

On-line sensor for measuring strength properties

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Sensor measures the MD and CD mechanical extensional stiffness of paper on-line, response is analyzed with a mathematical model, and results show the model closely agrees with measured response.

Researchers at the Institute of Paper Chemistry (IPC) indicated that the extensional stiffness of paper correlates to laboratory strength tests (1, 2). To determine the extensional stiffness, they measured the ultrasonic velocity in the paper. They related ultrasonic velocity to the elastic properties of paper by a mathematical model, with the working assumption that paper is an anisotropic, orthotropic, elastic medium of infinite extent. Plate wave theory then relates the elastic properties to ultrasonic velocity. According to the model, the machine-direction extensional stiffness of paper can be calculated by multiplying the basis weight times the square of the longitudinal ultrasonic velocity in the machine direction:

$$\text{MD ext. stiffness} = BW \times V_{md}^2$$

Experiments at Measurex verified that extensional stiffness measurements using ultrasonic techniques are well suited for the laboratory (3). On-line, we found difficulties that do not occur in the laboratory environment. Other researchers have reported similar experiences (1, 2, 4-6).

Coupling the ultrasonic signal into and out of the moving web is difficult, requiring high contact pressure. The signal strength obtainable on-line is much lower than it is under static laboratory conditions. Vibrations from the paper machine excite resonances in the transducers that produce noise at the frequencies of the measurement. Signal averaging is needed to overcome the extremely low signal-to-noise ratio and obtain acceptable accuracy. Because of the long time required for signal averaging and because of the high contact pressure, it is difficult to have the sensor scan the sheet continuously from a standard sensor platform. The on-line use of ultrasonic sensors has been limited to heavy paper and linerboard, possibly because of the high contact pressure required and the lower signal strength in lightweight sheets.

Measurex has developed a sensor that measures extensional stiffness mechanically and easily extends the

measurement to lightweight papers such as newsprint and sack. The new sensor provides a large signal-to-noise ratio with a 10-ms response time. It is compact, with a measurement diameter of about 76.2 mm (3 in.). It provides 100% continuous measurement and scans as part of the standard sensor platform.

Results of the Measurex on-line scanning digital strength sensor were published previously (3). In that article, the sensor outputs were shown to correlate with laboratory strength tests. Here, we describe sensor hardware and the theory of operation.

The sensor detects the extensional stiffness in the machine and cross-machine directions by measuring the force required to distort the traveling web in a controlled manner. Additional sensor inputs, such as basis weight or caliper, are not necessary to compute extensional stiffness. Other measurements, such as sheet moisture and temperature, are used with extensional stiffness to predict strength values.

Description of the sensor

Depicted in Figs. 1A and 1B, the sensor consists of a web-contacting ring, surrounding a proximity sensor, mounted on a platform above the web. A spherical section wheel is mounted on a platform below the web. The wheel is inserted approximately 3.5 mm into the middle of the ring to distort the web slightly as it moves through the sensor.

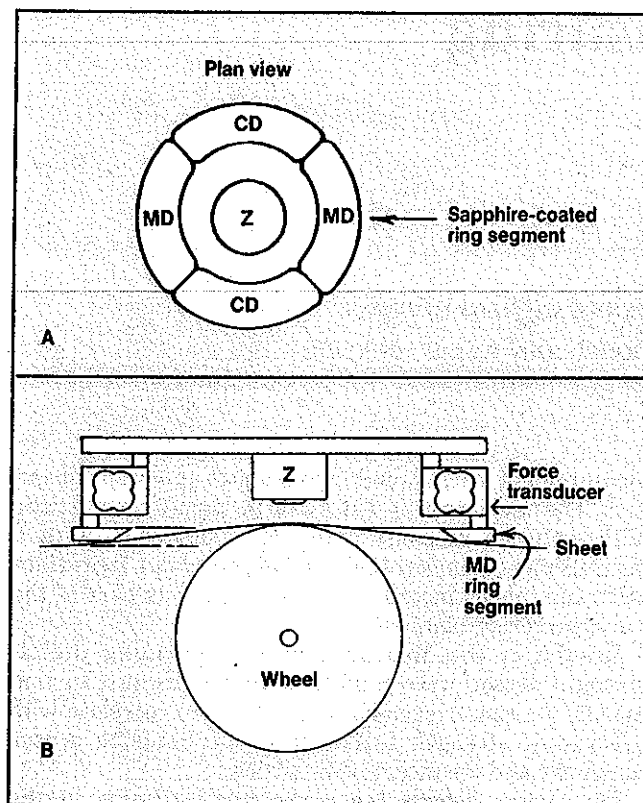
The ring is split into 4 segments, at 45° angles to the machine and cross-machine directions, with a force transducer mounted above each segment to measure the force applied to that segment.

The ring

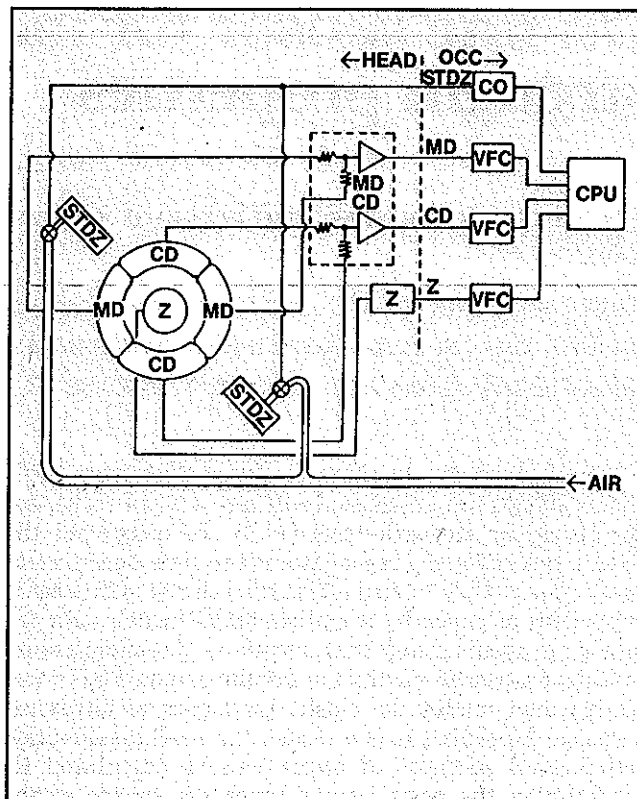
The four-segment ring allows the extensional stiffness to be measured in both the machine direction and cross-machine direction. Two segments integrate vertical force over ±45° in the machine direction, and two segments integrate over ±45° in the cross direction. Each segment is protected with a sapphire pad to eliminate wear.

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1. (A) The segmented ring contacts the moving web. (B) A spherical section wheel deflects the web into the center of the ring. A "Z" sensor measures the exact position of the wheel, and transducers measure the vertical force exerted by the web.



2. Signals from the two MD ring segments are added, and signals from two CD ring segments are added. These signals plus the "Z" signal go to voltage-to-frequency converters (VFC) then to the computer (CPU). Standardization is accomplished with a contact output (CO) from the computer.



Spherical section wheel

The contacting surface of the wheel is a 38.1-mm-wide section (1.5 in. wide) cut from a sphere 152.4 mm (6 in.) in diameter. The spherical shape ensures that there is MD/CD symmetry in the distortion produced by the wheel pressing the web into the ring.

Force transducers

The force transducers are designed to measure only the force normal to the plane of the ring. Horizontal forces produced by the friction of the moving web on the ring segments are excluded. The MD output of the sensor is the sum of the forces on the upstream and downstream ring segments, as shown in the block diagram of Fig. 2. The CD output of the sensor is the sum of the forces of the left and right ring segments.

"Z" sensor

A "Z" sensor, or proximity sensor, is located in the center and above the plane of the ring. It measures the position of the wheel relative to the plane of the ring. As the sensor scans, the "Z" sensor dynamically measures any variations in the distance that the wheel deflects the web. The measured "Z" variation is used in calculating extensional stiffness.

Standardization

The sensor performance is checked periodically off sheet during standardization. A known load is applied to the ring segments by an air cylinder and leaf spring and is compared to readings from the sensor. Standardization also verifies that the "Z" sensor is reading correctly. These standardization values then correct the sensor, ensuring long-term accuracy and repeatability.

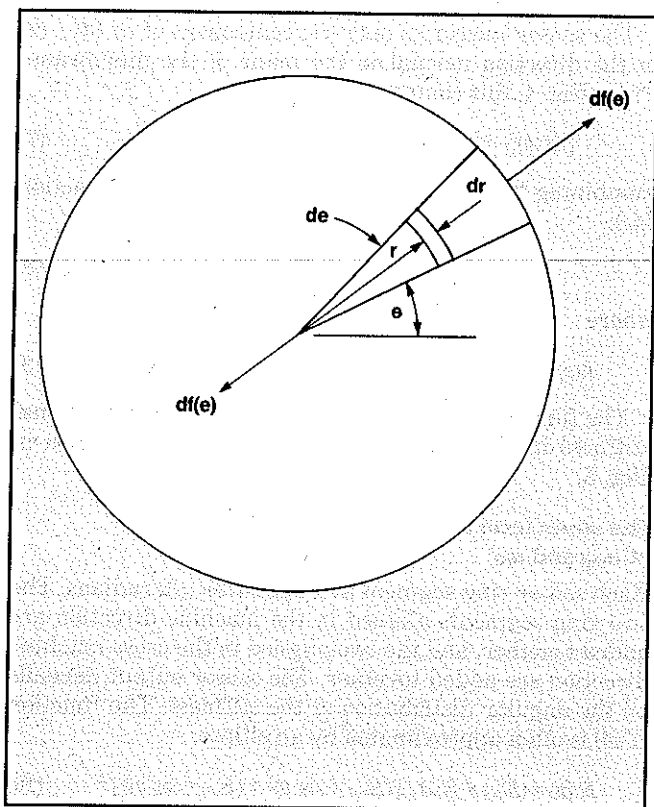
Theory of operation

A theoretical model has been constructed that allows us to predict the response of the sensor to changes in the extensional stiffness of the web. The model takes into account the effects of tension applied to the web. For the purposes of analysis, the traveling paper web is treated as an anisotropic elastic membrane. The elastic approximation is valid for small distortions applied briefly, as with the sensor. The sensor induces a strain of about 0.5% into the traveling web for about 10 ms.

We have also studied larger distortions, beyond the normal operating range of the sensor. The results are included in the appendix to provide a more complete understanding of the sensor.

The anisotropy of the elastic modulus can be described as an ellipse with its major axis in the machine direction and its minor axis in the cross direction (2).

3. The web is treated as an infinite elastic membrane. The force on an infinitesimal wedge of membrane distorted within the ring is derived using Eq. 1.



In the model, the web is considered to be an infinite membrane that is distorted from its plane by the wheel. The ring segments restore the membrane to its original place and define the boundary of deformation caused by the wheel. The assumption of the web acting as an infinite membrane is valid except toward the web edges, where corrections to the theoretical values are required.

In summary, these assumptions are:

1. Paper is an anisotropic, elastic medium.
2. The web is an infinite membrane under tension in the machine direction.
3. The elastic modulus has an elliptical angular distribution.
4. The ring defines the boundary conditions of the deformation.

The three terms: stress, tension, and bending resistance

The strength sensor has two outputs, corresponding to the machine direction of the paper machine, MD, and to the cross direction of the paper machine, CD. The outputs of the strength sensor are the result of three separate terms:

1. Stress caused by strain due to local distortion of the web by the sensor
2. Tension applied to the web by the paper machine

3. Bending resistance of the web.

At each slice i , then, the MD output is the sum of the responses to these three inputs—strain, tension, and bending:

$$\text{Output}_{\text{md}}(i) = (\text{strain term}) + (\text{tension term}) + (\text{bending term}) = + a_{\text{md}} \times E_{\text{md}}(i) \times t(i) \times L(z(i)) + [b_{\text{md}} \times T(i) \times \tan(\Phi)] + [c_{\text{md}} \times \beta(i) \times \Phi] \quad (1A)$$

where:

- E = Young's modulus
- t = caliper of the web
- L = the function relating $(E \times t)$ to stress caused by strain
- z = distance across which the sensor wheel pushes the web into the ring
- β = the coefficient of bending resistance of the web
- $z(i)$ = distance the wheel pushes into the ring
- R = radius of the ring
- T = the applied web tension
- Φ = angle of the web at the lip of the sensor ring to the normal plane of the web
- a, b, c = proportionality constants.

For the CD output, the equation is similar:

$$\text{Output}_{\text{cd}}(i) = + a_{\text{cd}} \times E_{\text{cd}}(i) \times t(i) \times L(z(i)) + [b_{\text{cd}} \times T(i) \times \tan(\Phi)] + [c_{\text{cd}} \times \beta(i) \times \Phi] \quad (1B)$$

To calculate extensional stiffness $(E \times t)$ from the sensor output, the values of the coefficients $(a_{\text{md}}, b_{\text{md}}, c_{\text{md}}, a_{\text{cd}}, b_{\text{cd}}, c_{\text{cd}})$ and the function $L(z)$ must be determined.

The strain term: derivation of $L(z)$

The strain term is determined by deriving $L(z)$. This function relates the extensional stiffness $(E \times t)$ to stress caused by strain as the sensor wheel pushes the web into the ring.

Radial strain effects. Consider first an infinitesimal wedge of membrane of angle $d\theta$ and radius R , as illustrated in Fig. 3. The stress distribution in the wedge can be determined. It is caused by an infinitesimal force $df(\theta)$ applied in the radial direction at the apex and an opposite restraining force at radius R . The force at any radius r along the wedge is related to stretch by the equation:

where

- dr = an increment of radius r
- $ds(r, \theta)$ = the stretch induced in element dr by force $df(\theta)$
- $d\theta$ = the infinitesimal angle of the wedge segment
- $df(\theta)$ = the increment of force applied in the radial direction
- $E(\theta)$ = the elastic modulus of the membrane as a function of θ
- t = thickness of membrane.

Tangential stresses and the Poisson effect. Although the applied strain is in the radial direction only, tangential stress will build up as a result of the Poisson effect. That is, by stretching the membrane in one direction, the radial direction, the membrane will try to become narrower in the other direction, the tangential direction. But since the membrane is assumed to be infinite, the tangential direction is restrained from becoming narrower, and tangential stress builds up.

Since the sensor is sensitive only to forces normal to the original plane of the membrane and since the symmetry of the design causes all tangential stress to be parallel to the original plane of the membrane, the sensor is insensitive to tangential stress. Stated in terms of the elastic constants matrix in cylindrical coordinates, the sensor is sensitive to only two diagonal elements of the matrix: (a) the coefficient relating radial stress caused by radial strain and (b) the coefficient relating shear stress caused by shear strain about the tangential axis.

The sensor is also sensitive to the two symmetric off-diagonal elements that relate radial stress to shear strain and shear stress to radial strain. These two off-diagonal elements are usually considered to be zero in paper. Our experience indicates that the bias they impart is certainly much less forcible; therefore, they have been ignored in this analysis.

Boundary conditions.

Equation 2 gives the force required to produce a stretch, ds , at point (r, θ) on the membrane. The stretch caused by an applied force is then:

$$ds(r, \theta) / dr = [df(\theta) / d\theta] / [E(\theta) t r] \quad (3)$$

The geometry of the sensor places boundary conditions on Eq. 3. The wheel distorts the membrane a distance z from the plane of the membrane and defines a minimum radius where the force is applied. The ring defines a discontinuity that forces the distorted membrane back to the original plane of the membrane at the radius of the ring, R . In mathematical terms:

1. At $r = r_{\min}$, then $z(r) = z(\text{wheel})$.
2. At $r = R$, then $z(r) = 0$.

The boundary conditions can be expressed as a boundary condition integral as follows:

$$z(\text{wheel}) = \int_{r_{\min}}^R [dz(r) / dr] dr \quad (4)$$

where

- $z(r)$ = the displacement from the plane of the membrane at radius r
- $dz(r)/dr$ = the slope of the membrane at radius r
- $r_{\min}$ = the radius where the membrane separates from the surface of the spherical section wheel. To a close approximation,
- $r_{\min} = z(\text{wheel}) \times (\text{wheel radius}) / R$

The function $L(z)$ is found by solving the boundary condition integral. From the geometry of the membrane (Fig. 4), the slope is:

$$dz(r) / dr = [(dr + ds)^2 - dr^2]^{1/2} / dr \quad (5)$$

By substituting Eq. 3 into Eq. 5 and Eq. 5 into Eq. 4, the boundary condition integral yields a function $A(z)$ such that:

$$df(\theta) / d\theta = A(z) E(\theta) t \quad (6)$$

The sensor measures only the component of $df(\theta) / d\theta$ in the direction normal to the plane of the membrane. From Fig. 4, this component is:

$$[df(\theta) / d\theta]_{\text{normal}} = [(df(\theta) / d\theta)] [dz / (dr + ds)] \quad (7)$$

Combining Eqs. 3, 5, and 6 into Eq. 7 yields the function $L(z)$:

$$[df(\theta) / d\theta]_{\text{normal}} = E(\theta) t L(z) \quad (8)$$

where

$$L(z) = A(z) [(2A(z)/R) + (A(z)/R)^2]^{1/2} / [1 + A(z)/R] \quad (9)$$

The function $L(z)$ relates sensor response to extensional stiffness in direction θ . A plot of $L(z)$ vs. z is shown in Fig. 5.

The strain term angular response: derivation of a_{md} and a_{cd}

Each sensor ring segment averages over $\pi/2$ radians. The two ring segments aligned in the machine direction are added together, and the two aligned in the cross-machine direction are added together. The sensor output depends on the angular distribution of the stiffness. The function $E(\theta)$ is often approximated by an ellipse:

$$E(\theta) = (E_{md} \times E_{cd}) / [(E_{md} \times \sin \theta)^2 + (E_{cd} \times \cos \theta)^2]^{1/2} \quad (10)$$

where

$$E_{md} = E(0)$$

$$E_{cd} = E(\pi/2)$$

After combining these equations (Eqs. 8 and 10),

$$(\text{strain output})_{md} = 4 \int_0^{\pi/4} E(0) t L(z) d\theta = a_{md} E_{md} t L(z) \quad (11A)$$

$$(\text{strain output})_{cd} = 4 \int_{\pi/4}^{\pi/2} E(0) t L(z) d\theta = a_{cd} E_{cd} t L(z) \quad (11B)$$

where

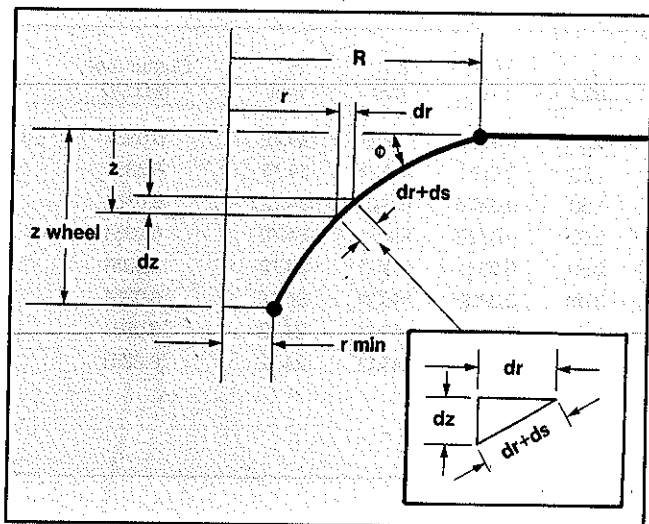
$$a_{md} = 4 \int_0^{\pi/4} E_{cd} / [(E_{md} \times \sin \theta)^2 + (E_{cd} \times \cos \theta)^2]^{1/2} \times d\theta \quad (12A)$$

$$a_{cd} = 4 \int_{\pi/4}^{\pi/2} E_{md} / [(E_{md} \times \sin \theta)^2 + (E_{cd} \times \cos \theta)^2]^{1/2} \times d\theta \quad (12B)$$

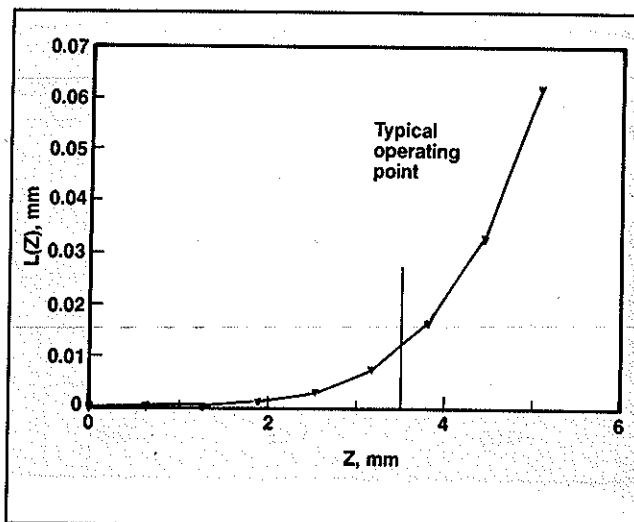
The elliptic integrals give the coefficients a_{md} and a_{cd} shown and are solved numerically. The integrals depend on the ratio of E_{cd} to E_{md} . Table I shows the values of the coefficients a_{md} and a_{cd} for various values of squareness E_{md}/E_{cd} .

An interesting result of this analysis is that the squareness of the web, E_{md}/E_{cd} , can be uniquely determined by the ratio of the sensor outputs for the machine and the cross-machine directions. Figure 6 shows the sensor output ratio for various web squareness ratios. The squareness can be determined without knowing the value of $L(z)$, since $L(z)$ is the same for both MD and CD sensor outputs.

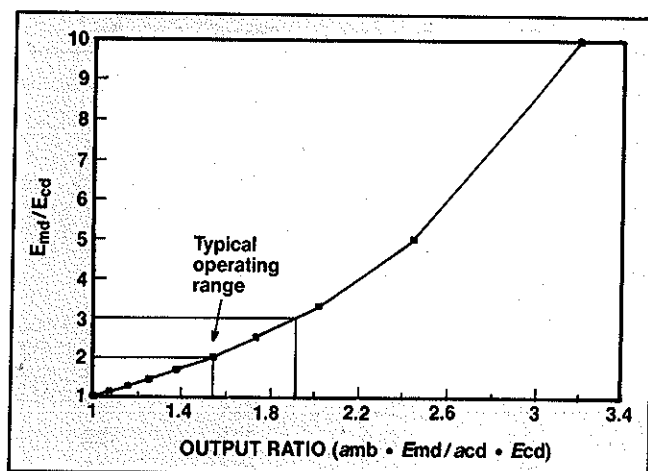
4. The boundary condition is that the membrane is restored to its original plane at the ring, as expressed in Eq. 4.



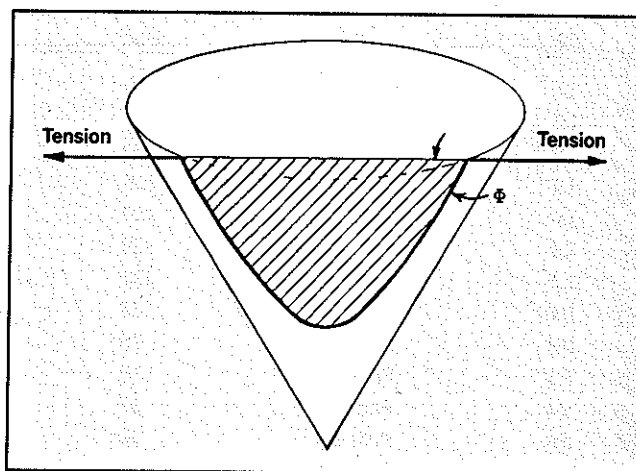
5. The function $L(z)$ relates the extensional stiffness to the force exerted on the ring segments.



6. The output ratio of the sensor can be used to determine the squareness of the web.



7. The applied MD tension affects the sensor output depending on distance from the center of the ring, y



Tension term: derivation of b_{md} and b_{cd}

To calculate the applied tension contribution to the sensor output, we assume that the applied web tension inside the ring is the same as the applied web tension outside the ring. The tension contribution to sensor output is calculated by a geometrical analysis.

By defining a set of cartesian coordinates with the machine direction as the x axis, the cross direction as the y axis, and the normal to the plane of the web as the z axis, the tension would normally run in the x direction with no y or z components. When the web is deformed, the applied tension within the web can be resolved into a z component and an x component, while there is still no y component.

The z component, which the sensor measures, depends on distance from the center of the ring. At a distance y from the center, a section is cut in the $x-z$ plane through the cone formed by the web within the ring, as in Fig. 7. The conic section forms a parabola. The z component

of the tension where the section meets the ring produces a force measured by the sensor:

$$df = T t dy \sin \phi \quad (13)$$

where $\sin \phi$ is the sine of the angle between the plane of the web and the parabolic section cut in the $x-z$ plane at a distance y from the center of the ring at the point where the parabola touches the ring.

The value of $\sin \phi$ can be found from the derivative of the equation for the parabola formed by the conical section. The MD output of the sensor is the force integrated over the MD ring segments:

$$(\text{tension output})_{md} = 4 \int_0^R \sin(\pi/4) T t \sin \phi dy \quad (14A)$$

Similarly, for the cross direction:

$$(\text{tension output})_{cd} = 4 \int_0^R \sin(\pi/4) T t \sin \phi dy \quad (14B)$$

I. Values of coefficients a_{md} and a_{cd}

E_{md}/E_{cd}	Coefficients	
	a_{md}	a_{cd}
1.00	3.142	3.142
1.11	3.080	3.196
1.25	3.000	3.252
1.43	2.900	3.308
1.67	2.772	3.360
2.00	2.621	3.400
2.50	2.396	3.452
3.33	2.108	3.480
5.00	1.712	3.500
10.00	1.128	3.520

II. Effect of applied tension on sensor output

z , mm	$\tan$ ϕ	b_{md} , mm	b_{cd} , mm	Output ratio, MD:CD
0.50	0.0077	149.21	24.72	6.0351
1.00	0.0170	149.21	24.72	6.0351
1.50	0.0277	149.21	24.72	6.0351
2.00	0.0396	149.21	24.72	6.0351
2.50	0.0531	149.21	24.72	6.0351
3.00	0.0680	149.21	24.72	6.0351
3.50	0.0842	149.21	24.72	6.0351
4.00	0.1026	149.21	24.72	6.0351

III. Description of samples

Sample no.	Grade	Basis weight, g/m ²	Stiffness		MD output at 3.2 mm, N		
			MD	KN/m CD	Measured	Theory	Dev.
L1	Liner	120	1082	340	38.9	34.0	-4.9
L2	Sack	45	320	176	20.8	22.6	1.8
L3	Liner	120	883	417	34.5	32.7	-1.8
L4	Liner	205	1379	507	43.5	39.9	-3.6
L5	Liner	229	1474	614	42.4	42.7	0.3
L6	Liner	336	1992	930	50.9	53.5	2.6
L7	Liner	439	2257	1106	57.7	60.2	2.5
P1	Photocopy	75	524	234	21.5	24.5	3.0
P2	Photocopy	75	596	206	24.1	24.4	0.3
P3	Printing	70	392	238	20.0	24.4	4.4
P4	Printing	87	266	315	26.0	23.4	-2.6
P5	Print-out	80	556	223	24.0	26.2	2.2
P6	Photocopy	75	621	276	23.3	27.8	4.5

The integrals were evaluated numerically and are tabulated in Table II. The values of the constants b_{md} and b_{cd} shown are the values of the integrals divided by the tangent of the angle, ϕ , formed at the rim of the ring. The table shows that the tension has a much smaller effect on CD output than MD output by a factor of 6.0351. This has been verified by experiment. The CD sensor output was much less sensitive than the MD sensor output was to changes in web tension. Experiments have shown that on-line, the tension contribution to the MD output for 205 g/m² (42 lb/100 ft²) is about 20% of the total MD output. Lab tests indicate that the tension contribution ranges from about 25% to 50% of total output over a wide range of linerboard grades at a tension of 1.7 N/mm (10 lb/in.). On-line, the applied tension is measured, and the tension contribution is corrected from the sensor output so that the strain contribution to output can be determined for calculating extensional stiffness.

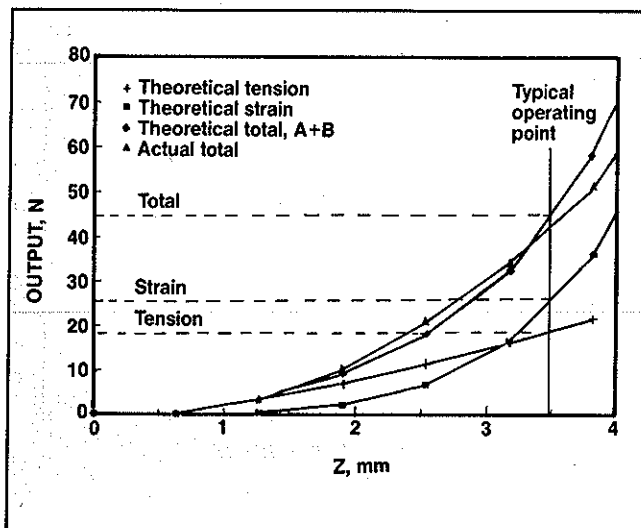
Bending term: determination of c_{md} , c_{cd} , and β

If an unrestrained sample of paper is placed in the sensor and the spherical section wheel is inserted, the force generated is caused by the bending resistance of the sample. For 122-g/m² and 439-g/m² linerboard, the bending resistance contributes 0% and 25%, respectively, to the total on-line measurement. On-line, a bending resistance corrector is measured and applied to the sensor output.

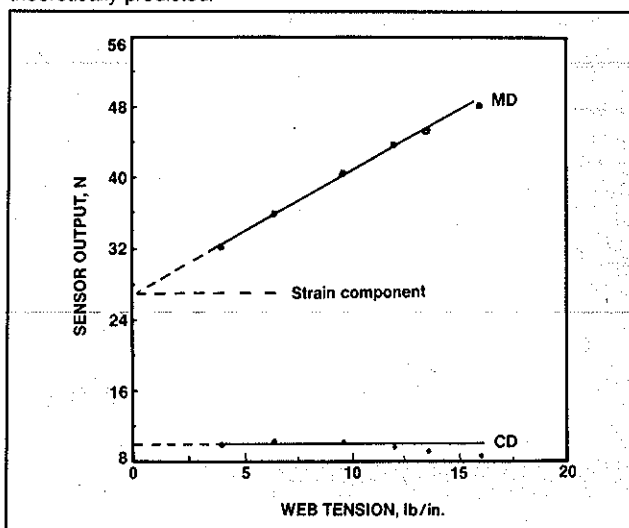
Comparison of theory to experiment**Theory compared to lab experiments**

Laboratory experiments have been performed with this sensor to determine the output as a function of z for several grades of paper ranging from linerboard to fine paper. The extensional stiffness of each sample was determined independently from the stress-strain curve measured on

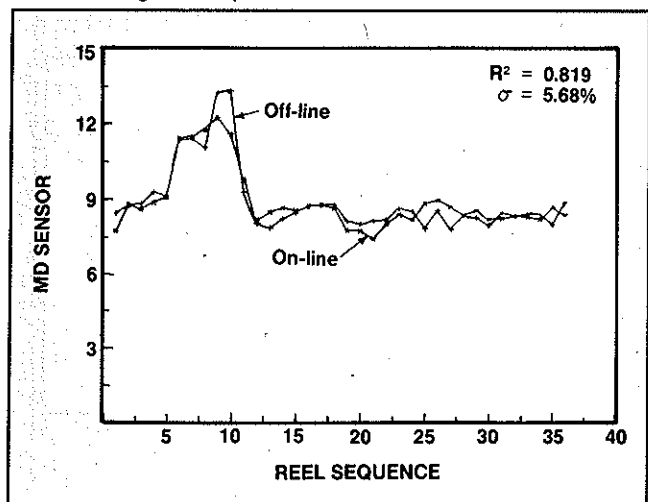
8. The theoretical total of strain plus tension components of sensor output compare closely to experimental results.



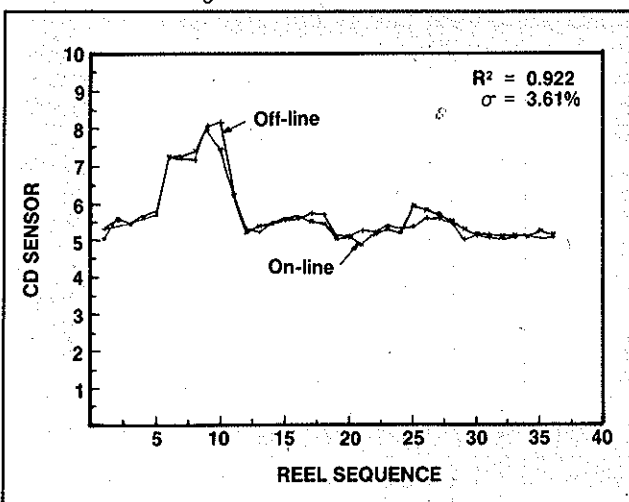
9. Extrapolating the sensor output vs. applied tension back to zero applied tension shows that the strain component is the same as theoretically predicted.



10. The on-line MD sensor output agrees closely with the off-line MD sensor readings on samples taken from the same reel.



11. The on-line CD sensor readings also agree closely with the off-line CD sensor readings.



a Chatillon tensile tester. Table III has a description of the samples used.

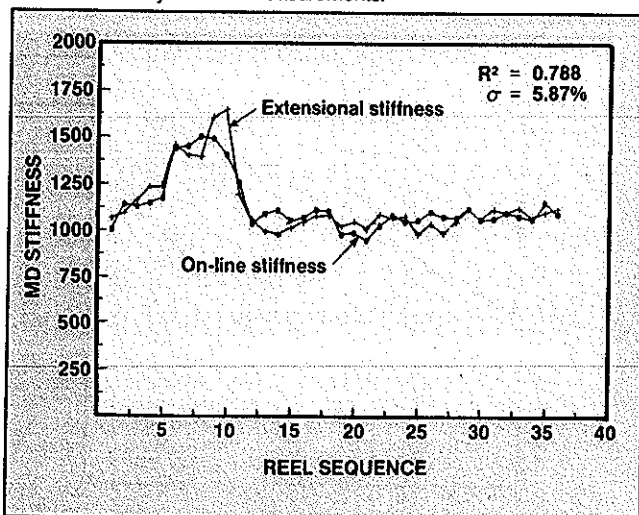
For the lab measurements, a device was built that holds a sample at a known tension and duplicates the on-line sensor. With this device, the sensor output can be measured for many different samples at various wheel displacements and at different applied tensions. This flexibility allowed us to test the theoretical model under a variety of controlled conditions.

Figure 8 shows theoretical and experimental results for 122-g/m² (25-lb/1000 ft²) linerboard. The plus signs represent the theoretical output resulting from applied tension. The squares show the theoretical output from strain. The diamonds are the total theoretical output, or the sum of tension plus strain outputs. The triangles showing laboratory sensor output indicate that the measured output is close to the theoretically calculated total output.

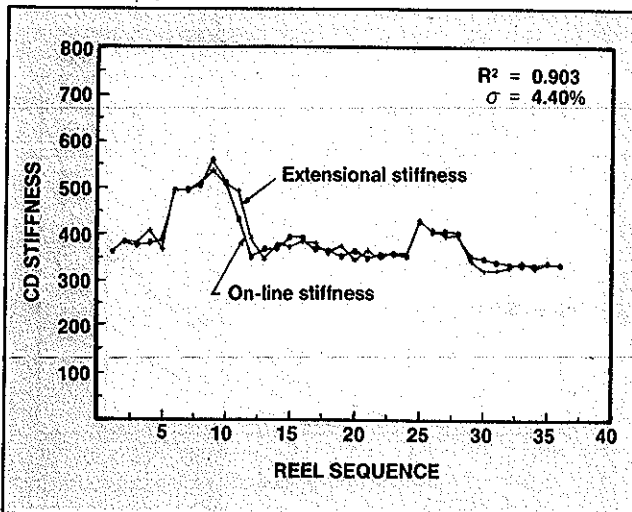
To determine how much the strain and tension components contribute individually to the total output, samples of the same paper were tested at different values of applied tension but only one value of z (3.5 mm). The results are shown in Fig. 9. By extrapolating the total output to zero applied tension, one can infer the strain contribution to be about 27 N. In Fig. 8, we see that the theoretically predicted strain contribution at 3.5 mm of z displacement is about 27 N. Thus, the theoretical model appears to be a good description of the sensor operation.

Results from the other samples are tabulated in Table III. These data show that the theory closely predicts the measured sensor output and is a good description of the sensor operation. Deviation between the theory and measurement indicates how well the sample conforms to the assumptions of the model. To obtain maximum accuracy, the deviations observed can be corrected by calibrating the sensor on each grade of paper.

12. The on-line sensor measurement of MD extensional stiffness correlates closely with lab measurements.



13. The on-line sensor measurement of CD extensional stiffness also correlates closely with lab measurements.



Appendix: large distortion effects

The assumption of elasticity implies that the stress-strain curve is a straight line. Under large distortions, beyond the normal operating range of the sensor, paper can exceed the elastic limit, and the stress-strain curve will be curved in this region. Equation 1 must then be modified to reflect the shape of the curve beyond the elastic limit.

After hundreds of tests, we have concluded that the slope of the stress-strain curve can be described by two regions. For strain less than a breakpoint value, S_b , the slope is a constant equal to Young's modulus.

$$\text{slope} = E(\theta) \text{ for } ds/dr < S_b \quad (A1)$$

For strains greater than S_b , the slope decreases exponentially:

$$\text{slope} = E(\theta) \times \exp[-k(ds/dr - S_b)] \text{ for } ds/dr > S_b \quad (A2)$$

where

- k = decay constant for the decreasing slope, approximately equal to 60, typically
- S_b = strain value at breakpoint, approximately equal to 0.005, typically.

The force is calculated by integrating the slope of the stress-strain curve from zero to the strain at the point on the wedge of membrane. For strain less than S_b , the results are the same as in Eq. 1:

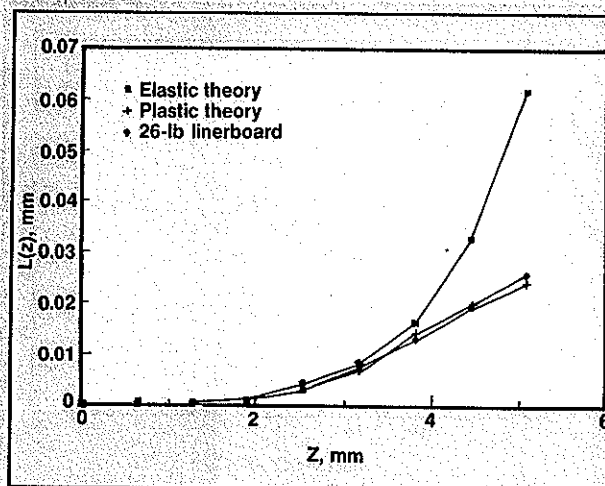
$$df(\theta) = E(\theta) \cdot r \cdot d(\theta) [ds(r, \theta)/dr] \text{ for } ds/dr < S_b \quad (A3)$$

For strain greater than S_b , there is a different result:

$$df(\theta) = E(\theta) \cdot r \cdot d(\theta) [ds(r, \theta)/dr] (S_b + 1 - \exp[-k(ds/dr - S_b)]/k) \text{ for } ds/dr > S_b \quad (A4)$$

Following the same method as before but using these starting equations, the new $L(z)$ function can be calculated for typical values of k and S_b . Results from tests on linerboard show that S_b is about 0.005 for both

14. By including plastic deformation in the calculations, the behavior of the sensor in the region beyond the normal operating range can be explained.



the machine and cross directions. The value for k is typically 60. Figure 14 shows $L(z)$ for $S_b = 0.005$ and $k = 0$ and 60. Over the normal operating range of sensor ($z < 4$ mm), there is little difference in the two curves. Above $z = 4$ mm, the curve for $k = 60$ shows a lower value of $L(z)$.

Off-line measurements compared to on-line measurements

To verify that the results obtained by the lab testing could also be obtained on-line, tests were conducted in which an on-line sensor was compared directly with the off-line sensor. For this series of tests, scan average readings from an on-line sensor on a linerboard machine were taken just before reel turnup. Samples were cut from the reel and were tested on the offline sensor.

This sampling method is the usual method employed for dynamic verification on paper machines. However, the method does have the difficulty that the samples cut for lab testing are not exactly the same parts of the web measured by the on-line sensor. Thus MD variations in the paper machine may show up as discrepancies between the on-line and lab results.

Thirty-six reels of sample and data were collected. All were 26-lb/1000 ft² linerboard except Reels 6-8, which were 38 lb/1000 ft² and Reels 9 and 10, which were 42 lb/1000 ft². Figure 10 compares the on-line results to lab sensor results for the machine direction, and Fig. 11 compares these results for the cross direction.

Results indicate good agreement between the on-line readings and the off-line sensor readings for both machine and cross directions. The one standard deviation of 5.7% with $r^2 = 0.819$ for the machine direction and of 3.6% with $r^2 = 0.922$ for the cross direction is typical for dynamic strength testing.

We also compared on-line sensor readings to extensional stiffness as measured on a laboratory tensile tester. These results gave one standard deviation of 5.9% and $r^2 = 0.788$ for the machine direction, as Fig. 12 shows. The standard deviation was 4.4% with $r^2 = 0.903$ for the cross direction, as shown in Fig. 13. The agreement between the on-line sensor readings and the independent determination of extensional stiffness validates the on-line measurement. □

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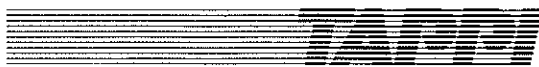
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