DIFFERENTIALLY DRIVEN S-WRAP ROLLS FOR IMPROVED TENSION ISOLATION

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ABSTRACT

Achieving adequate tension isolation is necessary in both the manufacture and subsequent processing of webs of all types. Several techniques currently are available including nips, vacuum rolls, driven rolls and S-wraps. From a combination of low cost and simplicity, S-wraps are the attractive alternative. They also are the best choice if the web is susceptible to surface damage. However, current S-wraps have deficiencies which are related to (1) torque loadings on the roll pair, and (2) problems controlling the web tension between the two rolls. These deficiencies can make it difficult to achieve good tension isolation. The differentially driven S-wrap system described here eliminates these problems and offers additional benefits. It provides a means to control the torque split between the driven rolls. This split makes it possible to shift the torque to the high tension side of the S-wrap where the available friction forces are higher. It also fixes the tension between the driven rolls without additional equipment. Finally, the differential action allows the rolls to operate at different speeds to adjust for differences in the roll diameters or web elongation.

NOMENCLATURE

b	Web width
E	Elastic modulus of web
f	Friction coefficient
F	Safety factor defined by equation
G	Shear modulus of elastomeric cover
K	Centrifugal force web loading $= \rho b t v^2 / g_o$
P_a	Entrained air pressure term $= p_a$ (air pressure) $b\,r$
Q	Surface to web stiffness ratio $= [G\, r^2\, \theta_W^2 / t\, \tau\, E]^{1/2}$
r	Radius of various rolls
s	Dimension along roll surface

S	Torque split to S-wrap rolls
t	Thickness of web
T	Web tension
$\boldsymbol{T}$	Normalized web tension = $(T - T_i) / (T_o - T_i)$
u	Normalized dimension along roll surface = $s / r\theta_W$
v	Web velocity
ε	Strain
θ_S	Angle where tension changes on a roll or micro-slip angle
θ_W	Wrap angle for the web on a roll
τ	Thickness of elastomeric cover
υ	Integration variable for u
ω	Angular velocity of roll

Subscripts

i	Web conditions entering a roll or S-wrapped pair of rolls
0	Web conditions at the exit of a roll or S-wrapped pair of rolls
m	Web conditions between an S-wrapped pair
1 or 2	Denotes first or second roll in an S-wrap

INTRODUCTION

There are three commonly used tension isolation devices in web handling processes. They are (1) vacuum rolls, (2) nip rolls and (3) S-wraps (see Figures 1 and 2). Vacuum rolls employ a mesh or some other porous surface and the vacuum pulls air into the roll. The negative pressure or partial vacuum holds the film firmly to the surface. By adjusting the internal pressure and selecting a good porous surface, a robust tension isolation system can be achieved. The only drawbacks to vacuum rolls are (1) the porous surface is subject to damage and (2) they are in general more costly than other approaches. Nip rolls are a pair of rolls, one with a smooth metal surface and the other with an elastomeric surface. The film passes through the nip formed by pressing these rolls together. A well designed nip roll is an effective means of isolating tension. It can damage the film, however, and it is not recommended for thin or delicate films. The roll with the elastomeric surface should be crowned to provide uniform contact pressure and the resulting roll pair is a high maintenance item.

The simplest approach is the S-wrap. Here, two driven rolls are placed in close proximity in such a manner as to maximize the wrap angle on both rolls (see Figure 2). The friction introduced by the web tension is used to isolate the tension across the roll pair. Elastomeric covered rolls are preferable for this application due to their naturally high friction. The primary advantage to this approach is that it is relatively inexpensive. The primary disadvantages are (1) limited tension isolation capability and (2) operational problems due to mismatched roll pairs.

S-wraps with elastomeric covered rolls pose particular problems. Elastomeric rolls can be ground to very uniform diameters across the roll width. Unfortunately, grinding to achieve a specific roll diameter with a tight tolerance is very difficult. Differences in the roll diameters in an S-wrap can cause serious problems and elastomeric rolls used in this application should be reground in pairs to minimize this problem. We will discuss the reason for this problem and explain why a differentially driven S-wrap eliminates this issue for all types of roll surfaces.

All types of tension isolation require that a change in the web tension occur within the bounds of the device. In these devices, the web must either elongate or retract when in contact with a roll surface to adjust for changes in the tension induced strain. This results in micro-slip between the film and a roll surface due to changes in the web length. Elastomeric rolls used as S-wraps or single driven rolls can be designed not to have this type of micro-slip.

We will present a means of designing a robust S-wrap system. It uses a differential drive system where the torque split has been adjusted to reflect the tension level on the up and down stream rolls. We also will present modified belt relationships for elastomeric covered rolls for the design of totally slip-free operation. A variety of potential applications for this approach will be presented.

THE IDEAL S-WRAP

A typical S-wrap is shown in Figure 2. Here, we are going to assume that there is no gross slip over any portion of the rolls and that they have identical surface speeds (the exact same diameter and a precision drive system). We also are going to consider a hard roll surface (high shear modulus as will be discussed later). The S-wrap will be operated in a tension increase mode. The tension rise will be increased from a modest value to the maximum achievable using these rolls. For a small tension rise, the relationship governing the tension is

$$\theta_{S2} = (1/f) \quad \mathrm{Ln}\{(T_0 - K - P_a)/(T_i - K - P_a)\} \tag{1}$$

where θ_{S2} is the active angle or angle where micro-slip is occurring. This is obtained from the standard belt equation with the added air term (see references [1 & 2]). The term micro-slip is defined as slip caused by the elastic behavior of the film. In areas where the web tension is changing, the web will grow or contract elastically. This can cause a small amount of slip at the roll surface. Here θ_{S2} is less than the wrap angle on roll 2 and $T_m = T_i$. If we increase the downstream tension to a point that θ_{S2} exceeds the wrap angle on roll 2, we need to use the following relationships

$$T_m = K + P_a + (T_0 - K - P_a)/\{\exp(f\,\theta_{W2})\} \tag{2}$$

$$\theta_{S1} = (1/f)\ \mathrm{Ln}\{(T_m - K - P_a)/(T_i - K - P_a)\} \tag{3}$$

$$\theta_{S2} = \theta_{W2} \tag{4}$$

The web tension for these cases are shown on Figure 3. The second case shows an active region on both the first and second rolls. Finally, the tension is increased until micro-slip is occurring over the full wraps on both rolls. This is the maximum tension rise that the S-wrap can support. The equations describing this case are

$$T_m = K + P_a + (T_i - K - P_a)\exp(f\,\theta_{W1}) \tag{5}$$

and

$$T_0 = K + P_a + (T_m - K - P_a) \exp(f\,\theta_{W2}) \quad (6)$$

and the web tension for this case also is plotted on Figure 3. These three cases describe the ideal performance of the standard S-wrap tension isolation system. When achieved the system works well. Note that micro-slip occurs on one or both rolls for the system discussed. The use of elastomeric covers, as will be shown, can minimize or eliminate this potential problem.

REAL S-WRAP PROBLEMS

Now lets turn our attention to the situation that occurs when the surface speeds on the two rolls are not identical. For this situation we will assume that the micro-slip angle is less than the wrap angle for both rolls. Under these conditions, the tension between the two rolls is controlled by the difference in surface speeds. The relationship defining tension between the two rolls is

$$T_m = E\,b\,t\,\{(r_2\,\omega_2 / r_1\,\omega_1) - 1\} + T_i\,(r_2\,\omega_2 / r_1\,\omega_1) \quad (7)$$

If $\omega_1 = \omega_2$, this can be rewritten in terms of strain as

$$\varepsilon_m / \varepsilon_i = T_m / T_i = 1 + (\delta r / r_1) + (\delta r / r_1) / \varepsilon_i \quad (8)$$

This strain ratio can be used to evaluate the potential for problems due to differing roll dimensions. Figure 4 shows a plot of this relationship. If we are working with a PET film, for example, we could design our process to run at a strain level of 0.002. This would correspond to an operating stress of approximately 7 MPa (1000psi). To keep the incremental strain below 10% for this case, $\delta r / r_1$ must be below 0.0002. The rolls would have to be machined to a tolerance of +/- 0.0002 cm/cm (in/in). This is possible for metal rolls but nearly impossible for rolls with elastomeric covers. Since elastomeric covers offer the highest friction, a solution is needed.

DIFFERENTIALLY DRIVEN S-WRAPS

The problem introduced by differences in the roll diameter can be eliminated by driving the roll pair by a differential transmission. This will allow the two rolls to seek speeds to achieve the proper surface velocity. If one roll has a larger OD, it will run at a slower rotational speed to compensate. Normally differentials have a fixed torque split due to the gearing involved. This can be 1:1 but it also can differ substantially from unity. If we define the torque split as S, the tension between S-wrap rolls can be obtained from

$$T_m = \{ T_0 + S\,T_i\,(r_1/r_2) \} / \{ 1 + S\,(r_1/r_2) \} \quad (9)$$

or the torque split to get a desired tension can be obtained from

$$S = \{ (T_0 - T_m)\,(r_2/r_1) \} / \{ T_m - T_i \} \quad (10)$$

One criteria that we could use is to define a safety factor, F, to avoid gross slip on either roll. F could be defined by

$$(T_m - K - P_a) / (T_i - K - P_a) = \exp (f_1 \theta_{W1} / F_1) \qquad (11)$$

If we write a similar relationship for roll 2 and set $F_1 = F_2$, we can derive the following relationship

$$\frac{f_1 \theta_{w1}}{\mathrm{Ln} \{ (T_m - K - P_a) / (T_i - K - P_a) \}} = \frac{f_2 \theta_{w2}}{\mathrm{Ln} \{ (T_0 - K - P_a) / (T_m - K - P_a) \}} \qquad (12)$$

which must be solved iteratively for S with equation 9. This simplifies to

$$S = \frac{T_0 - (T_0 T_i)^{1/2}}{(T_0 T_i)^{1/2} - T_i} = \frac{1 - (T_i / T_0)^{1/2}}{(T_i / T_0)^{1/2} - (T_i / T_0)} \qquad (13)$$

when the wrap angles, friction, radii and safety factors are equal on both rolls and K and P_a are small. A plot of S versus the tension ratio for the simplified case is included in Figure 5. This shows that the ideal torque split differs substantially from 1. Other approaches could be used to set the torque split but all of them should result in a higher torque going to the high tension side.

Numerous methods exist to drive rolls differentially. The gear box shown in Figure 6 has been developed and tested for this purpose. It is available in several sizes and in a wide range of ratios and torque splits [3].

NO-SLIP RELATIONSHIPS FOR ELASTOMERIC COVERED ROLLS

Micro-slip can lead to micro-scratches. Fortunately this is not a problem in most applications. When it is, tension isolation can be a difficult task. The standard belt relationships used above are valid for a hard surfaced roll and a thin belt. Here, no shear deformation in either the web or roll is considered. This is true normally because the friction is usually the weakest link and deformation occurs by micro-slip between the web and the roll. Firbank [4] looked at the case where the belt was thick and could deform in shear. We will be considering the case where the elastomeric cover can deform in shear. This type of deflection is pictured on Figure 7 which shows an unwrapped sketch of an elastomeric cover and a web. Over the wrap angle the web tension is changing and the web is elongating. If the frictional forces are sufficient, the cover will deflect in shear as shown. Figure 7 also includes an incremental element and the scheme used to normalize the analysis. Summing forces leads to

$$d\mathbf{T} / du - Q^2 \int_0^u \mathbf{T} \, d\upsilon = 0 \qquad (14)$$

where $\mathbf{T}$ is equal to 0 at u=0 and 1 at u=1. Under these conditions the solution is

$$\mathbf{T} = \exp [(u-1) Q] \qquad (15)$$

when $\exp[-Q] \ll 1$. For the solution to be valid and for the roll to operate slip free, this inequality must hold. It insures that the wrap angle is large enough to achieve tension isolation. A plot of the solution is shown on Figure 8.

We have assumed that the friction is adequate to prevent any slip between the elastomeric surface and the web. A calculation is needed to obtain the shear and determine if it is lower than the available friction forces. The shear for this case is given by

$$\sigma = \{ Q(T_0 - T_i)/(rb\,\theta_W) \} \exp[\,Q\,(u-1)] \qquad (16)$$

The maximum shear occurs at u=1 where the slope of the tension curve is highest (see Figure 8). Dividing the peak shear stress by the available friction, we get the following relationship

$$\frac{\sigma}{f\,(T_0 - K - P_a)/(rb)} = \left[\frac{Q}{f\,\theta_W} \; \frac{(T_0 - T_i)}{(T_0 - K - P_a)} \right] < 1 \qquad (17)$$

This inequality along with $\exp(-Q) \ll 1$ form design limits for a zero-slip roll installation.

To check the accuracy of the solution and reliability of the results, a finite element solution was obtained to the problem as described in Figure 7. The resulting tension rise in the web is plotted on Figure 8 for the case described in Table 1. Two sets of discrete data are included. The first is for the exact case in Figure 7 with no end effects due to elastomeric material outside of the wrap zone. These results are almost identical to that obtained from the solution in equation 15. The second case includes material outside of the wrap zone. This material through multi-dimensional effects impacts the tension near the end of the wrap zone. This is the most critical spot, since the shear stresses are highest at this point. The plot of results including material outside of the wrap zone shows that the closed form solution tends to underestimate the maximum shear stress and over estimate the required wrap angle based on equation 15. The more accurate finite element solution results has a maximum shear stress 33% higher than the closed form solution.

The best approach is to make a preliminary design using equations 15 and 17 and use a significant safety factor. Then, check the functionality of the design using a finite element solution. This approach makes the best use of both techniques. The simple method will get you close and the finite element method will insure accuracy.

APPLICATIONS FOR DIFFERENTIALLY DRIVEN S-WRAPS

Tension isolation is necessary for all web processing lines. If the tension control is more than a simple driven roll can handle, the differentially driven S-wrap should be considered. It has the simplicity of the standard S-wrap but none of the disadvantages. The threadup process should be considered, however. The roll on the high torque side will turn faster when no film is on the rolls. This is not a problem once the web is in place.

Potential applications for differentially driven S-wraps are as follows:

1. Tension control just downstream of an unwind or just upstream of a winder.
2. Tension control before or after coating stations. A unique application of this kind is illustrated on Figure 9. Here, an S-wrap is used to straddle a coating zone. The drive to the S-wrap is used to set the tension entering the upstream roll using some type of tension control system. A separate means, perhaps an additional S-wrap, is used to control the downstream tension. The tension in the coating zone between the S-wrap rolls is set by the torque split. Consequently, the other tension control systems can be used to set the tension in the coating zone. This simplifies the coating area by eliminating the need to put an additional tension control system in this zone.
3. Tension control coming out of an oven where the temperature is dropping and thermal contraction effects may make a conventional S-wrap difficult to use.
4. Heating or cooling rolls that are driven in pairs could use the differential approach to avoid problems with thermal expansion or contraction effects.
5. Applications involving several webs with greatly differing thicknesses and/or modulii. The differential drive will provide a high level of operational flexibility.
6. Driven roll systems involving rolls that can't be remachined to correct for radial inaccuracies. These include release, polished chrome and textured rolls. The differential corrects for dimensional differences.
7. Roll pairs where the surfaces of the two rolls differ dramatically such as chrome and elastomeric covered rolls operating together. The torque split capability can be used to reflect the differences in surface friction.
8. Two elastomeric covered rolls. Here, the problem with maintaining identical roll dimensions is eliminated.
9. Retrofits for problem S-wraps, to replace nips or single rolls that are not adequately isolating tension.

In most cases the replacement S-wrap will fit in the same space and operate with the same controls.

CONCLUSIONS

A differentially driven S-wrap for tension isolation is a significant improvement over the standard fixed drive approach. It makes the S-wrap approach more robust and increases the available applications for these devices. Rolls with elastomeric covers can be used without requiring match roll sets which are machined to exact tolerances.

The torque split control feature tends to distribute the load between the s-wrap pair. This can be used to distribute wear, increase the tension ratio achieved, or adjust for differences in the roll surfaces.

The differential drive makes the S-wrap useful in areas where the elongation of the web is changing substantially. Heating and cooling zones or operations with low modulus webs are good examples.

Elastomeric surfaced rolls can be used to minimize or eliminate micro-scratches produced in many tension isolation systems. The elastomeric surface can be designed to distort in order to avoid micro-slip that can cause these defects.

A variety of approaches are available to achieve the differential drive approach. Gear boxes designed specifically for this application also are available [3].

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3. Advantage Web Technologies, "Transmissions for Differentially Driven S-Wraps", Advantage Web Technologies, 20 Shawnee Drive, Chillicothe OH. 45601, phone (614) 773-7441, Fax (614) 868-9397, 1997.

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Table 1 Data for the Elastomeric Covered Roll Case

WEB	
Elastic Modulus	3448 MPa (500000psi)
Poisson's Ratio	0.2
Thickness	0.0254 mm (0.001")
ELASTOMERIC MATERIAL	
Elastic Modulus	2.07 MPa (300psi)
Shear Modulus	0.690 MPa (100psi)
Poisson's Ratio	0.5
Thickness	12.7mm (0.5")
GEOMETRY	
Wrap angle - Radius Product	254mm (10")
P_a	0
K	0
$Q^2 = 40 >> 1$	

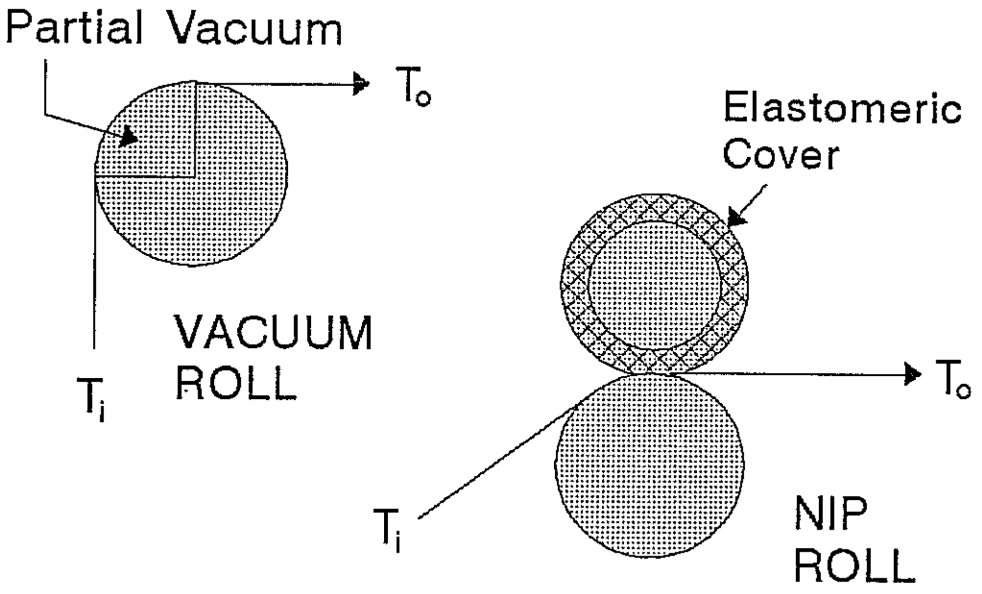

Fig. 1 Vacuum and Nip Roll Geometries

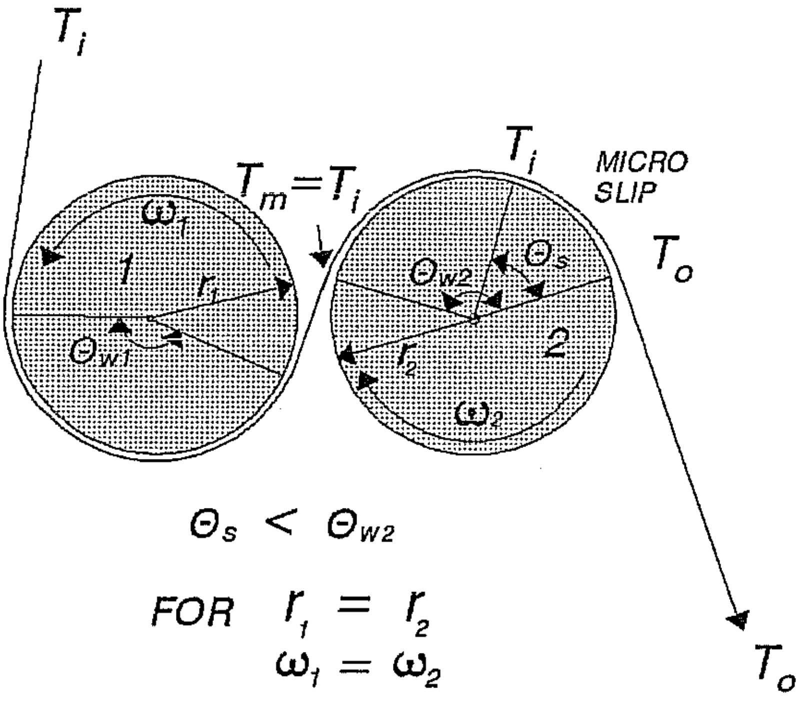

Fig. 2 Lightly Loaded S-Wrap

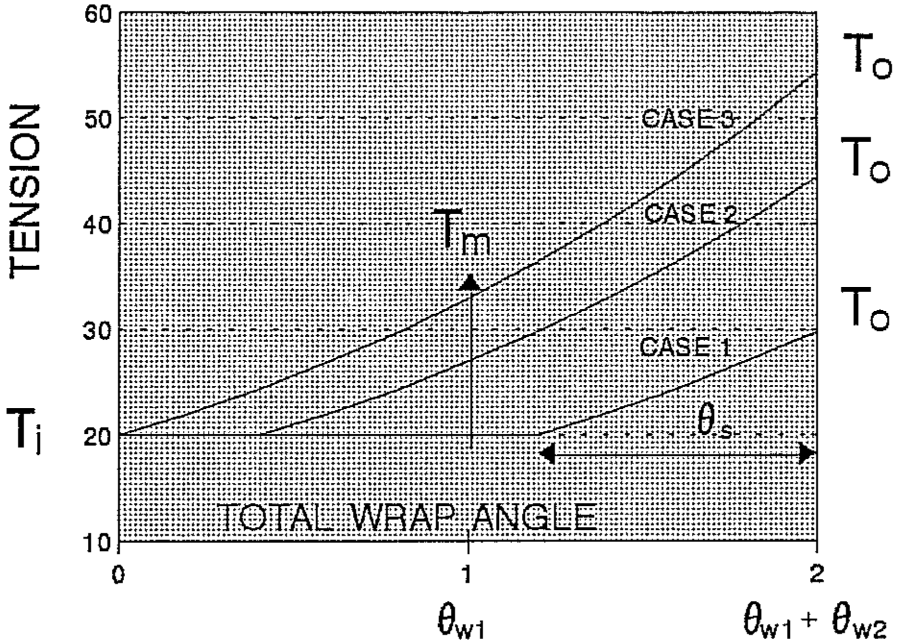

Fig. 3 Tension and Micro-Slip Angles for an S-Wrap

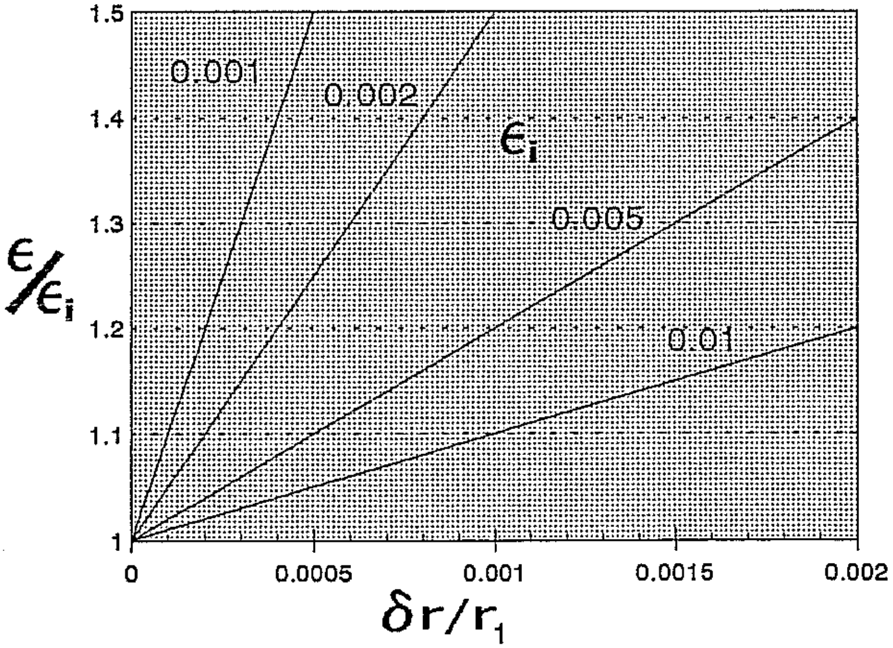

Fig. 4 Incremental Strain Increases Due to Radial Differences

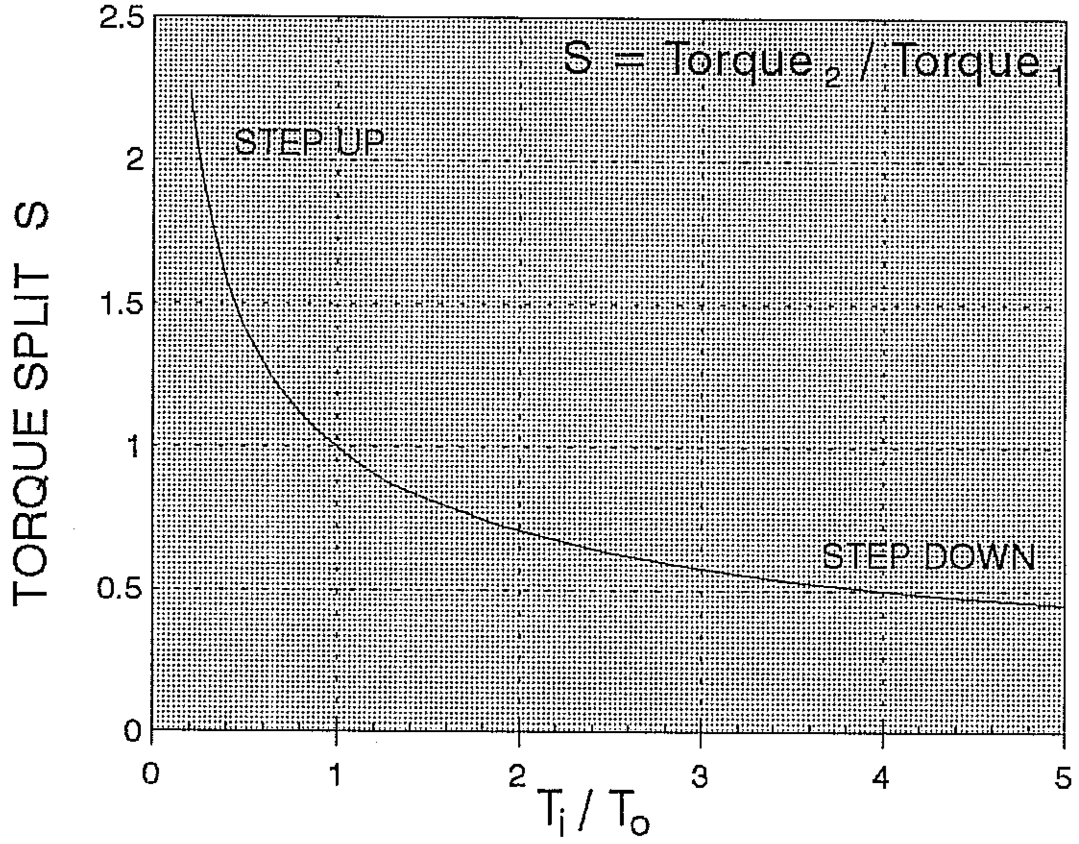

Fig. 5 Desired Torque Split Versus Tension Ratio for S-Wrap

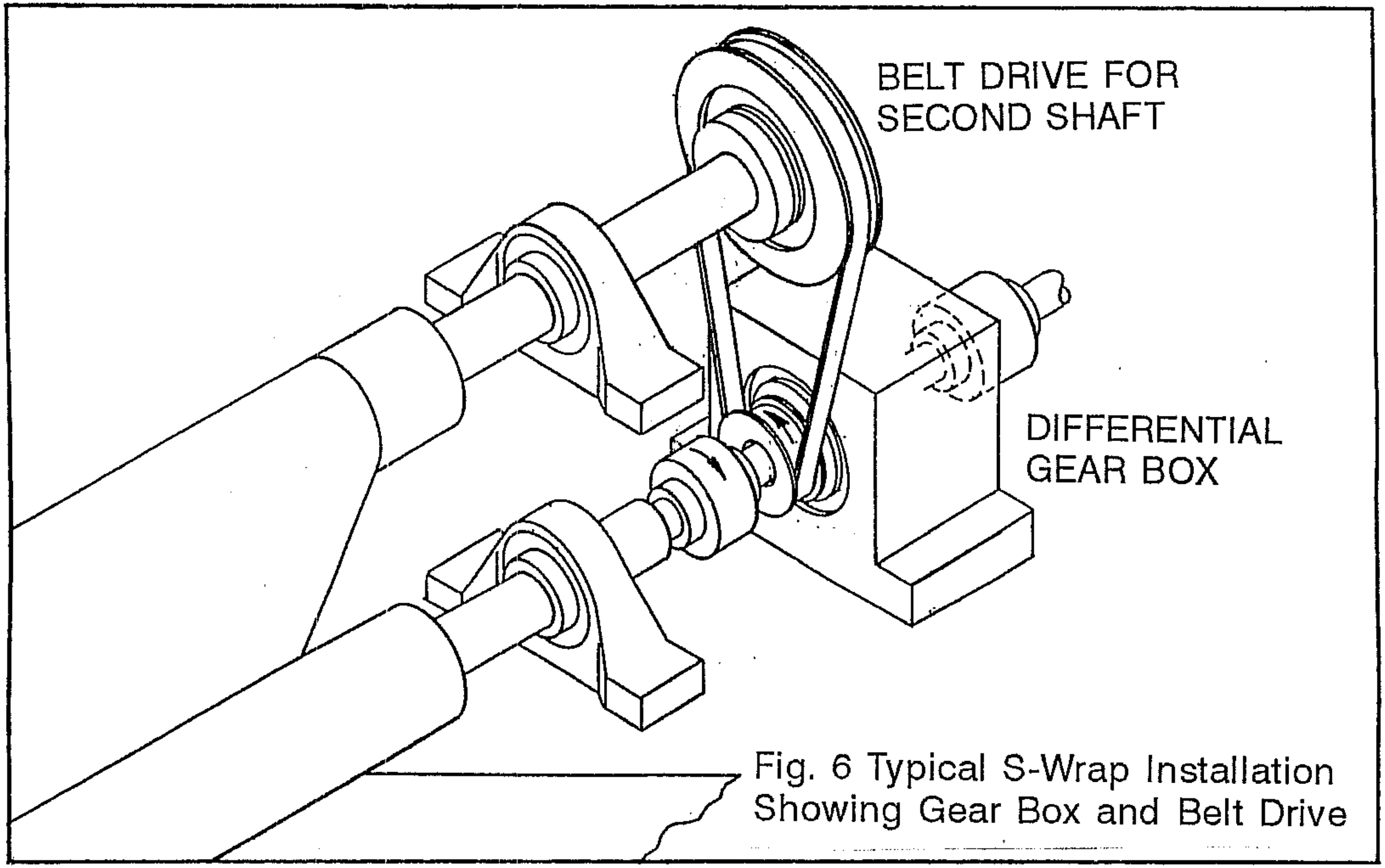

Fig. 6 Typical S-Wrap Installation Showing Gear Box and Belt Drive

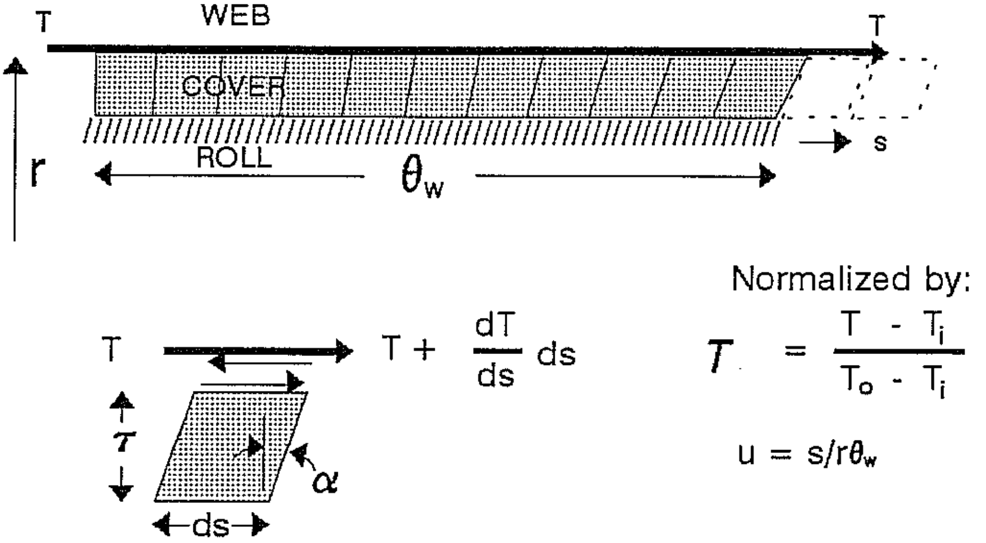

Fig. 7 Unwrapped Sketch of Roll Surface Deflection Model for Elastomeric Rolls

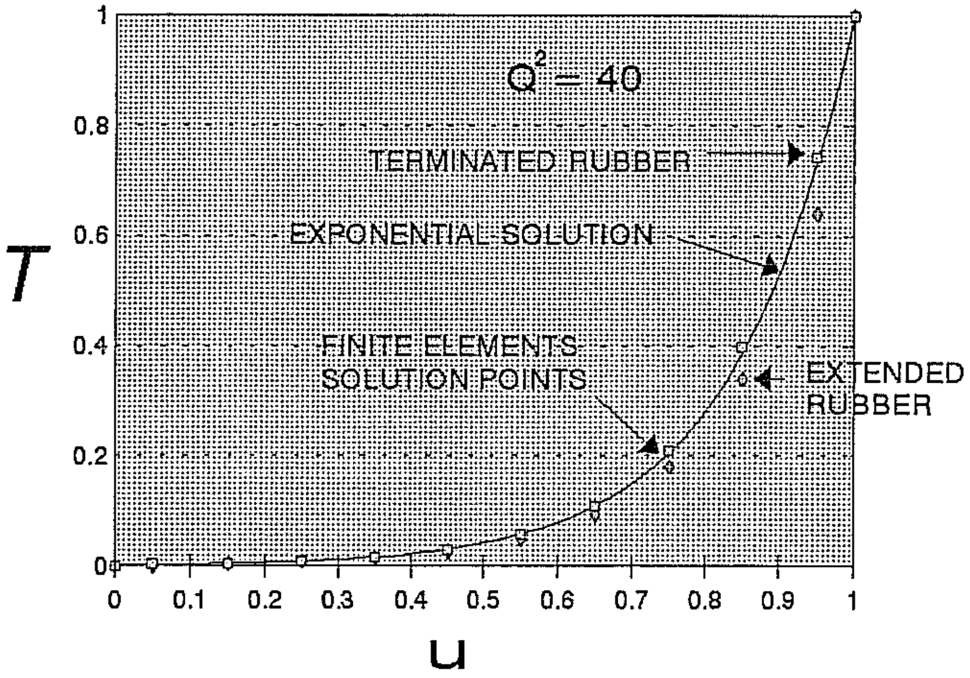

Fig. 8 Film Tension Rise on Elastomeric Rolls

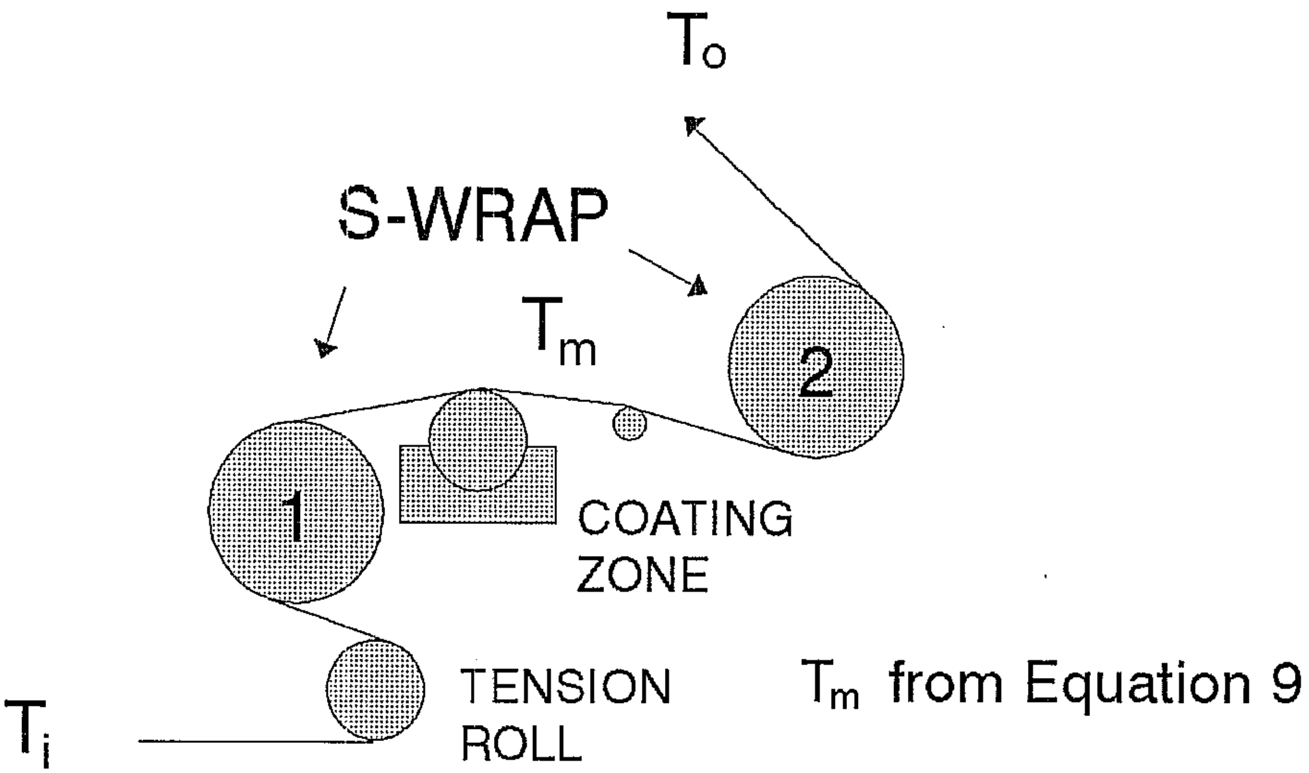

Fig. 9 Differentially Driven S-Wrap Straddling a Coating Zone for External Tension Control