudinal modes and shear modes in paper are about 5.0 cm and 2.5 cm, respectively, at 60kHz. The samples are about 20 cm square; therefore, the sheets are large enough to contain pulses a few wavelengths long. This is important, since a pulse traveling between transducers must be analysed before reflections off the sheet boundaries interfere at the receiver. Also, to avoid the influence of the near field effects which arise in two dimensional wave propagation, the transducers should be placed more than half a wavelength apart. The transducer spacings in the system are about 3.0 and 6.5 cm, so it is not safe to operate much under 60kHz when studying longitudinal waves. In summary, 60kHz is a proper choice for the resonant frequency for the transducers because at this frequency plate modes are nondispersive, attenuation is not prohibitive, and acceptable time resolution is possible.

The time-of-flight technique was chosen in preference to a continuous wave (CW) approach because reflections off the sample edges make CW methods unworkable. When the transmitter is activated by a continuous wave or a long pulse, the received signal is a complex interference between the directly transferred disturbance and reflections from the boundaries. If CW methods are to be applied, the direct propagation must be separated from reflections. In other applications, time delay spectrometry has been used for this purpose. Here, the transmitter frequency is swept, the receiver signal is mixed with the transmitter signal, and the mixed signal is Fourier analyzed. Each transmitter to receiver path is represented by a low frequency peak in the Fourier transform. In fact, the transit time is proportional to the Fourier transform peak. This approach was rejected for our application, since the 100kHz upper frequency limit resulted in very poor time resolution. Continuous wave techniques are conceptually attractive, but no practical scheme is apparent. Time-of-flight measurements seem to be the only viable approach.

Even for time-of-flight measurements on short pulses, care must be taken to avoid reflectional interference. In this system, a single cycle, 60kHz pulse is used to excite the transmitter. The transducers ring for many cycles, but only the first half cycle of the received signals are used in the cross-correlation time delay determination. This permits testing to within about 3 cm of the sample edge without concern over errors from reflectional interference. Since attenuation increases with frequency, the pulse shape is distorted by propagation through the sample. Therefore, using only the front end of the pulse to calculate time-of-flight causes an overestimate of the phase velocity. However, the absolute error amounts to around one percent and is insensitive to changes in paper variables. This is small compared with differences between samples, and it can be neglected.

As noted earlier, the apparatus uses only two transducers. In order to measure a time-of-flight velocity, their separation distance is changed, and the two recorded signals are compared. The mechanical apparatus necessary to implement this approach is more complex than one using two receivers (or two transmitters) unequally spaced from a transmitter (or a receiver). The three-transducer method, however, requires that the response of the two receiving transducers be closely matched. Our experience with three transducer systems has demonstrated that it is unrealistic to expect a pair of transducers to maintain the same interaction with the sample overtime. Two-transducer systems are repeatable over long periods of time, while three-transducer systems demand periodic calibration. Here, simplicity of design and speed of operation have been sacrificed for consistency of results.

The piezoelectric material in the transducers is lead zirconate titanate (PZT 5H). This is a dense ceramic with a large mechanical impedance. In order to impedance match the piezoelectrics to the samples, a parallel biomorph construction is used. To build a biomorph, two thin (~ 0.25 mm) plates of the PZT are bonded together with their polarities in the same out-of-plane direction. When a voltage is applied at the center electrode relative to the outside surfaces, one plate expands while the other contracts, causing the biomorph to bend. The bending yields greater motion per unit force than bulk waves in PZT and better coupling of energy into the sample. Biomorphs with a width of 6 mm are procured from Vernitron Inc. The edge which contacts the sample is rounded by pressing it between brass discs, 5 inches in diameter, and sanding off the excess. In the transducer mount, the biomorph is clamped with a set screw between two brass half moons. The length of biomorph from the clamp to the rounded free end determines the transducer's resonant frequency. The length of these transducers is 8 mm, making the resonant frequency 60kHz. Another advantage of the biomorph design is that transverse and longitudinal plate waves are generated with the same transducers. If the transducer separation is parallel to the biomorph polarization direction, longitudinal waves propagate between the transducers. If the separation is perpendicular to the direction of propagation, transverse waves are propagated. The modal purity of the transducers can be confirmed by noting the small signal when one transducer is set for transverse propagation and the other for longitudinal. This is not the first time that biomorph transducers have been used to generate plate waves in polymeric sheets.[1] Suitable commercial transducers are available from the H.M. Morgan Co., but our design enhances performance. The use of parallel (as opposed to series) biomorphs leads to electrical isolation of the active electrodes and better signal to noise ratios. Sensitivity is increased by using wider elements. In all, the signal to noise ratio is about twice that of the commercial transducers.

Mechanics

The stepping motor driven, rotating plate which holds the sample is called the platter. Its base is a 13-inch pitch-diameter chain sprocket which is spindle mounted. It revolves in a bearing attached to the instrument frame. A thin teflon spacer separates the frame from the platter. A stepping motor, which turns a one-inch pitch-diameter chain sprocket, is also attached to the frame. This sprocket drives the platter through a stranded wire reinforced cable chain. Since the stepping motor increments 1.8 degrees per step, the platter requires 2600 steps for a revolution. A magnet is mounted on the circumference of the platter, and a pulse is generated as the magnet passes a Hall effect detector secured to the frame. This provides the reference for aligning the principal axes of the sample at a chosen angle to the transducer separation.

The upper portion of the platter is the sample holder. A square metal plate with a lip on three sides is screwed to the platter base. A grooved Delrin slat is attached to each lip, producing a slot on three sides of the plate. A rectangular tray is machined to slide into the slotted plate from the open side. A sheet sample, which is nominally 8 inches square, is placed on the tray, and the tray is inserted into the platter slot. A layer of soft rubber separates the metal tray from the sample. This acoustically isolates the sample from the platter.

The transducers are suspended on a carriage above the platter. The carriage rides on two hardened steel shafts, mounted on either side of the frame, through ball bushings. Translation of the carriage allows the transducers to span the sample. The carriage is driven by a double acting air cylinder; it can be pulled back to the rear of the sample or pushed toward the front. In order to position the carriage at discrete, intermediate positions, a serrated aluminum rack is fastened along each side of the carriage. Stops mounted on the frame are pushed into the rack to interrupt the translation of the carriage at the proper time. The stops are driven by single-acting, spring-extend air cylinders.

The location of the carriage is sensed with a potentiometer fixed to the carriage. A chain sprocket is attached to the shaft of the potentiometer. The ends of a cable chain are held by clamps on the frame. The chain threads around the potentiometer wheel and back around another sprocket mounted to the carriage, as shown in Fig. 1. As the carriage translates, the potentiometer shaft rotates, and the voltage at the wiper of the potentiometer changes.

In order to alternate transducer separations, a second carriage is mounted on the translation carriage. One of the transducers is attached to this carriage, which rides on hardened steel shafts through ball bushings. Since the axis of these shafts is perpendicular to the axes of the translation shafts, the motion separating the transducers is perpendicular to translation. This carriage is driven by a double-acting air cylinder fixed to the translation carriage. Rigid stops insure that the difference in the two transducer spacings, achieved by pulling or pushing the air cylinder, is constant.

Rotation of the transducers about vertical axes for transverse and longitudinal operation is also achieved by double-acting air cylinders. A collar with a slotted lever arm controls the angular orientation of each transducer. The lineal motion of an air cylinder is converted to a rotation of a transducer by putting a yoke in the slot of a collar and applying the air cylinder drive to the yoke. Extension of the air cylinder results in a 90° rotation of the transducers.

A final pair of air cylinders are used to raise and lower the transducers. They are mounted on the carriages above the transducers. When air is applied, these double-acting cylinders elevate the transducers by pulling up on caps on the end of the transducer tubes. When released, the transducers descend until they are riding on springs inside the transducer tube. The tension of the springs and the extent of the fall can be manually adjusted. When unusually thin or thick samples are tested, it is necessary to use these adjustments to guarantee that there is sufficient transducer contact with no sample damage.

Electronics

The instrument electronics can be divided into three parts: the computer; commercial instruments; and custom wired circuitry. The computer which oversees the measurements is an Apple IIe with 64K of memory. Its functions are to initiate an acoustic pulse, analyze the received signal, activate the air cylinders and stepping motor, monitor platter rotation and carriage translation, calculate velocities and moduli, and display the results. The commercial instruments are a Wavetek model 143 function generator to drive the transmitter and a 5050AE Panametrics amplifier to preamplify the receiver signal. Home-made electronics include a 10 MHz analog to digital converter for the received signal, a buffer memory to store the digitized signal, a hardware multiply circuit to speed the cross-correlation calculation, a variable gain amplifier which adjusts the input signal level to match the range of the A/D, stepping motor and air cylinder drive circuitry, and an A/D for the translation carriage potentiometer.

An ultrasonic pulse sequence begins with a TTL level signal from the computer triggering the function generator to emit a 60kHz, single-cycle pulse (see Fig. 1). The pulse amplitude can be adjusted to 30 volts peak-to-peak, but it is normally set at about 15 volts peak to peak. The initial phase of the sinusoidal output can also be altered. A one-time adjustment of the phase was conducted so that, when a typical sample is tested, the received signal has a pronounced, positive first response. This signal is used to excite the transmitter. The resulting electrical signal at the receiver goes to the Panametrics preamp. This is a battery-powered, 20kHz to 2MHz band pass amplifier which can be switched to a 40 dB or 60 dB gain. It has been modified to run off line power to avoid the nuisance of changing batteries. The signal now goes to a line receiver in the custom electronics box. From there, it is fed to a MC3340 variable attenuator. The analog attenuation input of this chip comes from a digital to analog convertor. The computer sends digital inputs to the D/A through a parallel output port. In this manner, the computer can adjust the receiver signal level. After this selectable attenuation, the signal is amplified and passed by a line driver to the A/D board.

The measurement stategy depends on a digital analysis of the receiver signals. In order to resolve the 60kHz signals, a high speed analog to digital conversion is required. This is achieved with an A/D card made by TRW, built around their TDC1007 flash A/D chip which can do conversions at up to 30 MHz. In this application, it is run at 10 MHz, giving a 0.1 μsec time resolution of the received signal.

The outputs from the A/D are stored in a specially built high-speed buffer memory. It is made from two each 4k x 4 IMS1421 NMOS static RAM's built by Inmos. The address and data lines of this memory are normally connected through tristate buffers to the Apple buses. However, when an A/D conversion is triggered (off the same pulse that fired the function generator), these lines are controlled for a time by the A/D circuitry. To be specific, a set of counters sequence the address lines. Starting from zero when the transmitter is triggered, the counters increment the following 2048 A/D conversions, which are now gated to the RAM I/O lines, into consecutive address locations. Before starting a pulse at the "far" spacing, the signal from the "near" spacing is moved from the buffer memory, to other locations in memory. A 20 MHz crystal oscillator generates the clock which runs the counters and provides the timing for the convert signals to the flash A/D. The trigger pulse, which fires the function generator and starts the A/D, is synchronized with this clock to preclude any jitter in the received signal.

The computer keeps track of the location of the translation carriage by monitoring the voltage at the wiper of the carriage potentiometer. This voltage is digitized using a D/A and a comparator. The outputs of an Apple parallel port are connected to the digital inputs of the D/A. The analog output of the D/A and the wiper voltage are inputs to the comparator. The computer sequences the

D/A inputs and monitors the output of the comparator. The value of the digital input when the comparator switches states is taken as the wiper voltage.

The time-of-flight determination comes from a cross-correlation calculation. This requires many multiplications and additions of the data representing the "near" and "far" signals. Calculation time is decreased by using a TRW TDC1008 8 bit multiplier-accumulator chip. When the proper code is on the address bus, inputs from the Apple data bus are latched into this chip. After the calculations are complete, the chip drives the data bus, and the results are available to the central processor.

There are also drive circuits for the air cylinders and the stepping motor. The solenoids that control flow to the air cylinders are activated by AC line voltage. The TTL level signals from parallel ports on the computer are buffered in order to drive the relays that channel power to the solenoids. The stepping motor is controlled by two TTL lines off a computer parallel port. A commercial driver board interfaces the parallel port to the stepping motor. Pulsing one of the TTL lines increments the motor, while the state of the other line determines the direction of rotation.

Software

The central function of the computerized data analysis is to determine a time-of-flight by performing a cross-correlation calculation on the "near" and "far" signals. This operation was outlined in the General Description and is now discussed in more detail. The main executive programs operating the instrument are written in Basic. However, Basic is too slow for the many repetitive calculations needed in the signal analysis routines, and these are done in assembly language.

One assembly language signal analysis routine defines the first peak in the "near" signal. This begins with a "baseline" analysis which is a characterization of the signal before the arrival of the acoustic pulse. Its purpose is to determine the average value and maximum deviation from the average of the initial segment of the received signal. The length of the baseline, which is about 50 data points, is adjusted by the software, depending on the anticipated velocity of the mode being propagated. After the baseline analysis, the computer starts from the end of the baseline interval and sequentially examines the data representing the signal. The point at which the signal exceeds the baseline average plus four times the maximum deviation is designated as the beginning of the first peak. Subsequent data are examined until a baseline crossing is detected. This is the end of the first peak and the limit of the "near" signal data in the cross-correlation calculations.

The automatic gain control is also an assembly language routine. When a new acoustic mode is initiated, the gain on the input amplifier defaults to a value that puts typical signals in the proper range for the A/D. If the first peak saturates the A/D, the gain, which has 256 discrete levels, is reduced by eight, and a new receiver signal is tested. This continues until an unsaturated first peak is generated. If the operator decides that this beginning gain is too low, the program can be interrupted, and the gain adjusted manually. After the carriage translates to a new sample location, the gain increments by eight and is reduced only if the first peak saturates. The signals taken during the gain control adjustments are plotted on the CRT display. If more than one pulse was necessary, the signals are superimposed and the progress of analysis can be observed.

Signal averaging is performed after the gain is fixed in the correct range. Five signals are digitally averaged to generate a composite signal, which has an improved signal to noise ratio. If the operator intercedes, the number of signals averaged can be changed. As they are received, the signals are superimposed on the CRT display. When the gain adjustment and the signal averaging are complete on the "near" and the "far" signals, all of the earlier signals are removed from the display, and the composite signals are exhibited. Fig. 4 is a print-out of the CRT display showing typical composite signals. Notice in the top figures the vertical line that designates the limit of the first peak on the "near" signals and the shorter lines that are the limits of the baselines on the "near" and "far" signals.

(Fig. 4 here)

The time-of-flight calculation is accomplished with an assembly language cross-correlation algorithm and an optimization routine written in basic. The first step in the cross-correlation program is to shift the "far" signal back by a number of data points called the "offset". Each "near" data point, acquired before the end of the first peak, is multiplied by the "far" data point which it corresponds to after the offset. These numbers are added together to give the value of the cross-correlation function for this offset. Unless an operator overrides normal procedure, the optimization routine defaults to a beginning offset that is typical for the mode being studied. After the first cross-correlation calculation is complete, the offset is incremented by one, and the process is repeated. If the second summation is larger than the first, the offset continues to increment until a maximum is reached. If the first summation is larger, the offset decrements until a maximum occurs. In either case, a quadratic equation is fit to the maximum and the sums on both sides of the maximum. The displacement offset value which gives a peak in the quadratic equation is taken as the displacement of the "far" signal from the "near" signal. The time-of-flight is 100 nsec times this displacement, and the velocity is the separation difference divided by the time-of-flight. The CRT now displays the "far" signal shifted to the left by the offset at the maximum summation. See the lower curves on Fig. 4. If the initial offset is grossly in error, the "far" and the "near" signals could misalign by a wavelength. The operator would observe this, interrupt the program, and enter a different starting offset. When the carriage translates to a new position on the sample, the starting offset is the offset at the maximum of the previous position. After a velocity is calculated it is displayed on CRT along with the test number, the running average, and standard deviation.

The elastic characterization routine most commonly used was described in the general description section. Another useful program measures the time-of-flight velocity of the quasilongitudinal waves as a function of angle from the MD. The operator sets the number of signals to be averaged and the number of test locations for each angle. The testing begins with an MD determination as performed in the elastic characterization program. Velocities are then measured at each five degree rotation of the platter. The average velocity squared values (specific stiffnesses) and standard deviations are printed out along with a polar plot of the results. A typical report is presented in Fig. 5.

(Fig. 5 here)

The operator can enter an instrument check-out routine from the elastic characterization or the orientation program. This allows the basic operations of instrument to be selected and performed individually. The platter can be rotated, the carriage translated, or the transducers rotated. "Near" and "far" signals can be taken and displayed, and the operator can set the preamplifier gain and the function generator output accordingly.

The major basic programs begin with an initialization procedure for platter rotation and carriage translation. First, the platter rotates to its "home" position. This leaves the sample holder square with the front of the instrument, and allows the sample to be placed on the slide tray and inserted into the instrument. The computer identifies home as a specific number of steps past the first detection of the magnet by the Hall effect transducer. The carriage initialization begins by retracting the translation stops, then pushing the carriage full forward, and pulling it all the way back. The potentiometer readings at the two extremes are noted. The locations of the intermediate locations are calculated by extrapolation. The potentiometer voltages that trigger release of the stops in later carriage translations are determined by this calculation. The carriage then moves to its starting point.

References

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6. Habeger, C. C., Baum, G. A. Tappi (1986).
7. Graff, D. F., Wave Motion in Elastic Solids, Ohio State University Press (1975).
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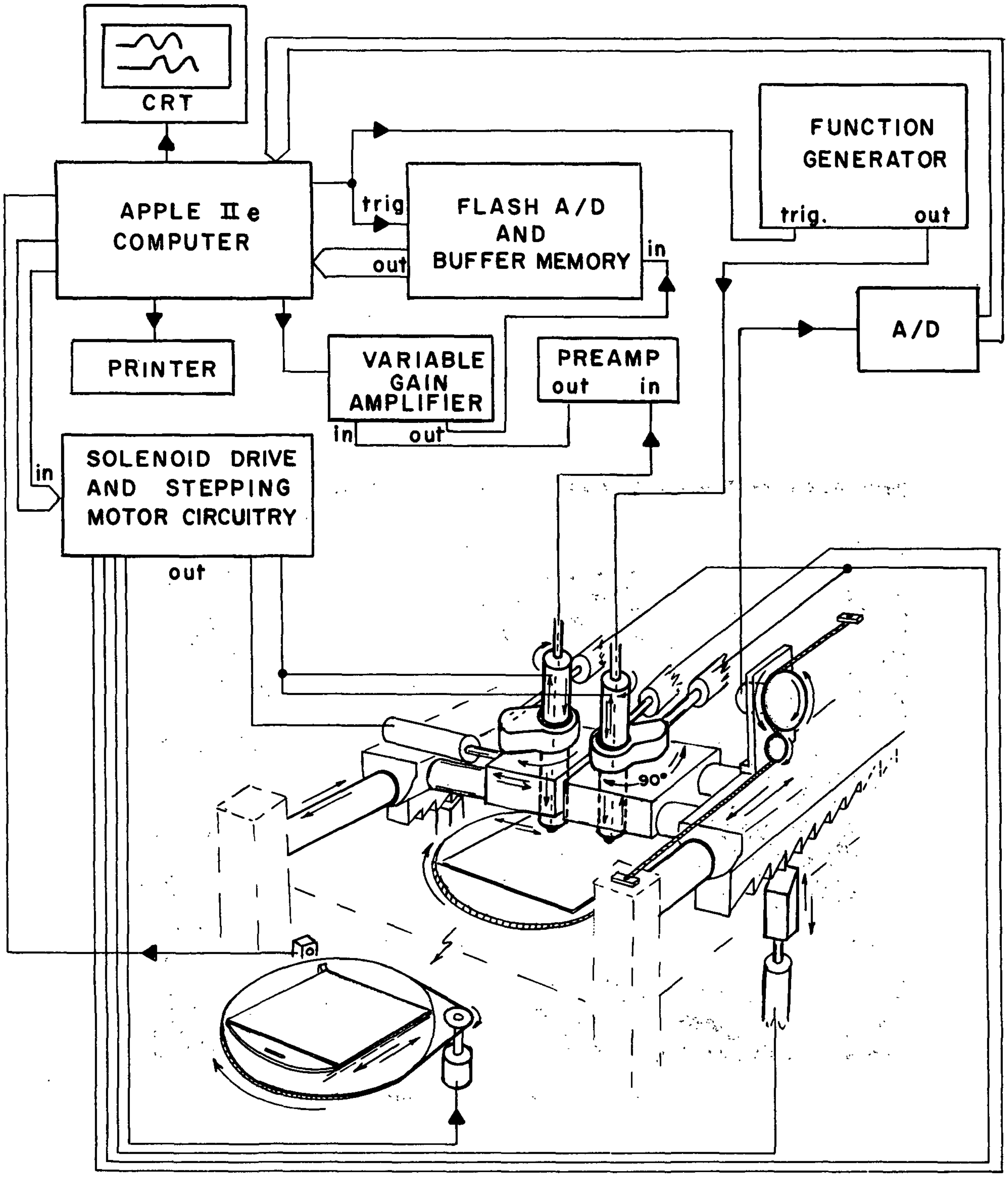
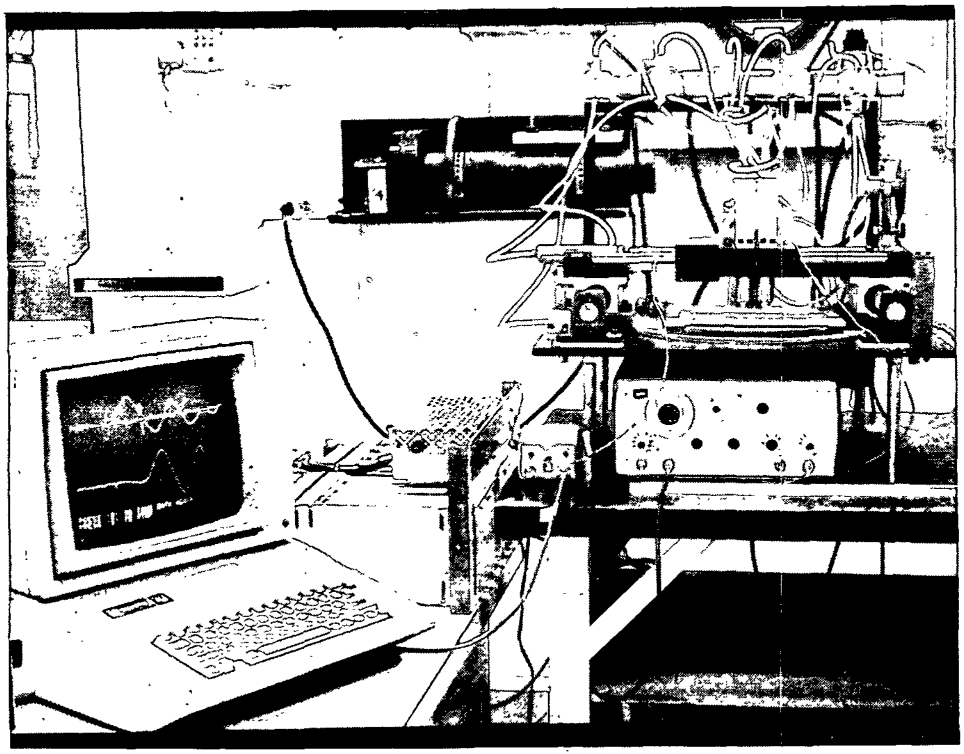


1. Mechanical and electronic schematic of the automated ultrasonic velocity apparatus.



2. Photograph of the apparatus.

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                THE INSTITUTE OF PAPER CHEMISTRY
               TWO TRANSDUCER VELOCITY MEASUREMENT

OPERATOR :C HABEGER
DATE :2 25 86
PROJECT: 86-4

SAMPLE : JR 1  SPECIMEN 5

LONGITUDINAL TRANSDUCER SEPARATION = 35.2  MM
SHEAR TRANSDUCER SEPARATION        = 35.2  MM

SAMPLE TIME = .1  MICRO SEC

MODE        TESTS    VELOCITY   ST DEV   V SQR     ST DEV     SIG AV
                      KM/SEC    KM/SEC  KM2/SEC2  KM2/SEC2

MD LONG      16       3.101      .059     9.62      .36          6
CD LONG      16       2.464      .019     6.07      .09          6
SHEAR        16       1.669      .016     2.79      .05          6
45 SHEAR     16       1.668      .015     2.78      .05          6


MODULI CALCULATIONS

MD-CD G. MEAN V SQR = 7.64  KM2/SEC2

STIFFNESS RATIO = 1.58
NUXY            =  .20
NUYX            =  .32

G. MEAN NU = .25

DENSITY = .682  GM/CM3

EX =    6.13  GPA          EX/RHO =    8.98  KM2/SEC2
EY =    3.87  GPA          EY/RHO =    5.67  KM2/SEC2
G  =    1.90  GPA          G/RHO  =    2.79  KM2/SEC2

THE MD-CD G. MEAN E/RHO = 7.14  KM2/SEC2
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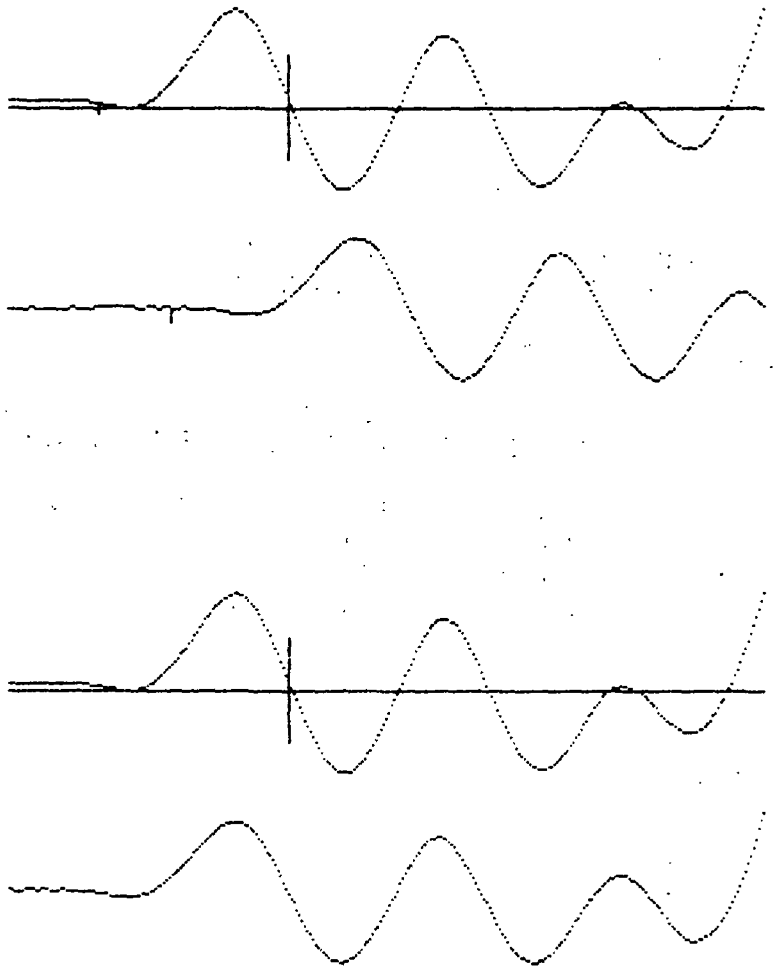
3. Printout for the in-plane moduli test.



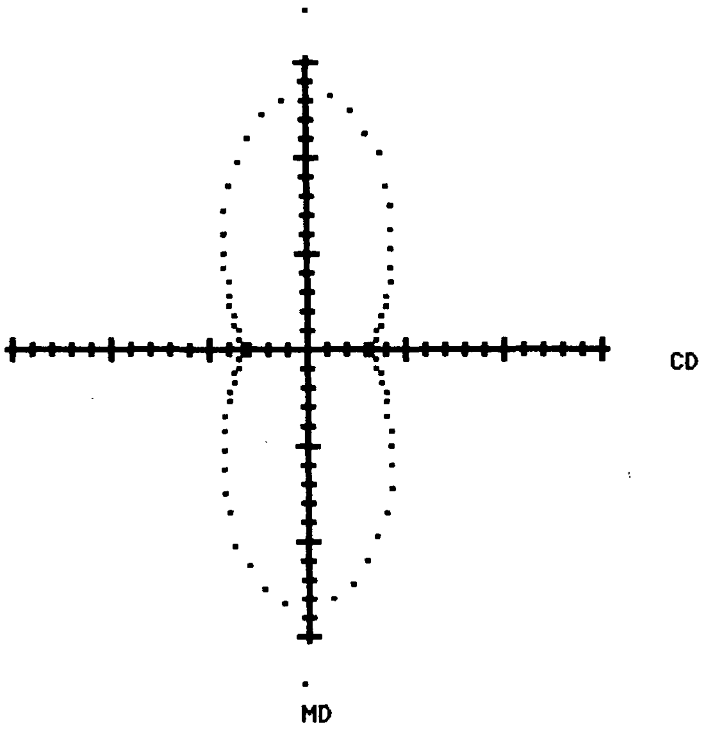
4. Composite "near" and "far" signals as displayed by the CRT before (top) and after (bottom) cross-correlation. Every other digitized point is shown up to the capacity of the display.

THE INSTITUTE OF PAPER CHEMISTRY
LONGITUDINAL SPECIFIC STIFFNESS (VEL SQR) VS ANGLE TO MD

OPERATOR:	CHUCK	DATE	:APRIL 21 1986
PROJECT :	3467	SAMPLE :	A 31

ANGLE DEGREES	VEL SQR KM2 / SEC2	STD DEV	ANGLE DEGREES	VEL SQR KM2 / SEC2	STD DEV
0	13.22	.32	90	3.18	.14
5	13.21	.25	95	3.26	.15
10	12.65	.58	100	3.47	.17
15	11.62	.52	105	3.74	.11
20	10.80	.36	110	3.95	.15
25	9.47	.32	115	4.16	.07
30	8.59	.34	120	4.51	.09
35	7.60	.31	125	4.86	.03
40	6.78	.25	130	5.30	.16
45	5.98	.35	135	5.86	.18
50	5.41	.27	140	6.58	.19
55	4.92	.27	145	7.24	.22
60	4.50	.23	150	8.31	.04
65	4.18	.26	155	9.39	.22
70	3.92	.20	160	10.46	.11
75	3.73	.07	165	11.42	.11
80	3.47	.20	170	12.37	.27
85	3.24	.16	175	13.03	.39

TEST PER 5 DEGREE INCREMENT = 16 SIGNALS AVERAGED = 6
THE ANGLE TO MAJOR PRINCIPAL AXIS = .6



PLOT OF VEL SQR VS ANGLE AS SEEN FROM FELT SIDE

5. Printout for the square of the longitudinal velocity as a function of orientation.