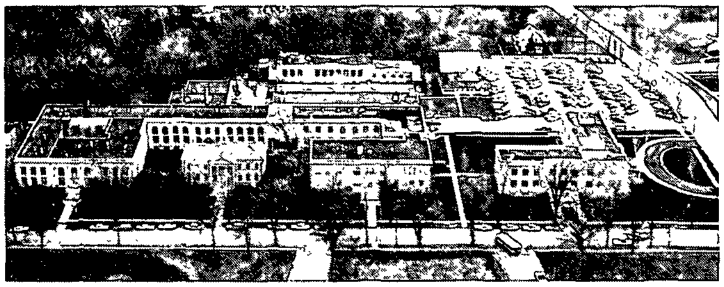

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POLAR DIAGRAMS OF ELASTIC STIFFNESS: EFFECT OF MACHINE VARIABLES

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Polar Diagrams of Elastic Stiffness: Effect of Machine Variables

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POLAR DIAGRAMS OF ELASTIC STIFFNESS: EFFECT OF MACHINE VARIABLES

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ABSTRACT

Polar diagrams of specific elastic stiffness have been measured on CD strips of commercial papers and on special laboratory sheets. The results provide information about operating conditions on the paper machine including fiber orientation, wet straining, and MD and CD drying restraints. This paper discusses how the shape, size, and angle of lean of the resultant polar diagrams are affected by the process variables. A new parameter, the "effective" stiffness, is defined. This provides a description of the collective effect of the operating variables which appears to be superior to the arithmetic average or geometric average of the MD and CD stiffnesses. The results, which reveal the complex nature of the interactions between headbox conditions, draws, and CD drying effects, should be beneficial in improving headbox design and in understanding CD variations in paper mechanical properties.

INTRODUCTION

Equipment has been developed at The Institute of Paper Chemistry which can measure the orthotropic elastic stiffnesses of paper in the laboratory and on the paper machine [1-4]. The elastic stiffnesses are sensitive to paper machine operating conditions and often can be related to the end-use tests normally used to characterize paper [5]. A recent development is the ability to automatically measure specific elastic stiffnesses as a function of angle from the machine direction. This instrument has been described in detail elsewhere [6]. It measures the longitudinal specific stiffness (related to C_{11} and C_{22} or Young's moduli E_{MD} and E_{CD}) or the shear specific stiffness (related to C_{66} or G_{MD-CD}). When the elastic stiffnesses are plotted *vs*. angle from the MD, as a polar graph, the results typically look like those shown in Fig. 1. The area and major axis of the generally elliptical shape can be computed and the angle the latter makes with the MD determined.

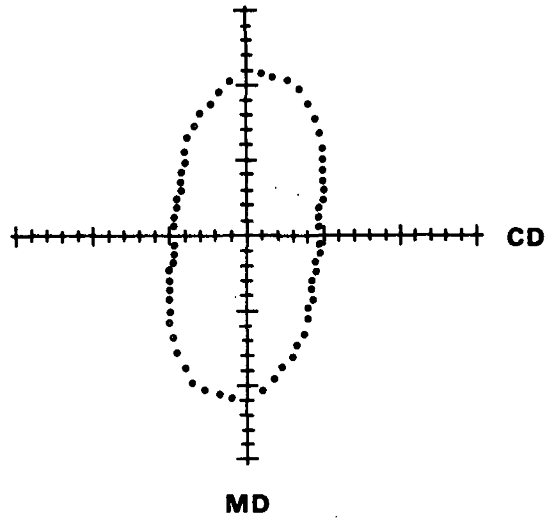

Fig. 1. Typical in-plane polar plot.

The shape, area, and angle of lean of the polar "diagrams" typically vary across the width of the paper machine. Figure 2 shows five such diagrams taken at regular intervals across the web for a fine paper, starting from the front side of the machine. The variations in shape, size, and angle of lean are related to changes in the level and direction of fiber orientation, refining, wet pressing, stretching of the wet paper web in open draws, and nonuniform drying conditions in the web. The variations in the inclination of the major axis of the ellipse with the machine direction (MD) of the paper (e.g., Fig. 1 or Part E of Fig. 2), are traceable to transverse stock flows from the headbox and have been discussed in detail elsewhere [7]. This paper primarily deals with the effects of machine variables on the shape and size of the diagrams. Such information can be useful in interpreting the nature of the interactions between variables across the width of the paper web.

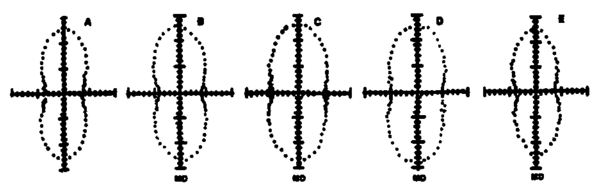

Fig. 2. Five polar diagrams taken across the web. A is near the front side, E the drive side.

RESULTS AND DISCUSSION

Lean Angle

Figure 3 shows two laboratory sheets made from the same furnish and having the same nominal basis weights. The circular shape is the result obtained for a handsheet made on a Noble and Wood machine, for which the fiber orientation would be expected to be random (no preferred fiber orientation). The elliptical shape was obtained for a sheet made in a Formette Dynamique anisotropic sheet former, in which there is some fiber orientation along the machine direction. The ratio of the stiffnesses along the MD compared to the CD for this latter case is about 1.4. The elliptical shape clearly is related to the extent of fiber orientation in the paper. Later we will see that it is also related to the extent of wet straining.

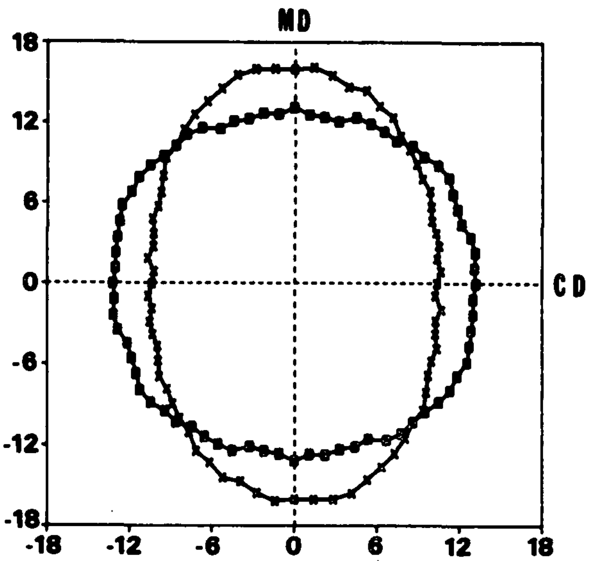

Fig. 3. C_{11} measured at various angles to the MD for a handsheet (squares) and oriented paper (X's).

In Fig. 3 the major axis of the ellipse for the Formette sheet is exactly along the MD. Figure 1 is a polar diagram for a commercial sheet in which the major axis is about 8 degrees clockwise from the MD. This angle of inclination is caused by stock flows from the headbox which have a component that is at right angles to the MD. Such transverse flows apparently deposit fibers onto the paper machine wire that have a preferred orientation at some angle to the MD. It has been shown that the angle of lean does not depend on wet stretching or drying conditions. Commercial samples displaying various angles of lean were immersed in water for extended periods of time, dried, and remeasured. In all instances there was no change in the lean angle, even though the area of the polar diagrams decreased [7]. Figure 4 illustrates this for two commercial samples.

The observance of a lean angle is quite common. To date we have made measurements on numerous CD strips from many paper machines manufacturing a variety of grades. In most cases there is some angular offset of a few degrees, which typically varies from point to point across the paper machine. The angular displacement may be as large as plus or minus 15 degrees. In such cases, it is not unusual to experience difficulty during a subsequent converting operation or end-use application. Figure 5 shows lean angle vs. position for four CD strips taken from the same machine. In our experience the profile or pattern for a given machine seems to make a fairly reliable "fingerprint" of that machine. There does not seem to be any common pattern, however, in the measured CD profiles of angular displacement from machine to machine.

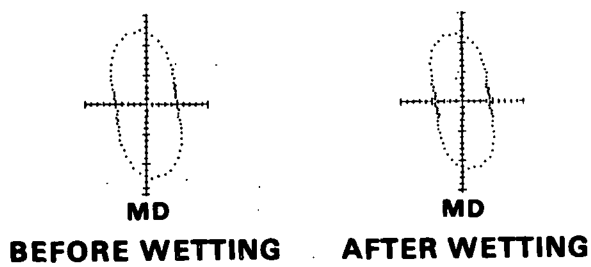

Fig. 4. Polar diagrams for a fine paper, before and after wetting and redrying. The wetting does not affect the angle of lean.

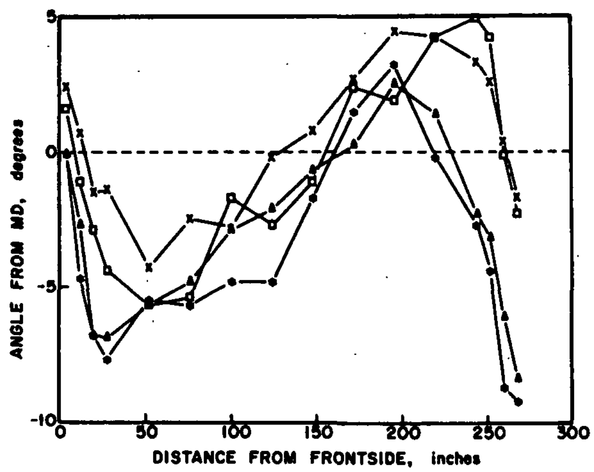

Fig. 5. Angle of lean vs. position across the machine for four separate reel turnups. Diagrams like these seem to be a "fingerprint" of the headbox and slice conditions.

Fiber Orientation, Wet Straining, and Drying Restraints

In an attempt to elucidate the effects of fiber orientation, wet straining, and drying restraints on the shape and size of the polar diagrams, southern pine unbleached kraft sheets were prepared under various conditions and constructions. Two layer composite papers were made by wet pressing together Formette Dynamique sheets having a nominal basis weight of about 100 g/m^2 and an anisotropy of 1.62 due only to the orientation of fibers in the sheets. The resultant 200 g/m^2 sheets were wet strained or dried under various conditions. In each case duplicate sheets were made. Values reported below are the average of the two sheets.

The results are shown in Fig. 6 for the four constructions and drying conditions. In sample A the two plies were aligned with their MD directions parallel, and the composite was wet pressed and then dried under full MD and CD restraint. No shrinkage was allowed. Sample B had the same construction with parallel MD directions and was wet pressed to the same pressure but dried under only MD restraint. There was about 6.5% shrinkage in the CD direction during drying. Sample C also had the machine directions of the two plies aligned, but after wet pressing was stretched in the MD about 2% while still wet. It was then dried under MD and CD restraint. After drying, a 2% shrinkage was measured in the cross machine direction, presumably a consequence of the MD wet straining. In sample D the two plies were oriented so that their MD's were perpendicular and the composite was then wet pressed and dried under MD and CD restraint.

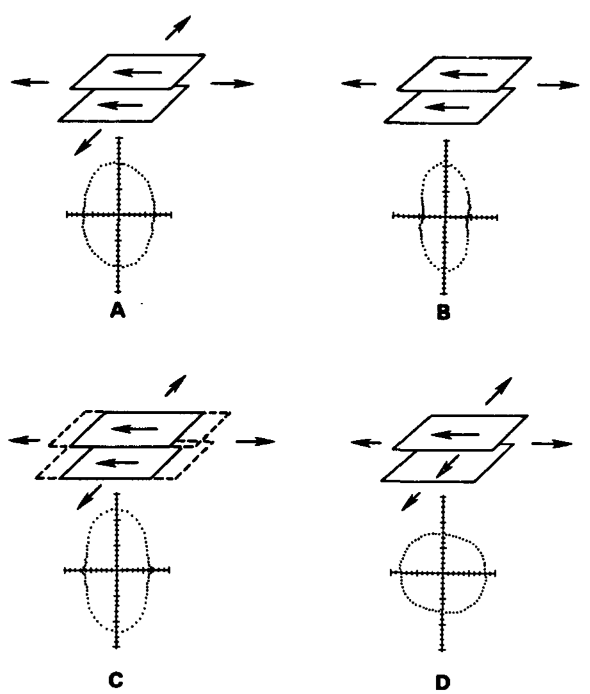

Figure 6. Four different paper constructions and drying conditions, and the resultant polar diagrams.

The polar diagrams measured for the different constructions and drying conditions are also shown in Fig. 6. In A the elliptical shape is due only to the orientation of the fibers in the two layers. The anisotropy ratio (C_{11}/C_{22}) for the composite is 1.54. Sample B differs from A in that it was allowed to shrink in the CD. The resultant polar diagram is quite different from that found for A. It no longer has the elliptical shape but appears "necked down" in the cross machine direction, similar to the results obtained for Samples A and E in Fig. 2, near the edges of the paper web. The area of the polar diagram for 6B is much less than that found for 6A, about 152 $(km/s)^2$ vs. 225 $(km/s)^2$, again a result of the CD shrinkage during drying. (It may be possible to obtain a necked down diagram similar to that observed here which is due entirely to some particular distribution of fibers in the paper. That is clearly not the case here. Most likely the changes in shape found for commercial grades are not caused by differences in the distribution of fibers from point to point, but rather are caused by the shrinkage effects described here.)

Sample C differs from A only in that it was wet strained 2.3% before drying. The polar diagram for C has an elliptical shape similar to that for A except that the anisotropy ratio has increased to 2.05. There is a very slight increase in the area of the diagram to 239 $(km/s)^2$. In D, where the two plies were oriented at right angles, the resultant polar diagram is a circle, as expected, having an anisotropy of 0.98 and an area of 227 $(km/s)^2$.

The experiments described in Fig. 6 illustrate that the size and shape of the polar diagrams can vary with changes in fiber orientation, wet straining, and drying restraints. Comparison of samples A and D suggests that the area of the polar diagrams is independent of fiber orientation and possibly wet straining (Sample C). CD shrinkage, however, resulted in a decrease of about 30% in the area (Sample B).

Increasing the level of refining or wet pressing increases the area of polar diagrams as shown in Fig. 7, which shows an unbleached hardwood kraft pulp beaten to five levels. The wet pressing pressure was varied over three levels at each refining level. Other sheet preparation parameters remained constant, except at the CSF level of 350 mL, where two levels of fiber orientation are shown. The size of the polar diagrams is clearly sensitive to the level of refining and wet pressing, as expected.

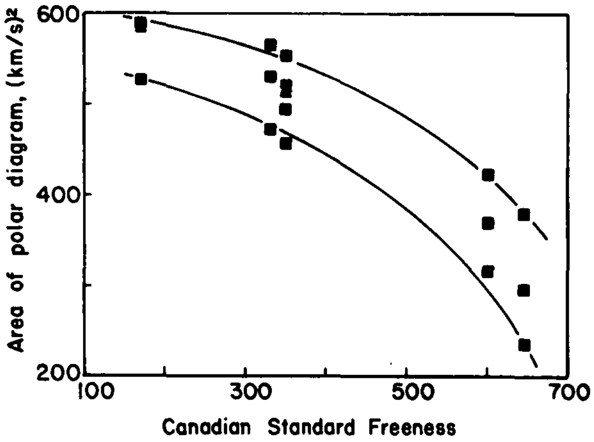

Fig. 7. The areas of the polar diagrams increase with increasing refining and wet pressing. There are three wet pressing levels at each refining level. The six points at 350 CSF represent two different fiber orientation levels.

Since refining and wet pressing effects would be expected to be uniform over the width of the web, changes in the shape and area of the polar diagrams taken across the web, such as those shown in Fig. 2, would best be explained in terms of a nonuniform CD shrinkage between the center and edges of the web. An increase in the CD shrinkage as one goes outward toward the sides would account for both changes. This, of course, also would explain the often observed lower values for mechanical properties near the edges of the web.

Effective Stiffness

It is common for the papermaker to use a single number to characterize production when possible. For example, the squareness or anisotropy ratio or arithmetic or geometric mean of MD and CD properties is often used. Polar diagrams such as those shown in Fig. 1, 6B, or 2A, however, suggest that such ratios or averages will be misleading because of a lean angle or a necked down shape. The area enclosed by the polar diagram appears to be a useful quantity in this respect, but there is a more meaningful way to express the results. The "effective stiffness" is taken as the radius of a circle having the same area as the measured polar diagram, as shown in Fig. 8. Figure 9 compares specific effective stiffness *vs*. the geometric specific stiffness for the eight specimens (four constructions) described in Fig. 6. Note that in all cases the effective stiffness value is greater than the geometric mean value. This turns out to be true in the case of commercial papers as well, as we will see next.

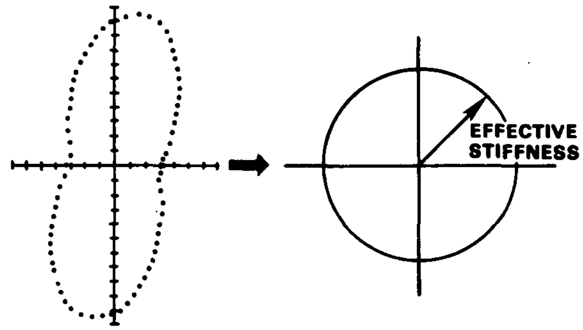

Fig. 8. The "effective stiffness" is defined as the radius of a circle having the same area as the polar diagram.

Commercial Paper Samples

Polar diagrams have been obtained for a large number of commercial papers. Most testing has been done on CD strips in which information was sought concerning the nature of the flows from the headbox. Figure 10 shows a fine paper sample in which polar data were obtained every eight inches across the width of the web. In this case the angular displacement is a maximum on the front side of the machine (about six degrees) and decreases gradually until it approaches zero near the back side. Figure 11 shows polar diagrams taken near the front side (A), middle of the web (B), and back side (C). In addition to the changing lean angle, the area of the polar diagram from the center of the web is noticeably larger than those taken from the edges, similar to the behavior noted in Fig. 2. Figure 12 shows that the polar diagram areas have a maximum at the center of the web. Again, based on the experiments described in Fig. 6, the behavior seen in Fig. 12 could be explained in terms of a nonuniform CD shrinkage between the center and edges of the web.

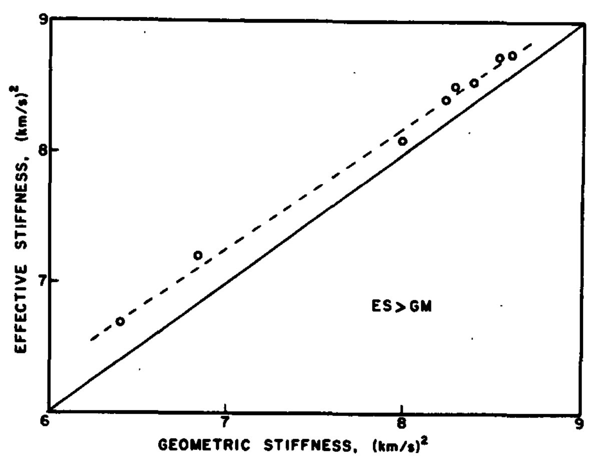

Fig. 9. Effective stiffness *vs*. geometric stiffness for the experimental sheets.

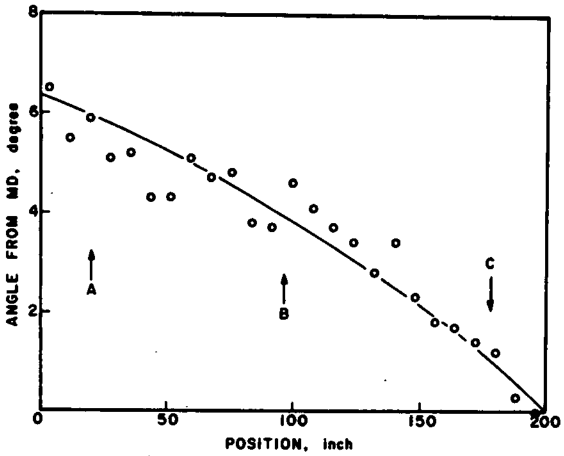

Fig. 10. Angle from MD vs. position. The letters show where the profiles in Fig. 11 were obtained.

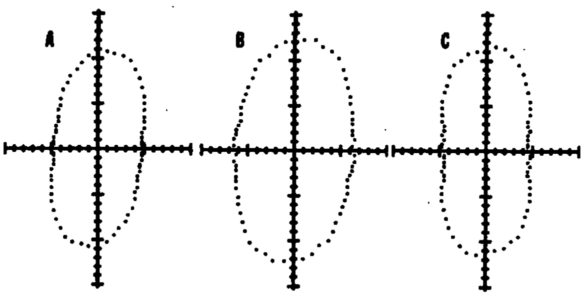

Fig. 11. Polar diagrams taken from three different CD web positions as shown in Fig. 10.

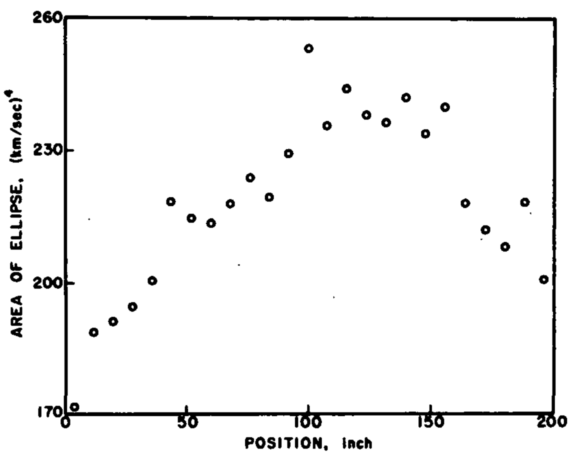

Fig. 12. Area of ellipse vs. position for same specimens as in Fig. 10.

The same argument explains why other mechanical properties show the same convex curvature in CD profiles. The MD or CD specific elastic stiffnesses vs. position, as shown in Fig. 13, for example, both show this behavior. Figure 13 also shows the geometric mean value of the specific stiffnesses. Figure 14 compares the specific effective stiffness, defined above, and the geometric stiffness. The difference between the two quantities increases as we go toward lower stiffness levels. The lowest stiffness levels are from specimens taken near the edges of the web (Fig. 13) and which tend to have the necked down shape. Thus the calculated geometric mean values would not appear to be very reliable indicators of product quality, especially near the edges of the web. For the same reasons, the MD/CD ratios would vary across the web with higher values at the edges. A plot of anisotropy ratio vs. position for the specimens depicted in Fig. 10-14 shows such a concave upward behavior.

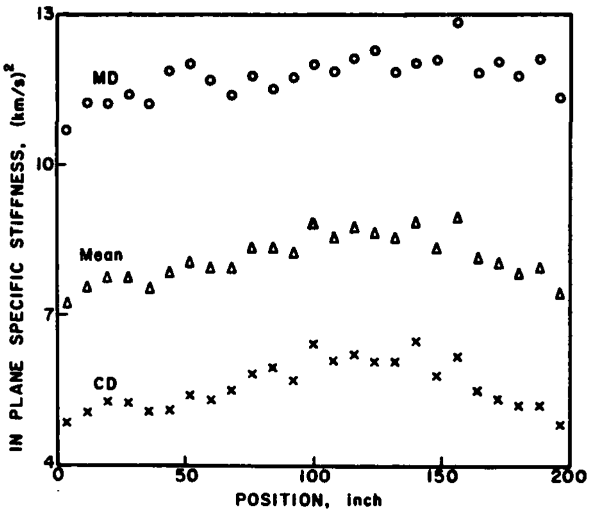

Fig. 13. In-plane specific stiffnesses vs. position for fine paper specimens of Fig. 10.

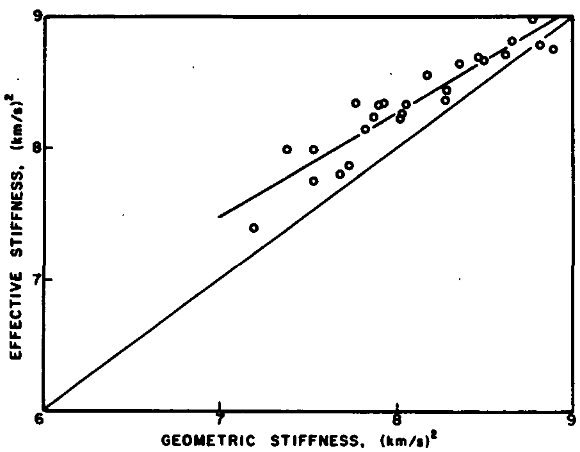

Fig. 14. Effective stiffness vs. geometric stiffness for the fine paper specimens in Fig. 10.

Because nonuniform drying restraints in the CD affect the local values of the measured mechanical properties (especially those measured in the CD), geometric mean values or anisotropy ratios may give misleading information concerning paper quality. The specific effective stiffness may be a more meaningful parameter.

CONCLUSIONS

For a given furnish, sheet mechanical properties are determined by conditions at the slice (jet-to-wire speed differentials), the level and uniformity of wet pressing pressure, the extent of stretching of the web in any open draws, the MD restraint applied as the web passes through the dryer section, and the CD restraint (or lack thereof) offered by the dryer felts and contact with the cans during drying. Variations in sheet mechanical properties in the cross machine direction are a consequence of differences in how these variables interact locally. The nature of the interactions is often difficult to ascertain using traditional testing methods.

The study of polar diagrams, however, seems to offer considerable insight as to how process variables interact and suggests the possibility of separating their effects. Transverse stock flows at the slice are traceable to the angle of lean of the polar diagrams. An increase in the pressing pressure (or refining) increases the area of the polar diagrams but does not change shape. An increase in wet stretching (draws) increases the ellipticity (or anisotropy ratio) of diagrams, but not the area. A change in CD (or MD) restraint in the dryer section during drying changes both the area and shape (anisotropy ratio) of the polar diagrams. The effective stiffness parameter may be a more meaningful number in describing the quality of the product than those quantities more commonly used.

The study of polar diagrams and their concomitant application to problems will help us to better understand paper machine operations and how to develop more uniform product quality. There is more information that can be obtained, however, which promises to be as important or even more important. A simultaneous measurement of a thickness direction (ZD) elastic stiffness provides additional information concerning the state of wet pressing (or refining) and wet stretching. For example, for the experimental sheets discussed in Fig. 6 the ZD specific stiffness changes by about 100% as a consequence of the changes in wet straining and drying restraints. The ZD stiffness decreases as wet straining or restraint during drying incRefining or wet pressing would offer equally large effects in the opposite direction. An increase in wet pressing pressure, for example, would cause ZD stiffness to increase substantially [8]. We are working to develop equipment that will quickly enable us to obtain polar diagrams and measure ZD elastic stiffness.

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