

A biaxial web tension transducer

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ABSTRACT *A transducer has been developed to measure the web tension in both the machine and cross-machine directions simultaneously. The instrument also measures tension in a localized area on the web, as opposed to an average tension over a large area. It measures tension by contacting the web but without inducing additional tension. The transducer senses the tension in the web and produces a series of light and dark optical patterns that can be correlated to tension. It is capable of measuring biaxial tension to within 0.5 lb/in., and it could be adapted for industrial use.*

KEYWORDS

Instrumentation
Optical
instruments
Process control
Rolls
Runnability
Transducers
Webs

In the paper industry, increases in web tension can lead to excessive tension bursts and can decrease runnability (1, 2). In the film industry, tension must be carefully controlled to avoid bagging and slack edges. In both the paper and film industries, it is difficult to produce a web with uniform caliper. Local yielding or bursts can occur as a result of nonuniform tension distribution on the web.

Once the tension in a web is known, however, it can be used to calculate the stresses. The stresses in the web are a function of the tension and the web geometry (primarily thickness). If the web's stresses are known, failures can be prevented. The knowledge of these stresses can also be used to predict strain and elongation if the modulus of elasticity is known. The calculations for stresses, strains, and elongations are straightforward, but accuracy depends on having reliable values for tension.

There are many circumstances in which an average tension measurement from rolls mounted on load cells can be unacceptable. Not only does nonuniform caliper lead to nonuni-

form machine-direction (MD) tensions across the web width, but web-spreading devices such as curved-axis rolls and concave rolls also induce nonuniform web tensions in both the machine direction and the cross-machine direction (CD).

Therefore, we have developed a transducer that can make local measurements of the MD and CD tension. We used this transducer to study the stresses induced in a web by a curved-axis roll.

Design criteria

The web tension transducer meets the following design criteria:

1. It can measure tension in both the machine and cross-machine directions with reasonable accuracy.
2. It can measure tension in a localized area on the web, as opposed to an average tension over a large area.
3. It measures the tension by physically contacting the web, but it does not induce additional ten-

sion into the web.

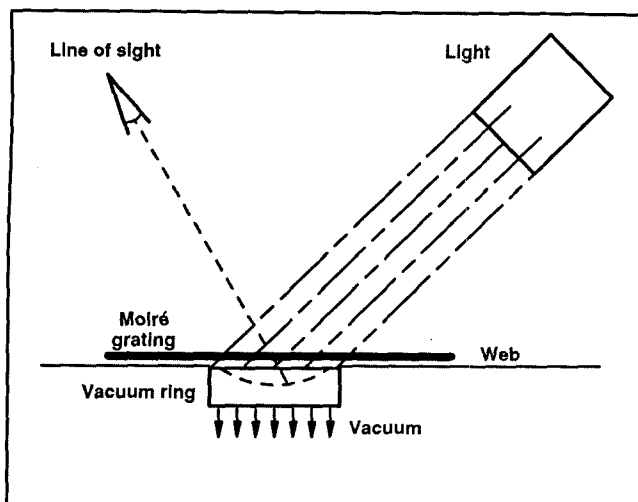
There are several web tension transducers that are commercially produced, some of which can make local measurements of MD tension by either spring deflection or sonic techniques (3-7). The ability to measure in both the MD and CD directions makes this tension transducer unique.

Operating principle

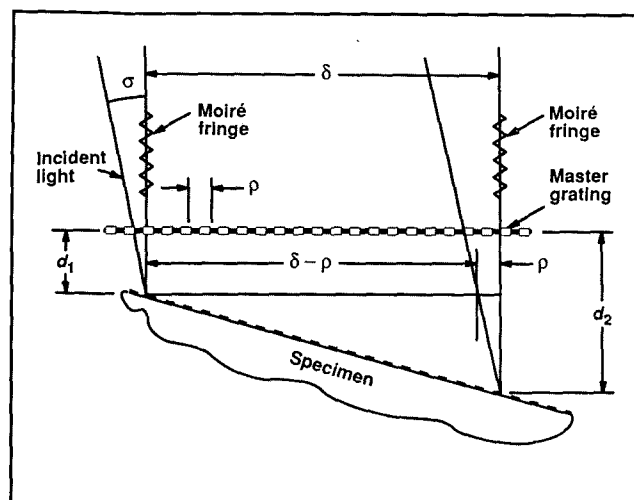
The transducer senses the tension in the web and produces a series of light and dark optical patterns that can be correlated to tension. The transducer first forces an out-of-plane deflection into the web using a vacuum source. This vacuum is applied to the web through a circular ring. The amount of deflection caused by the vacuum can be used to closely approximate the maximum tension, whether it is in the machine direction or cross-machine direction. (Here, the tension will always be assumed to be greater in the machine direction.)

The CD tension is then found by forcing a predetermined point dis-

1. Transducer setup



2. Definition of variables in the moiré method



placement into the web through a circular ring. The MP and CD tension causes differing out-of-plane web deformations in the machine and cross-machine directions inside the circular ring.

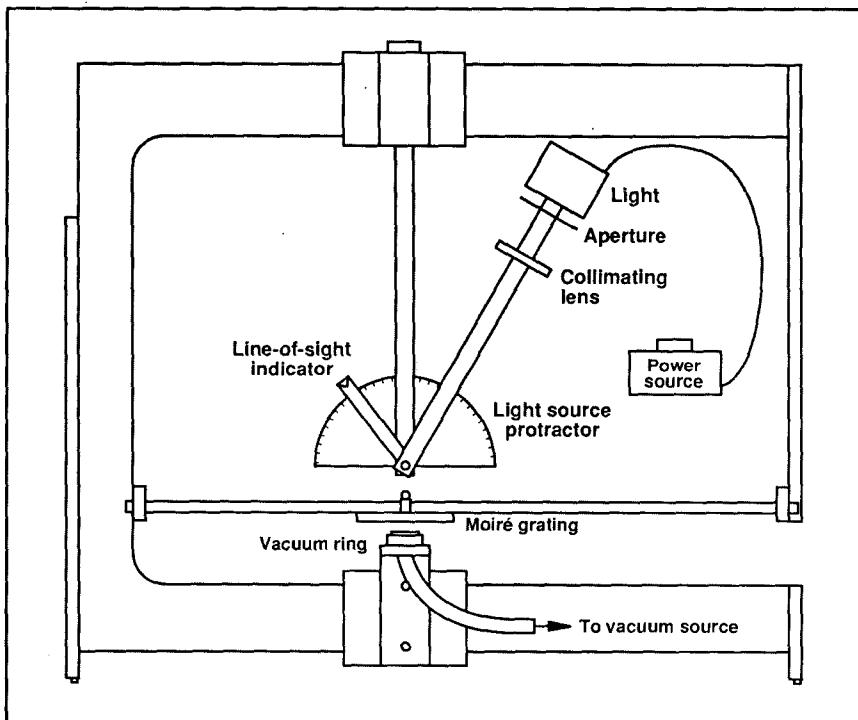
The deflections caused by the vacuum ring and point displacement are both measured using an optical method known as the moiré fringe technique. This technique makes it possible to measure the whole field of the out-of-plane deformation of the web. The procedure produces optical interference fringe patterns that directly correspond to deflection. These deflections are then correlated to the tension in both the machine and cross-machine directions.

The major components of the transducer

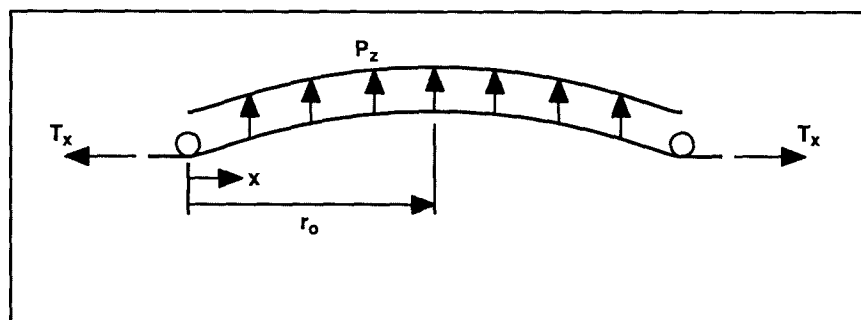
Figure 1 is a simplified sketch of how the transducer works. The purpose of the vacuum ring is to impart a uniform pressure on the web inside a circular boundary condition. Accordingly, the ring is designed to apply a uniform and symmetrical support for the web. In addition, the edges on the boundary were polished to minimize the drag between the web and ring.

Three different vacuum rings were designed to allow us to select the optimum size for different web materials. The rings tested were 1 in., 1.5 in., and 2 in. in diameter. Overall, for the working tension range of 0.5–5 lb/in., the 1-in. ring performed best for the various materials used in our tests. The 1-in. ring also worked well for measuring tension in small localized

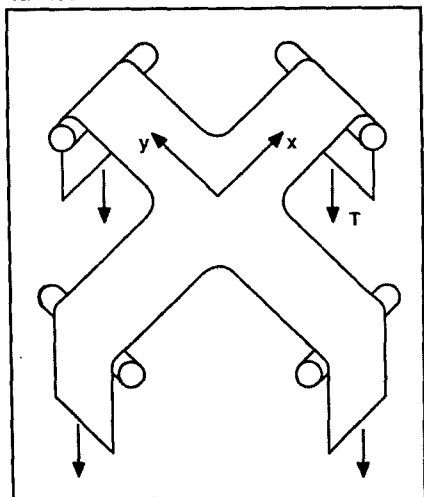
3. Diagram of the transducer



4. A web modeled as a catenary passing over a vacuum ring



5. Static test fixture used for transducer calibration



areas.

The vacuum is supplied to the ring from a controlled source. The vacuum source consists of a pump that builds vacuum in a reservoir. This reservoir supplies a precise vacuum to the ring by using a needle valve as a regulator. The vacuum is monitored using a mercury manometer that accurately reads the vacuum in the range in which the transducer is used. The manometer is located close to the ring so as to provide the best measurement of the vacuum where the web and ring contact. The leakage between the web and ring is minimal, so another needle valve near the regulating valve is used as a bleed to maintain flow in the system.

The purpose of the displacement rod and circular boundary plate is to force a predetermined displacement into the web through a circular hole. The rod is made from a standard micrometer caliper that is accurate to 0.0005 in. The spindle is ground to a hemispherical shape and polished, to provide the most uniform displacement while minimizing drag or friction. The circular boundary plate is made from a thin plate with a circular hole. The hole acts as a circular boundary. The enforced displacement is located at the center of the hole. Three different sizes of holes were used — 0.5 in., 0.75 in., and 1 in. The 1-in. hole provided the best resolution of tension without buckling the web for the range of materials and tensions studied.

The deflection measurement is performed using the moiré fringe technique. The method is based on

shining light from a collimated light source through a moiré grating onto the deflected surface. The moiré grating is a sheet of glass with small parallel lines on the surface. The grating used on this transducer has 200 lines per inch. As the collimated light passes through the grating and onto the deflected surface, it will cast shadows for each grating line.

As the observer views the deflected surface through the grating, a series of fringe patterns or dark bands will be seen if the grating and deflected surface are not parallel. Each dark band represents a relative displacement from a reference datum. In Fig. 2, the fundamental variables of the moiré method for out-of-plane displacements are defined. The following equation from Dally (8) is used to calculate the out-of-plane displacement with reference to a datum:

$$w = np/\tan \gamma \quad (1)$$

where

- w = out-of-plane displacement ($d_2 - d_1$)
- n = order of moiré fringe at the point
- p = pitch of the master grating
- γ = angle of incidence of the collimated light.

The light source is a projector bulb with an aperture followed by a collimating lens. A variable voltage power source is used for varying the light intensity. The light intensity and the angle of incidence were adjusted for various web materials such that the reflected glare was reduced, making the fringes easier to view and record. A camcorder was used to observe and record the fringe patterns. A diagram of the transducer is shown in Fig. 3.

Theory of operation

Vacuum ring arrangement

The theoretical analysis of the web passing over the vacuum ring is analogous to a catenary under tension subjected to a normal pressure, as shown in Fig. 4. The governing differential equation for this type of problem is given by Rivello (9) as:

$$d^2w/dx^2 = -P_z/T_x \quad (2)$$

where

- w = out-of-plane deflection of the web

P_z = pressure exerted perpendicular to the plane defined by the machine and cross-machine directions

T_x = tension in the direction of the major axis.

Equation 2 is a second-order differential equation that requires two boundary conditions for solution. The boundary conditions for this problem are (a) a known zero out-of-plane deflection of the web at the ring boundary and (b) that the slope of the web at the center of the ring must be zero. Mathematically, we can state the boundary conditions as follows.

For Condition A:

$$w(0) = 0$$

For Condition B:

$$dw/dx (r_0) = 0$$

Rearranging Eq. 2 and integrating yields:

$$dw/dx + (P_z/T_x)x + C_1 = 0 \quad (3)$$

Substituting Boundary Condition B yields the value of the constant of integration C_1 as:

$$C_1 = -(P_z/T_x)r_0 \quad (4)$$

and substituting C_1 into Eq. 3 yields:

$$(dw/dx) + (P_z/T_x)x - (P_z/T_x)r_0 = 0 \quad (5)$$

Integrating Eq. 5 yields:

$$w + (P_z/2T_x)x^2 - (P_z/T_x)r_0x + C_2 = 0 \quad (6)$$

Substituting Boundary Condition A will determine that C_2 is zero. Thus, the final equation for the deflection of the catenary is:

$$w = (P_z/2T_x)x^2 + (P_z/T_x)r_0x \quad (7)$$

The deflection of the web at the center of the ring will be:

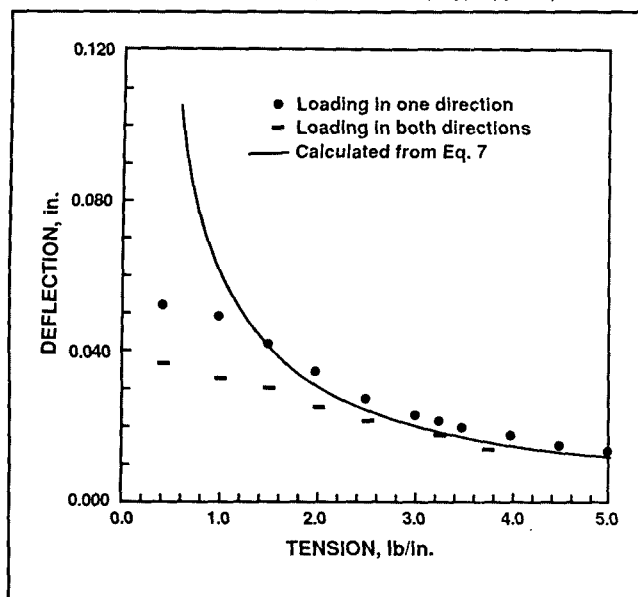
$$w(r_0) = (P_z r_0^2)/2T_x \quad (8)$$

To derive this equation, we made the initial assumption that the web could be analyzed as a catenary. The validity of this assumption is assessed in the section on experimental results.

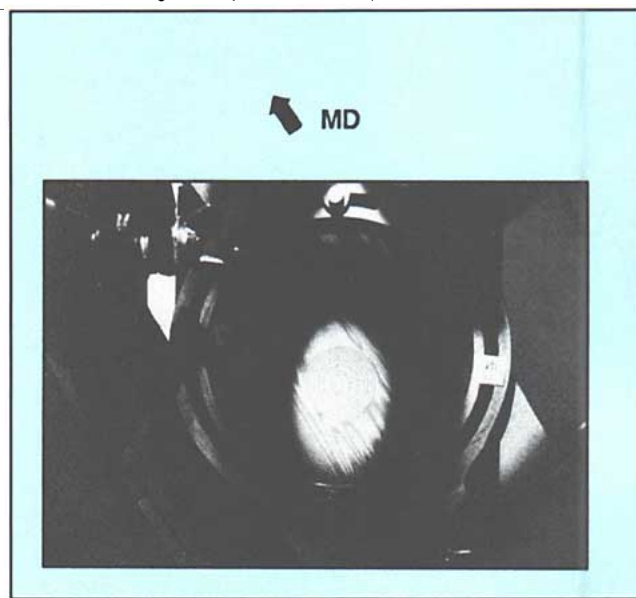
Enforced deformation arrangement

The enforced deformation arrangement is much more difficult to analyze than the vacuum ring arrangement.

6. Comparison of web deflections for uniaxial and biaxial loading with theoretical solution (1-in. ring, 0.5 psi vacuum, polypropylene)



7. Concentric circular moiré fringes for a MD tension of 2.5 lb/in. using a 1-in. vacuum ring with a pressure of 0.5 psi



1. Deflection data for the vacuum ring

Y-direction tension, lb/in.	Tension in the x direction, lb/in.								
	0.42	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50
0.00	... ^a	0.0338	0.0300	0.0288	0.0275	0.0262	0.0250	0.0238	0.0225
0.42	0.0325	0.0300	0.0288	0.0275	0.0262	0.0262	0.0250	0.0238	0.0225
1.00		0.0288	0.0275	0.0262	0.0262	0.0250	0.0238	0.0225	0.0225
1.50			0.0262	0.0250	0.0250	0.0238	0.0225	0.0225	0.0225
2.00				0.0250	0.0238	0.0225	0.0225	0.0225	0.0212
2.50					0.0225	...	0.0212	0.0212	0.0200
3.00						...	0.0212	0.0200	0.0188
3.50							0.0200	0.0188	0.0188
4.00								...	0.0175
4.50									0.0175

^aThe web buckled. 1 fringe = 0.005 in.

Ring diameter = 1 in. Vacuum = 1.0 psi. Static crucifix. 4 in. wide.

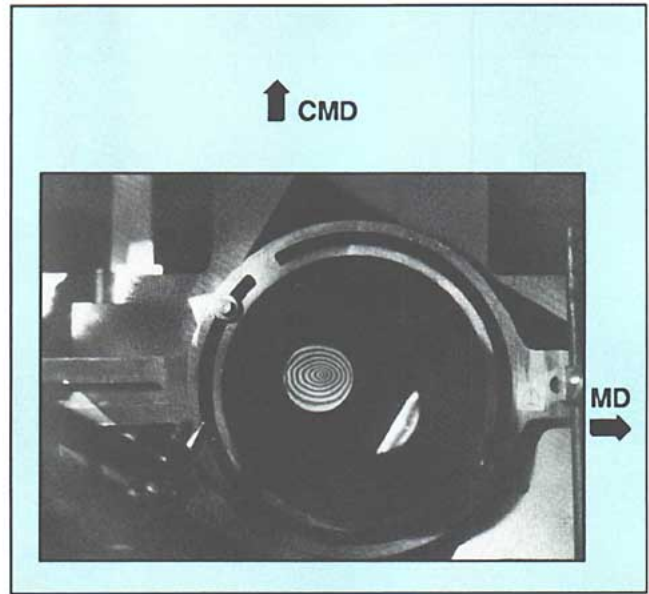
Clear polyester (1.2 mil). Surface painted white. Line of sight = 0.0 degrees.

Light source = 45°.

8. Concentric circular moiré fringes for an MD tension of 2.5 lb/in. and a CD tension of 2.5 lb/in. with an enforced deflection of 0.038 in.



9. Concentric elliptical moiré fringes for an MD tension of 2.5 lb/in. and CD tension of 0.0 lb/in. with an enforced deflection of 0.038 in.



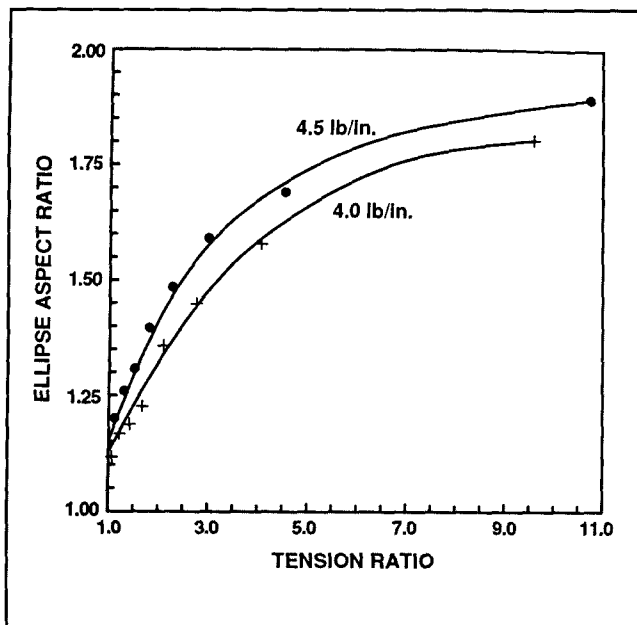
II. Ellipse aspect ratio and tension ratio data

Y-direction tension, lb/in.	Ratio	Tension in the x direction, lb/in.								
		0.42	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50
0.00	Aspect	... ^a	1.32	1.43	1.53	1.61	1.69	1.75	1.87	1.98
	Tension	...	...	...	...	...	...	...	...	...
0.42	Aspect	1.01	1.23	1.29	1.42	1.51	1.65	1.71	1.80	1.89
	Tension	1.00	2.38	3.57	4.76	5.95	7.14	8.33	9.52	10.7
1.00	Aspect		1.10	1.19	1.24	1.33	1.45	1.50	1.58	1.69
	Tension		1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50
1.50	Aspect			1.10	1.16	1.24	1.32	1.37	1.45	1.59
	Tension			1.00	1.33	1.67	2.00	2.33	2.67	3.00
2.00	Aspect				1.10	1.16	1.22	1.29	1.36	1.49
	Tension				1.00	1.25	1.50	1.75	2.00	2.25
2.50	Aspect					1.10	...	1.21	1.23	1.40
	Tension					1.00	...	1.40	1.60	1.80
3.00	Aspect						...	1.17	1.19	1.31
	Tension						...	1.17	1.33	1.50
3.50	Aspect							1.11	1.17	1.26
	Tension							1.00	1.14	1.28
4.00	Aspect								1.12	1.20
	Tension								1.00	1.12
4.50	Aspect									1.16
	Tension									1.00

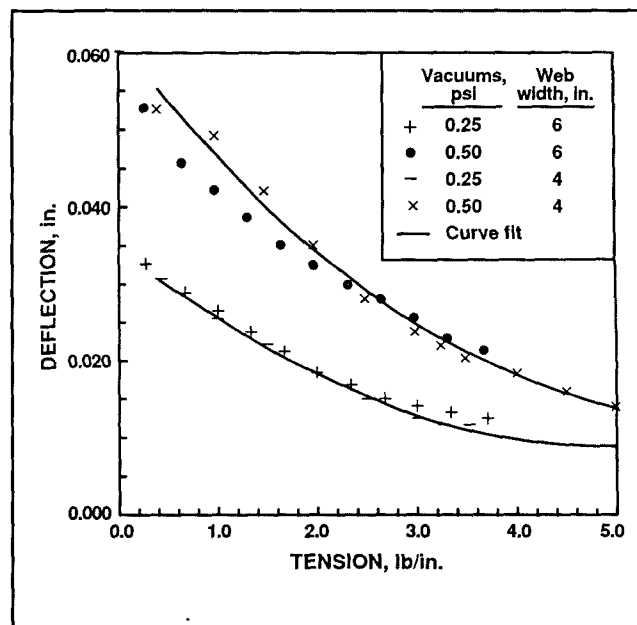
^aThe web buckled.

Ring diameter = 1 in. Deflection = 0.038 in. Static crucifix, 4 in. wide, 0.020 in. from top (4th fringe). Clear polyester web. Surface painted white. Line of sight = 0.0 degrees. Light source = 45°.

10. Ellipse aspect ratio vs. tension ratio for x-direction tensions of 4 and 4.5 lb/in.



11. The effect of web width on measured web deflections (1-in. ring, various vacuums, various web widths, polypropylene)



The moiré fringe patterns are elliptical and are a function of the ratio of MD to CD tension and the bending stiffness of the web, even though this ratio is small. An analytical solution of this problem requires the solution of the von Karman differential equations for large deflections of plates simplified for membrane analyses (10).

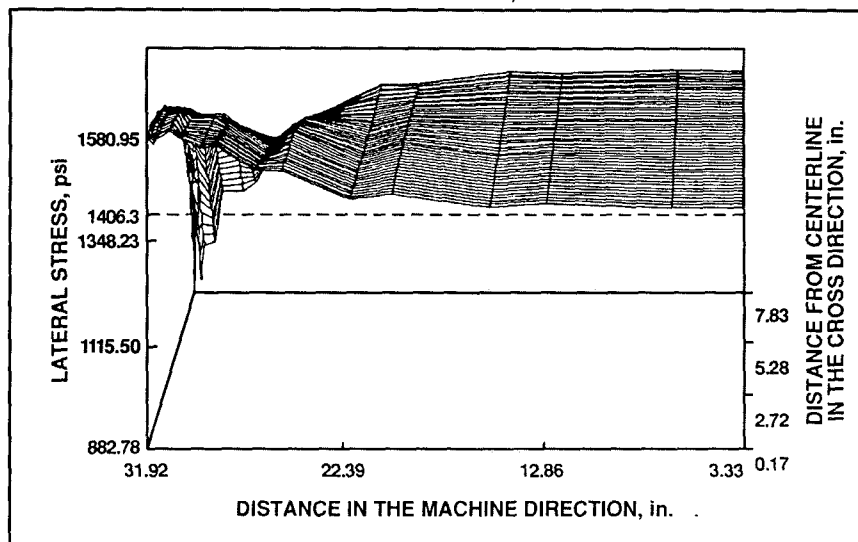
Exact solutions of these equations are cumbersome and have been achieved only for a very few cases. For the case at hand, in which there are enforced displacements and the tension varies depending on direction, no exact solution exists. Either finite difference or finite element techniques must be employed to obtain discrete solutions. Since these approximate solutions are case-dependent and would not lend themselves to the understanding of the physics of this tension transducer, no such analyses will be presented here.

Experimental results

Static condition

Two different types of web material have been used in testing the transducer. Both polyester and polypropylene have been tested with different web widths and calipers. Webs were cut to a crucifix shape, as shown in Fig. 5, such that a tension could be

13. Theoretical MD stress levels in a web prior to the entry of a curved-axis roll (Web thickness = 0.020 in. Web width = 16 in. Coefficient of friction = 0.35. Roller radius = 1.0 in. Web tension = 450 lb. Roller arc radius = 1000 in. Roller width = 18 in.)



applied in both *X* and *Y* directions to a test coupon.

Testing shows that for most webs the maximum deflection for the vacuum ring is primarily a function of the maximum tension from either the machine direction or cross-machine direction. Figure 6 is a plot comparing deflections for which there is loading in one direction to deflections for which there is equal loading in both directions. The theoretical deflections calculated using Eq. 7 are

shown as well. The agreement is excellent above tensions of 2 pli, indicating that the effects of bending stiffness must be accounted for at lower tensions. Nevertheless, the empirical data shown in Fig. 6 represent valid calibration curves for deflection and tension regardless of the theoretical solution.

In Table I are web deflections calculated for the vacuum ring under various loading conditions. The data show that once a load is applied in one

III. Fringe data and MD tensions for the curved axis roller

Place in web, in.	Bow plane parallel to web		Bow plane 45° to the web	
	No. of fringes	Tension, lb/in.	No. of fringes	Tension, lb/in.
0.5	7.00	0.40	7.25	0.80
1.5	6.25	1.33	6.25	1.33
2.5	6.00	1.50	6.00	1.50
3.5	6.00	1.50	5.75	2.00
4.5	6.00	1.50	5.50	2.50
5.5	5.75	2.00	5.50	2.50
6.5	5.50	2.50	5.50	2.50
7.5	5.50	2.50	5.50	2.50
8.5	5.50	2.50	5.50	2.50
9.5	5.50	2.50	5.50	2.50
10.5	5.50	2.50	5.50	2.50
11.5	5.50	2.50	5.50	2.50
12.5	5.25	3.00	5.50	2.50
13.5	5.25	3.00	5.50	2.50
14.5	5.25	3.00	5.75	2.00
15.5	5.25	3.00	5.75	2.00
16.5	5.50	2.50	5.75	2.00
17.5	5.50	2.50	5.75	2.00
18.5	5.75	2.00	5.75	2.00
19.5	5.75	2.00	5.75	2.00
20.5	5.75	2.00	6.00	1.50
21.5	6.25	1.33	6.25	1.33
22.5	6.50	1.20	6.25	1.33
23.5	7.00	0.90	6.50	1.20
24.5	7.50	0.40	6.75	1.00
25.5	8.00	0.00	7.25	0.80

Ring = 1 in. in diameter. Vacuum = 1 psi. Total tension = 52 lb. Web = 26 in. wide. Roller diameter = 3.5 in. Roller arc radius = 500 in. Clear polyester (1.2 mil). Surface painted white. Line of sight = 0.0 degrees. Light source = 45° and 7.5 in. from roller axis. Web wraps roll at 90° angle to radius.

IV. Ellipse data and lateral tensions for the curved axis roller

Place in web, in.	Bow plane parallel to web		Bow plane 45° to the web	
	Aspect ratio	Tension, ^a lb/in.	Aspect ratio	Tension, ^a lb/in.
0.5	... ^b	0.00	2.00	0.00
1.5	1.07	0.20		
2.5	1.15	0.20	1.56	0.00
3.5	1.25	0.20		
4.5	1.36	0.20	1.56	0.40
5.5	1.50	0.20		
6.5	1.50	0.40	1.44	0.75
7.5	1.50	0.40		
8.5	1.67	0.40	1.44	0.75
9.5	1.67	0.40		
10.5	1.67	0.40	1.44	0.75
11.5	1.67	0.40		
12.5	1.67	0.40	1.44	0.75
13.5	1.67	0.40	1.44	0.75
14.5	1.67	0.40		
15.5	1.67	0.40	1.44	0.40
16.5	1.50	0.40		
17.5	1.50	0.40	1.44	0.40
18.5	1.50	0.20		
19.5	1.50	0.20	1.44	0.40
20.5	1.36	0.20		
21.5	1.25	0.20	1.56	0.00
22.5	1.15	0.20		
23.5	1.07	0.00	1.56	0.00
24.5	1.00	0.00		
25.5	... ^b	0.00	2.00	0.00

^aThe tensions here are approximate due to difficulty in calibrating the transducer at such low lateral tensions.
^bThe web buckled.

Ring diameter = 1 in. Deflection = 0.038 in. Total tension = 52 lb. Web = 26 in. wide. Roller diameter = 3.5 in. Roller arc radius = 500 in. Clear polyester (1.4 mil). Surface painted white. Line of sight = 0.0 degrees. Light source = 45° and 7.5 in. from roller axis. Web wraps roll at 90° angle to radius.

direction, small loads applied in the other direction have little effect on the deflection until they approach the magnitude of the original load, which is rarely the case. The fringe patterns for the vacuum ring arrangement were always concentric circles, a representative sample of which is shown in Fig. 7.

The fringe patterns for the enforced displacement vary from concentric circles, as shown in Fig. 8, to concentric ellipses, as shown in Fig. 9. The

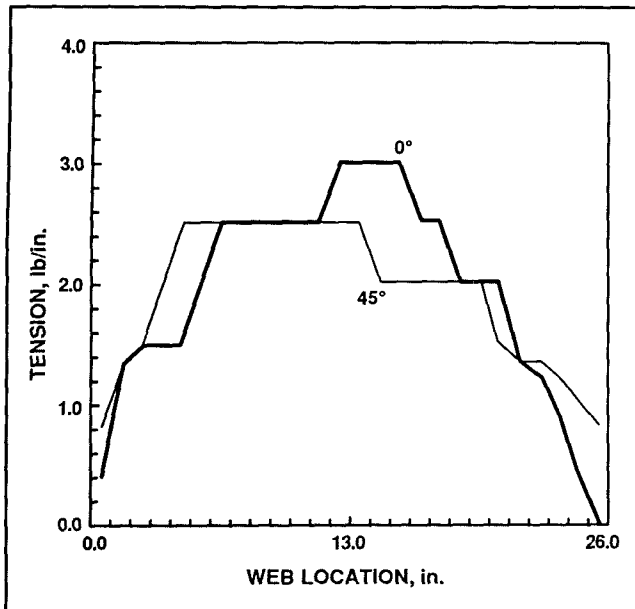
fringe patterns are circles if the tensions are the same in both directions. If the tensions in the two directions differ, ellipses are formed. The shape of these ellipses is directly related to the tension in each direction.

If the tension in one direction is known, the ellipse dimensions from the forced displacement can be used to determine the tension in the other direction by one of two methods developed. One method is to use a

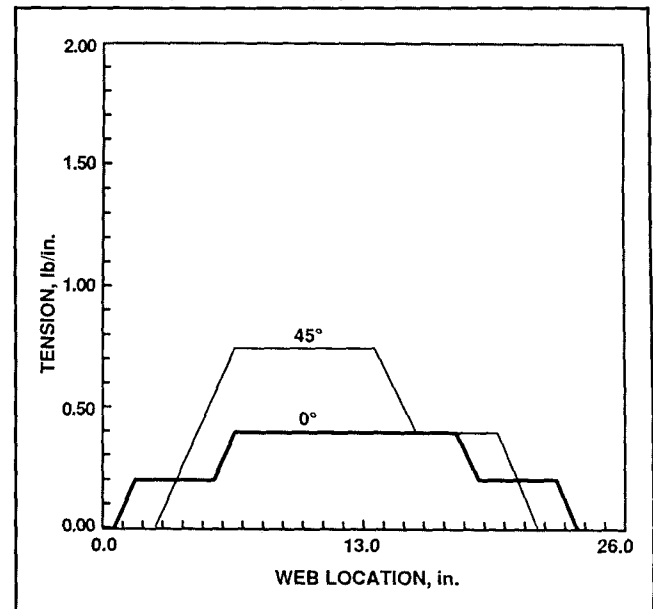
table of ellipse dimensions for various loading conditions. The other is to use plots of the aspect ratios of the ellipses versus a ratio of the tensions in the two directions. The aspect ratios are calculated by dividing the major axis dimension by the minor axis dimension. Table II gives the aspect ratio and tension ratio values for a forced displacement. Figure 10 is a sample plot of aspect ratio versus tension ratio for the data given in Table II.

The accuracy of measuring biaxial

12. MD tension measured in a web prior to the entry of a curved-axis roll (Web thickness = 0.0014 in. Web width = 26 in. Roller diameter = 3.5 in. Web tension = 52 lb. Roller arc radius = 500 in. Roller width = 40 in. Web composition = clear polyester.)



14. CD tension measured in a web prior to the entry of a curved-axis roll (Web thickness = 0.0014 in. Web width = 26 in. Roller diameter = 3.5 in. Web tension = 52 lb. Roller arc radius = 500 in. Roller width = 40 in. Web composition = clear polyester.)



tensions can be increased by using a table of deflections for various loading conditions for the vacuum ring. This table and the ellipse tables will result in better predictions than will result if we assume that all tension is in one direction with the vacuum ring and obtain the other direction from just the ellipse data.

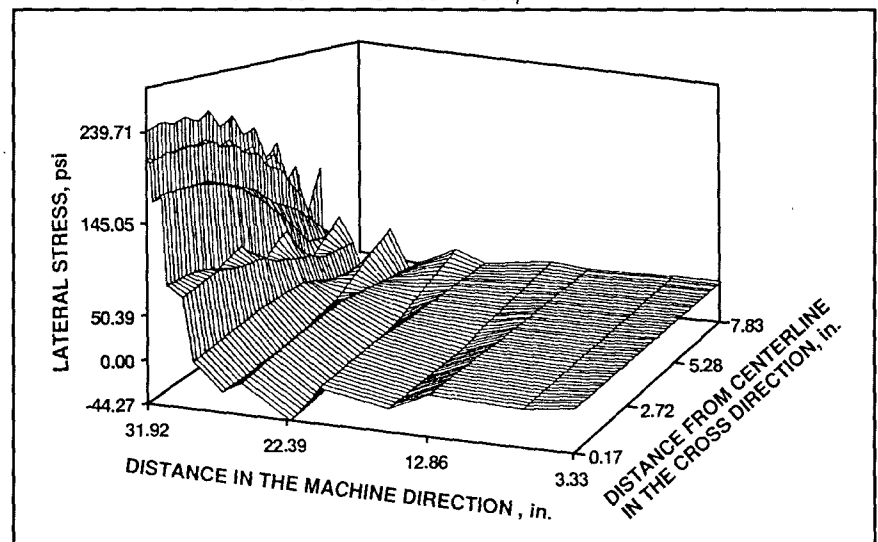
The width of the web appears to have minimal effect on the vacuum ring deflection. Figure 11 is a plot of the various deflections for webs of different widths.

With the current setup, the best resolution that can be obtained for measuring deflections is approximately 0.001 in. This measurement is with the light source set at an angle of 45° from the vertical and the line of sight set at 22.5° from the vertical. If these angles are increased, the resolution increases. For this resolution, we also assume that the fringes can be interpolated to 1/4 of a fringe.

Dynamic condition

The transducer was used to measure the variation in tension across the width of a curved axis roller. The roller used was a Fife Spread Master® with a diameter of 3.5 in. and a radius of curvature of 500 in. Testing verifies that a curved axis roller causes the MD tension to increase in the center of the web and to decrease towards the

15. Theoretical CD stress levels in a web prior to the entry of a curved-axis roll (Web thickness = 0.020 in. Web width = 16 in. Coefficient of friction = 0.35. Roller radius = 1.0 in. Web tension = 450 lb. Roller arc radius = 1000 in. Roller width = 18 in.)



edges. The testing was done with the curved axis roller set in two different positions. In the first position, the bow plane is parallel to the incoming web. In the second position, the bow plane is set at a 45° angle below the incoming web.

Figure 12 shows how the tension in the machine direction varies across the width of the web for each of the two positions of the curved axis roller. Table III gives the actual tension values across the web for both of the

roller positions. Figure 13 shows a plot of theoretical MD stresses and how they vary across the web width. The theoretical stresses were computed by a finite element code that was developed to incorporate the dynamic boundary conditions of a curved axis roll (11). These stresses are for a different roller and web material, but they can be used to see that, qualitatively, the basic behavior is the same.

The dynamic testing showed that

the vacuum ring induced minimal drag upon the web. This means that accurate measurement of the web tension can be made. The testing done with the enforced displacement rod verified that the curved axis roller causes the CD tension to increase in the center of the web and decrease toward the edges. **Figure 14** shows how the CD tension varies across the width of the web for each of the two positions of the curved axis roller. **Table IV** gives the CD tension values for both of the roller positions. Due to the difficulty in calibrating the transducer at such low CD tensions, these values are approximate.

Figure 15 shows a plot of theoretical CD stresses and how they vary across the web width for the same conditions that resulted in the MD stresses shown in Fig. 13. Again, these stresses are for a different roller and web material, but they can be used to see that the basic behavior is the same.

Conclusions

The web biaxial tension transducer meets the design criterion and is the first transducer we are aware of that can measure both the MD and CD tension. This transducer is capable of measuring biaxial tension to within 0.5 lb/in. This resolution is adequate for many applications. The transducer can be used to measure uniaxial tension with resolution better than 0.5 lb/in. if there is no CD tension and if accurate calibrating techniques are used.

For example, the resolution could be increased to 0.2 lb/in. if a moiré grating with a pitch of 2000 lines/in. were used. Even greater resolutions are possible if other means of measuring either the web slope or deformation were employed. Fiber optic or laser reflection techniques would achieve this end, but various webs will have varying reflectivities, making calibration more difficult. Ultrasonic techniques would not be affected by reflectivity if adequate sensitivity could be obtained. With proper development, this transducer could be adapted for industrial use. □

Literature cited

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