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ELASTIC PROPERTIES, PAPER QUALITY, AND PROCESS CONTROL

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ABSTRACT
The elastic properties of paper are fundamental parameters that describe the small strain mechanical response in three dimensions. It is now possible to routinely measure seven of the nine elastic stiffnesses associated with paper, all on a single specimen. The elastic stiffnesses are sensitive to paper manufacturing conditions, allowing one to study the effects of a change in any machine operating variable on the three dimensional elastic behavior of the paper. The elastic stiffnesses can be related to a number of (destructive) end-use tests, making them useful indicators of product quality. Some of the elastic stiffnesses can be measured on the paper machine, providing both continuous monitoring of product quality and, eventually, control of the paper machine itself.

INTRODUCTION
The elastic properties of a material describe its deformation when a stress or combination of stresses are applied to it. For an isotropic material, one which has no directionality, there would be three elastic properties: a Young's modulus, $E$, relating axial stress and strain; a shear modulus, $G$, relating shear stress and shear strain; and a Poisson ratio, $v$, the ratio of the lateral contraction to the axial extension during uniaxial stressing. Only two of the three elastic properties for an isotropic material are independent. If any two are known, the third can be computed according to $G = E/(2(1+v))$.

For paper, the manufacturing process results in symmetry conditions which require nine elastic properties ($1,2$). These include three Young's moduli (one in each principal direction), three shear moduli, and three Poisson ratios. Six of these parameters are defined in Fig. 1 and 2. The three Poisson ratios also could be determined from the three experiments shown in Fig. 1. If the nine elastic properties of paper are known, the three dimensional response of the paper to applied stresses is known. Such information is valuable in characterizing the end-use behavior of paper and for use in modeling containers or other structures.

Procedures have been developed at The Institute of Paper Chemistry for measuring the nine elastic properties of paper or other sheet materials ($3-5$). Seven of these are measured routinely in the laboratory. Measurements have been made on essentially all grades of paper and board, nonwovens, wood, and some plastics. There are limitations, however. The minimum sample size is around 6 by 6 inches, although measurements of elastic properties in the thickness direction can be made on smaller specimens. There is a minimum thickness for the z-direction measurements, however, of about 0.004 to 0.008 inch, depending on the surface roughness. There is no minimum thickness for elastic property measurements made in the (MD-CD) plane of the paper. As a consequence of these physical limitations on sample size, most of the three dimensional work has been carried out on board samples. The in-plane elastic properties measured on thin samples, however, are also useful in understanding the effect of process variables on properties and providing improved characterization of end-use performance.

THEORY
The elastic properties are determined by measuring the velocity of ultrasound in the paper. The theory has been described in detail elsewhere ($2-5$), and only a brief overview will be given here. The generalized Hooke's Law for a three dimensional material is

$$\sigma_i = \sum_{j=1}^{6} C_{ij} e_j,$$

where $i$ and $j$ have values from one to six and where $\sigma_i$ is the stress, $e_j$ is the strain, and the $C_{ij}$ are...
the elastic stiffnesses. The nine elastic stiffnesses are related to the "engineering elastic constants" viz. Young's moduli, shear moduli, and Poisson ratios, see, for example, Ref. 3.

Three of the stiffnesses are easily determined by measuring z-direction bulk wave velocities:

\[ C_{33} = \rho v_L^2 \]
\[ C_{44} = \rho v_S^2 \]
\[ C_{55} = \rho v_K^2 \]

where

\[ v_L = \text{velocity of bulk longitudinal wave in the z-direction} \]
\[ v_S = \text{velocity of bulk shear wave polarized in the y direction} \]
\[ v_K = \text{velocity of bulk shear wave polarized in the x direction} \]
\[ \rho = \text{apparent density} \]

The constants \( C_{11} \) and \( C_{22} \) can be determined by propagating longitudinal waves in the machine (x) and cross-machine (y) directions, respectively. The velocities of \( V_{Lx} \) and \( V_{Ly} \) may then be used to compute \( C_{11} \) and \( C_{22} \) from:

\[ C_{11} = \rho v_L^2 \]
\[ C_{22} = \rho v_L^2 \]

The coefficient \( C_{66} \) is easily determined by measuring the velocity of a shear wave propagated in either the x or y direction with polarization in the y or x direction, respectively. The expression for \( C_{66} \) is:

\[ C_{66} = \rho v_K^2 \]

This shear velocity can be measured on either plate or bulk materials.

The constant \( C_{12} \) is obtained by propagating a shear wave, polarized in the x-y plane, at a direction 45° to both the x and y axes. The expression for \( C_{12} \) in this case is:

\[ C_{12} = \frac{1}{2}[2\rho v_S^2(45°) - 1/2(C_{11} + C_{22}) - C_{66}]^2 - \frac{1}{2}[C_{11} - C_{22}]^2 \frac{1}{2} - C_{66} \]

where \( v_S(45°) = \text{velocity of the in-plane shear wave propagated in a direction 45° to the x and y directions} \)

The stiffnesses \( C_{13} \) and \( C_{23} \) are more difficult to obtain, and are not measured routinely at present. The following discussions will relate only to the seven stiffnesses mentioned above.

The experimental techniques for determining \( V_{Lx}, V_{Sy}, V_{Sk-y}, \) and \( V_{Sx-z} \) have been previously described (4). These velocities are determined by measuring the transit time of a short burst of sine waves (pulse) through the specimen. Two piezoelectric transducers are used as depicted in Fig. 3. These transducers were specially designed by IPC staff for this purpose. The output pulse from the function generator is amplified and fed to the sending transducer and coincidently triggers the oscilloscope and starts a time interval counter. The mechanical disturbance transmitted through the specimen is detected by the receiving transducer and is converted back to an electrical signal, which is amplified and displayed on the oscilloscope. By adjusting a delay-time multiplier knob on the scope, the instant of triggering of a second delayed time base is controlled by the operator. The scope provides visualization of the precise point of triggering. Coincident with the triggering of the delayed time base is the delayed GATE OUT which stops the counter. Delay-time intervals are averaged by the digital display counter. The measurements are corrected for delays in the transducers and electronics. By time-averaging the time intervals, delay times can be measured to the nearest nanosecond.

The type of system used for measuring \( V_{Lx}, V_{Ly}, V_{Sk-y}, \) and \( V_{Sx-z} \) is shown in Fig. 4. These measurement techniques also have been discussed in detail previously (3,4). There are two major changes in the in-plane measuring equipment, however. The first involves the use of a cross correlation method to improve the measurements. Briefly, the idea is to use a linear array of three transducers with the outer two transducers transmitters, and the inner one a receiver. The receiver is placed closer to one transmitter than the other. When the transmitters are alternately fired, signals with two different delay times are received by the middle transducer. These signals are digitized and their cross correlation function is calculated. The first maximum in the cross-correlation function gives the time difference, \( \Delta t \), between the arrival of the two signals. The velocity is then calculated as the difference in the transducer spacing divided by \( \Delta t \). Variations in sheet structure are accounted for by sampling over the sheet.

A schematic of the overall operation is presented in Fig. 5. The transmitter signals are initiated by a pulse generator, which fires a short pulse of sine waves from a signal generator and triggers the analog to digital conversion of the receiver signal. In normal operation, the signal generator output is a one to five cycle pulsed RF
signal at 30 to 80 kHz, adjusted to give a 500 Hz repetition rate.

When activated by the pulsed RF signal, the bender transducers oscillate in the plane of the sheet. If the transducers are placed so that their direction of motion is parallel to their separation, a longitudinal plate wave is generated in the sheet and detected at the receiver after a time delay. Alternatively, the polarization can be perpendicular to the transducer separation, and a shear wave is generated and detected. In either case the receiver signal is amplified by a preamplifier and sent to a Biomation analog to digital recorder.

The digital output of the Biomation is then transferred to an Apple II Plus computer. For rapid data acquisition, the Apple is programmed in assembly language to control the input signals from both transducer pairs. The computer can do signal averaging on the received input signals.

The two received signals appear roughly as in the computer display shown in Fig. 5. After a dead time (flat portion) which is greatest for the long transducer setting (shown on the bottom), the sinusoidal signal is received. To avoid interference from waves reflected off the sample edges, only the first peak of the received signal is used in the analysis. The signal analysis limit, controlled from the keyboard by the operator, is indicated by a vertical line on the top CRT curve. The difference in delay time between the two signals is calculated using the cross-correlation technique mentioned above. This program is written in assembly language to obtain fast operation. The velocity of sound in the sheet is then found by dividing the difference in transducer separations by the time difference.

Paper is quite heterogeneous and the measured sound velocity can vary with transducer position on the sheet. To get an estimate of the average velocity and velocity variation in the sheet, a number of tests are performed. The operator inputs the number of tests to be averaged and places the transducers at the first position. The cross-correlation calculation is done, and the velocity calculated and displayed. The operator now raises the transducers off the sheet, the sheet is moved to a new position, and the test is repeated. The CRT displays the latest velocity, the average velocity, and the standard deviation. The process is repeated until the prescribed number of tests is complete, at which point the final velocity average and standard deviation are displayed on the CRT and printed. The cross-correlation calculations are carried out so fast that they are done while the operator moves the sheet, so data can be taken as fast as the operator can reposition the sheet and tap the appropriate key.

The second major change is the automation of the in-plane measurement system. A description, together with the details of the cross-correlation method, will be published elsewhere (6). A schematic of the device is shown in Fig. 6. This system automatically determines MD and CD directions in the sheet, measures the four velocities and their
standard deviations, and computes and outputs the specific elastic stiffnesses (elastic stiffness/density), or the engineering parameters if a density value is inputted. The device is also programmed to measure the elastic stiffnesses as a function of angle to the MD. Such measurements have proven useful in studying transverse headbox flows and other machine operating variables. Figure 7 depicts polar graphs of specific longitudinal stiffness where there is a transverse flow from the headbox, as evidenced by the lean of the elliptical envelope away from the MD.

The automatic system takes about 7 to 9 minutes to measure the four in-plane elastic stiffnesses. An operator can measure the three-out-of-plane specific stiffnesses in typically less than one-half hour. Thus in less than an hour, seven of the nine elastic stiffnesses can be measured, all on a single specimen of paper. Table 1 gives some typical values. The following sections describe how these elastic stiffnesses may be used.

### Elastic Properties and Machine Variables

The relationships between paper machine variables and the in-plane (MD-CD) elastic properties have been studied by a number of authors (7-18). Relationships between process variables and both in-plane and out-of-plane parameters have received less attention. Figures 8-10 illustrate how the three longitudinal stiffnesses depend on fiber orientation, wet pressing (density), and wet straining (19) for a bleached softwood commercial kraft pulp refined to about 500 CSF. The fiber orientation was varied by changing the relative speeds of the pulp slurry and wire in a Formette Dynamique anisotropic sheet former, and the density was changed by wet pressing. After wet pressing, the sheets were strained in the MD while wet (35 to 40% solids) to levels of 1.2 and 2.4%. The sheets were then restrained in both the MD and CD (but not the ZD) during drying.

<table>
<thead>
<tr>
<th>Apparent Density, $\rho$, kg/m$^3$</th>
<th>$C_{11}$</th>
<th>$C_{22}$</th>
<th>$C_{33}$</th>
<th>$C_{12}$</th>
<th>$C_{13}$</th>
<th>$C_{23}$</th>
<th>$C_{44}$</th>
<th>$C_{55}$</th>
<th>$C_{66}$</th>
<th>$E_x$</th>
<th>$E_y$</th>
<th>$E_z$</th>
<th>$v_{xy}$</th>
<th>$v_{xz}$</th>
<th>$v_{yz}$</th>
<th>$G_{xy}$</th>
<th>$G_{xz}$</th>
<th>$G_{yz}$</th>
<th>$\nu_{xy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carton stock</td>
<td>780</td>
<td>8.01</td>
<td>3.84</td>
<td>0.042</td>
<td>1.36</td>
<td>0.92</td>
<td>0.91</td>
<td>0.099</td>
<td>0.137</td>
<td>2.04</td>
<td>7.44</td>
<td>3.47</td>
<td>0.040</td>
<td>0.15</td>
<td>0.008</td>
<td>0.021</td>
<td>0.099</td>
<td>0.137</td>
<td>2.04</td>
</tr>
<tr>
<td>Linerboard 42 lb</td>
<td>752</td>
<td>0.059</td>
<td>0.050</td>
<td>0.060</td>
<td>2.08</td>
<td>9.98</td>
<td>3.39</td>
<td>0.050</td>
<td>0.060</td>
<td>2.08</td>
<td>0.099</td>
<td>0.137</td>
<td>2.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linerboard 90 lb</td>
<td>691</td>
<td>8.12</td>
<td>3.32</td>
<td>0.032</td>
<td>1.19</td>
<td>0.113</td>
<td>0.082</td>
<td>0.104</td>
<td>0.129</td>
<td>1.80</td>
<td>7.46</td>
<td>3.01</td>
<td>0.029</td>
<td>0.117</td>
<td>0.109</td>
<td>0.021</td>
<td>0.104</td>
<td>0.129</td>
<td>1.80</td>
</tr>
<tr>
<td>Boxboard</td>
<td>775</td>
<td>0.043</td>
<td>0.083</td>
<td>0.099</td>
<td>1.36</td>
<td>6.03</td>
<td>2.32</td>
<td>0.083</td>
<td>0.099</td>
<td>1.36</td>
<td>0.119</td>
<td>0.182</td>
<td>0.119</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laboratory BKSW</td>
<td>721</td>
<td>10.9</td>
<td>6.40</td>
<td>0.172</td>
<td>0.290</td>
<td>0.343</td>
<td>3.09</td>
<td>10.3</td>
<td>6.04</td>
<td>0.182</td>
<td>0.290</td>
<td>0.343</td>
<td>2.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrugating medium</td>
<td>682</td>
<td>0.103</td>
<td>0.046</td>
<td>0.053</td>
<td>1.58</td>
<td>6.89</td>
<td>2.68</td>
<td>0.046</td>
<td>0.053</td>
<td>1.58</td>
<td>0.167</td>
<td>0.083</td>
<td>0.167</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Three dimensional bulk stiffness.

*Poisson ratios are dimensionless.

*BSW, bleached kraft softwood.
In general, the elastic stiffness in the direction of fiber orientation or the direction of wet straining increases, while the properties in both the CD and ZD tend to decrease. The restraint in both MD and CD directions after wet stretching is thought to represent the situation existing near the center of the paper web in a modern, wide, paper machine. Near the edges of the web CD shrinkage can occur, since there is no outward force preventing it. In the case when CD shrinkage is allowed, the CD modulus shown in Fig. 9 may not decrease with MD wet straining (18). Hun (20) has shown that the solids content is important in determining the magnitude of the wet straining effect. Only small increases in modulus are observed upon wet straining at solids above about 60%.

Figure 9 shows the behavior of the three anisotropy ratios $R_{xy}$, $R_{xz}$, and $R_{yz}$ as functions of wet straining at two wet pressing levels (21). The anisotropy ratios are defined as $R_{xy} = C_{11}/C_{33}$, $R_{xz} = C_{22}/C_{33}$, and $R_{yz} = C_{11}/C_{22}$. The in-plane anisotropy, $R_{xy}$, increases with increasing wet strain, as expected, since $C_{11}$ is increasing (in the direction of wet straining) while $C_{22}$ is decreasing. Above about 3.5% wet strain the sample ruptures. Wet pressing should not produce any in-plane anisotropy. At nonzero wet strains, however, it may be that higher wet pressing pressures lead to a different value for $R_{xy}$. In these experiments the wet pressing operation was carried out prior to wet straining, just as on a paper machine. If there is an interaction between wet pressing and wet straining, it must be small, at least in the range of densities studied here.

For $R_{xz}$ or $R_{yz}$ at zero wet strain, however, the wet pressing pressure has quite a large effect on the anisotropy. Increasing the pressure from 25 ps (solid line) to 100 ps (dashed line) decreases $R_{xz} (=R_{yz}$ at zero wet strain) from about 75 to 55. Higher pressing pressures probably would decrease this ratio even more, although it is unlikely that the ratio would ever approach one, even with 100%
bonding, because of the inherent anisotropy of the collapsed ribbonlike fibers.

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Wet straining of the sample causes both $R_{xz}$ and $R_{yz}$ to increase. This happens even though $C_{11}$ is increasing and $C_{22}$ is decreasing (as in $R_{xy}$), because $C_{33}$ is decreasing faster than $C_{22}$. It is apparent that a given level of $R_{xz}$ (or $R_{yz}$) can be reached by different combinations of wet pressing and wet straining. The additional effects of refining and fiber orientation, both in and out of the plane, should also be included in the analysis. The implications of these anisotropy ratios on end-use performance need to be established.

The effects of fiber orientation, wet pressing, and wet straining on the shear stiffnesses are similar to those for the longitudinal stiffnesses. Table 2 summarizes how the stiffnesses behave with increases in the three variables if the experiments are carried out as described earlier.

---

Table 2. Effect of machine variables on elastic moduli

<table>
<thead>
<tr>
<th>Elastic Stiffness</th>
<th>Fiber Orientation (MD)</th>
<th>Wet Pressing</th>
<th>Wet Straining (MD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{11}$</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$C_{22}$</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$C_{33}$</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>$C_{66}$</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>$C_{44}$</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>$C_{55}$</td>
<td>+ (sm)</td>
<td>+</td>
<td>- (sm)</td>
</tr>
</tbody>
</table>

*($+$) = increase, ($-$) = decrease, (0) = no change.

*These results are for the case where the sheets were wet strained at 35 to 40% solids and then dried under restraint in both MD and CD directions. Other drying conditions may give different results. See text.

The effect of these variables on the Poisson ratios has not been studied extensively. While $V_{MD-CD}$ and $V_{CD-MD}$ are functions of wet straining and fiber orientation, their product is not very sensitive to these variables (22). The quantity $(V_{MD-CD}V_{CD-MD})^{1/2}$, is a measure of how interrelated the tensions in the MD are to those in the CD.

Collectively, the results in Fig. 8-10 and Table 2 suggest that the elastic stiffnesses for paper are not independent but that process variables affecting a given parameter may affect related properties in predictable ways. An example of this is an empirical relationship of the form $C_{66} = a(C_{11}C_{33})^{1/2}$ where $a$ is a constant independent of machine variables, if $C_{11}/C_{33}$ is less than about 3.5 (22). This result is similar to the relationship between the elastic properties of an isotropic material, discussed earlier. Htun and Fellers (18) showed that the geometric mean of MD and CD properties are often invariant under the action of increased fiber orientation and wet stretching of the web. In the case of elastic stiffnesses, it seems that the geometric mean of the longitudinal stiffnesses in any plane is highly correlated with the shear stiffness in that plane, since similar relationships exist in the other two symmetry planes as well. Thus $C_{55} = b(C_{11}C_{33})^{1/2}$ and $C_{44} = c(C_{22}C_{33})^{1/2}$, where $b$ and $c$ are constants. Taken together, a single relationship exists between the elastic stiffnesses, viz.

$$C_{11}C_{22}C_{33} = K(C_{44}C_{55}C_{66}).$$

The implication is that changes in paper machine variables change the relative magnitudes of the longitudinal and shear stiffnesses, but that changes in the furnish (species, pulping, yield, or refining) will change the slope of the line, $K$. This hypothesis is currently being tested.

Elastic Parameters and End-Use Performance

Most paper specifications involve tests which are taken to be descriptive of the end-use performance of the material. Such tests are usually destructive, and can only be made on samples taken at reel turnup. Changes in paper machine variables such as rush-drag, wet pressing, or wet straining,
however, often affect the elastic properties and strength properties in the same way. It is perhaps not surprising then, that values for many of the common paper tests often correlate with certain elastic parameters, at least over the ranges of values experienced in the paper mill. The exceptions are apt to be changes in furnish or in formation. This observation is significant, since it is possible to measure the three-dimensional elastic properties of most papers nondestructively using the ultrasonic methods. These can then be used to predict a number of the destructive test values. In this way it is possible to study the effect of process variables on end-use tests or to monitor product quality.

Figure 12 shows how MD or CD tensile strength varies with $C_{11}$ or $C_{22}$. The data, covering a rather broad range of tensile strengths (either MD or CD), fall along a single line. The samples are those depicted in Fig. 8-10. Figure 13 shows how the ZD tensile strength (internal bond strength) varies with $C_{33}$ for the same array of samples. Such results suggest that a given elastic stiffness might be used to predict tensile strength, or to monitor the changes in MD, CD, and ZD tensile strength with process changes. Measurements on only one specimen would be required to do this. Similar results are obtained if one compares density specific parameters, i.e., breaking length vs. $G/\rho$ (or $E/\rho$). Such correlations have also been found to hold for machine-made papers.

![Fig. 12](image_url)  
**Fig. 12** MD and CD tensile strengths plotted against $C_{11}$ or $C_{22}$, respectively.

![Fig. 13](image_url)  
**Fig. 13** ZD tensile strength plotted against the ZD elastic stiffness, $C_{33}$.

![Fig. 14](image_url)  
**Fig. 14** MD and CD STFI compressive strength plotted against the products $C_{11}C_{55}$ and $C_{22}C_{44}$, respectively. The regression line coincides with the expected behavior (23).

Table 3 lists the relationships that have been studied relating the physical properties of paper with elastic stiffnesses (24). While such relationships may not be valid for all paper grades or basis weights, the use of elastic stiffnesses to evaluate end-use performance and to study the interactions between process variables and paper properties has so far been very productive. Work is continuing in this area.

**On-Machine Measurements**

A practical application of the relationships between elastic stiffnesses and paper quality factors has been made in a device which measures elastic stiffnesses on the paper machine. The first such sensors, tested on carton stock and more extensively
on linerboard, measured $C_{11}/p$ and $C_{66}/p$ (25, 26). After correcting these values for moisture and temperature variations, they were used to predict the bursting strength, CD ring crush, and CD-STFI compressive strength of the linerboard on a continuous basis.

Table 3. End use tests and elastic parameters.a

<table>
<thead>
<tr>
<th>Property</th>
<th>Elastic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD tensile strength</td>
<td>$C_{11}$ (~EMD)</td>
</tr>
<tr>
<td>CD tensile strength</td>
<td>$C_{22}$ (~ECD)</td>
</tr>
<tr>
<td>ZD tensile strength</td>
<td>$C_{33}$ (~EZD)</td>
</tr>
<tr>
<td>MD/CD tensile ratio</td>
<td>$C_{11}/C_{22}$</td>
</tr>
<tr>
<td>MD compressive strength</td>
<td>$C_{11}C_{55}$ (~EMD*MD-ZD)</td>
</tr>
<tr>
<td>CD compressive strength</td>
<td>$C_{22}C_{44}$ (~ECD*CD-ZD)</td>
</tr>
<tr>
<td>MD bending stiffness</td>
<td>$C_{11}T^3$</td>
</tr>
<tr>
<td>CD bending stiffness</td>
<td>$C_{22}T^3$</td>
</tr>
<tr>
<td>Internal bond strength</td>
<td>$C_{33}$</td>
</tr>
<tr>
<td>Bursting strength</td>
<td>$C_{11} + C_{22}$</td>
</tr>
<tr>
<td>Flutability</td>
<td>$C_{11}$ and $C_{55}$</td>
</tr>
<tr>
<td>Combined board performance</td>
<td>$C_{22}$ and $C_{44}$</td>
</tr>
</tbody>
</table>

a $T =$ caliper, $C_{ij} =$ elastic stiffness.

The real payoff for such a sensor, however, will probably be in paper machine control. Both $C_{11}$ and $C_{66}$ are sensitive to process and paper machine variables, but in different ways, and thus permit "tuning" the paper machine to provide optimum board properties. Eventually this capability could lead to automatic control of the papermaking process. Commercial instruments to monitor elastic properties on-machine are just now becoming available (27).

SUMMARY

In summary, the elastic properties of paper form a basic set of parameters which are useful for monitoring the effects caused by changes in process variables, capable of predicting end-use performance, and overall, helping us to better understand the fibrous network we call paper. Elastic parameters also are important in product design and modeling, e.g., in the construction of tubes, boxes, food containers, etc. Eventually their use will help us control the paper machine automatically. Because most of the elastic parameters needed to describe paper can now be determined easily and nondestructively using wave propagation methods, the opportunity exists to move forward in each of these areas.

REFERENCES
