THE EFFECTS OF NIP PARAMETERS ON MEDIA TRANSPORT

by

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ABSTRACT

The mechanics of a web being transported through a set of elastomeric rollers has been investigated. Three general classes of roller materials are identified. These nip materials are then characterized by the speed at which they transport a web, and how that speed changes due to a number of design factors. The issue of media skew is also addressed, and examples are given of how different nip materials will or will not cause skew. Finally, design tradeoffs are discussed for the three classes of materials.

INTRODUCTION

There are many processes that use nips to transport both continuous and cut sheet webs. Film and paper manufacturing, paper handling in photocopiers, and thermal printers are a few. Although most thermal printers are small enough to sit on a desktop, the mechanics of nip transport are the same as a multi-million dollar paper machine. An understanding of the mechanics of nip transport is very important to the successful design of these systems. This paper will focus on how the choice of roller materials will affect the nip's ability to transport media. A designer of nip transport systems is faced with a number of design choices, one of the most important being the nip material. This paper will discuss three classes on nip materials : polyurethanes and rubbers, foamed rubbers and open cell foam. These material classes will then be characterized by their performance in transporting media under a number of conditions. For the duration of this paper, the word media will be used to represent whatever material a nip is transporting, whether it is a cut sheet or a continuous web.

Figure 1a shows a plane strain view of a transport nip. If the two rollers are identical, then figure 1a and figure 1b are *equivalent*. See Johnson [1986], Soong [1981], or Diehl, Stack and Benson [1993] for a more detailed explanation. This "symmetry" condition in 1b allows for more efficient modeling, and will be used throughout this paper. Note also that the configuration in figure 1b is a common geometry for a roller that transports sheets in a photocopier. Unlike continuous web transports, cut sheets are usually transported by a single roller against a rigid floor. This study will ignore frictional effects between the sheet and the floor for the single roller case, but see Stack [1995a] for situations where friction is important.

In order to model media transport, a nonlinear finite element simulation has been developed by the MFSP specifically for modeling nip mechanics. The simulation (NONCON-RS) is capable of modeling nonlinear roller materials, the large strain behavior of the roller itself and three dimensional frictional contact between the roller and a rigid surface. In addition, the model fully couples the effects of roller deformation and the motion of media in the nip. This allows us to compute not only the motion of media in the nip, but the effects of the media's motion on the nip itself. See Stack [1995a, 1995b] for a more detailed description of the computer simulation and it's capabilities.

OVERDRIVE AND UNDERDRIVE

When media is transported by a set of elastomeric rollers, it is often the case that the speed of the media is different from the nominal surface speed of the rollers away from the nip. See Johnson [1986], Laumer [1987], Diehl [1995], Diehl, Stack and Benson [1993]. This difference in speeds is influenced by a number of factors, including the material behavior and thickness of the elastomer, the engagement of the rollers, and the tension in the media. To compare and contrast different roller material properties, we will first focus on how roller material behavior influences media speed.

Figure 2 shows a plane strain elastomeric nip roller before and after contact. Before contact, each particle on the surface of the roller spins with the same tangential speed, V_0. After contact, points far away from the nip spin with that same speed. Assuming that the media does not slip within the nip, each point on the roller inside the nip and it's corresponding point on the media must move together. We will call the speed of the media (and therefore the speed of the roller particles within the nip) v. Depending upon the strain in the nip, this speed v can be greater or less than the nominal surface speed of the roller V_0. We define the speed ratio λ to be

$$\lambda = \frac{v}{V_0} \tag{1}$$

When λ is not equal to 1, the media is moving at a different speed than the roller. We can now define overdrive and underdrive as

$$\begin{aligned}\text{Overdrive} &: \lambda > 1 \\ \text{Underdrive} &: \lambda < 1\end{aligned} \tag{2}$$

where overdrive means that the media is moving faster than nominal roller velocity V_0 and underdrive means that the media is moving slower than V_0. Note that this definition is a relative measure, and it will allow us to more easily compare different roller characteristics.

Looking again at figure 2, we can see why the media will move at a different velocity than the nominal surface speed of the roller. Depending upon what type of elastomeric covering we use for the roller, the strains in the covering will be different. The "hoop" strain (circumferential strain) defines how fast a particle on the outside of the roller will move. Larger hoop strains (more bulging) lead to faster media speed. Picture a particle about to come into contact with the nip. If the roller material has a high Poisson's ratio, the outer surface of the roller will be stretched and therefore the hoop strain will be positive. The material particles near and in the nip must travel a longer distance (because they are stretched) than those far away from nip in the same length of time. Therefore they must be moving faster. If the roller has a small Poisson ratio (close to zero) the strain in the outer surface will actually be negative, and particle will travel a shorter distance. Therefore rollers that have small Poisson Ratio's will tend to underdrive. With this knowledge, we can now investigate how different nip materials will transport media.

ROLLER MATERIAL CLASSES

Different roller materials will lead to different amount of hoop strains, and therefore different media speeds. The material parameter that controls how much a particular material will bulge is Poisson's ratio. There are three classes of elastomers that are normally used to make transport rollers. These material classes were defined in Stack [1995a, 1995b]. Rubbers and polyurethanes are almost incompressible, and therefore have a Poisson ratio that approaches 0.5. On the other end of the spectrum, open cell foams (such as the foam normally used in seat cushions) has a Poisson's ratio very close to zero. Some foams in fact can have negative Poisson's ratios! (Cork is a natural example). In the middle of these two material classes are foamed rubbers, similar to the material used in a mouse pad. These materials have a Poisson's ratio between 0.2 and 0.4. Table 1 summarizes these three different material classes.

Material Class	Poisson's Ratio
Rubber, Polyurethane	0.4 - 0.5
Foamed Rubber	0.2 - 0.4
Foam	0.0 - 0.2

Table 1 - Roller Material Classes

It is usually not sufficient to describe the behavior of a soft foam material by a constant Poisson's ratio. On the other hand, linear materials are well defined using the elastic modulus and a single Poisson's ratio. Metals are the classic example. Unfortunately, open cell foams usually display a highly nonlinear relationship between the principal and transverse strains, leading to an effective Poisson's ratio that is not a constant. However, even though the effective Poisson ratio may vary, they rarely go above 0.2 for foam materials. Therefore for our studies, we will implement a material law that gives a single Poisson's ratio for any strain. This will allow us to compare and contrast these different material classes, and not "muddy" the waters with Poisson's ratios that vary with strain. For this study, it is not our intent to focus on a particular material, but rather a general class of materials. However, our formulation is hyperelastic, therefore any suitable material law (including those that lead to non-constant Poisson ratios) can be modeled. See Diehl [1995] for an exhaustive study on the nonlinear behavior of a variety of nip materials.

The strain energy density function used to describe all three material classes is invariant based, and is known as the Brockman Law (Brockman [1986])

$$W = \frac{\mu_0}{2}\left[I_1 - 3 + \frac{2}{\beta}(J^{-\beta} - 1) \right] \tag{3}$$

where I_1 is the first strain invariant, J is the square root of the third strain invariant, μ_0 is a material parameter that represents the initial shear stiffness and β is related to the Poisson's ratio by

$$\beta = \frac{2\nu}{1 - 2\nu} \tag{4}$$

where ν is Poisson's ratio. One of the advantages of this law is that even for large strains, the effective Poisson ratio change is negligible. Most hyperelastic laws have a fair amount of coupling between the strain and Poisson's ratio. Therefore it is an excellent law to use when we would like to control the effective Poisson ratio. Because it is invariant based it is very efficient to compute numerically, because the invariants can be found easily from the Green's strain. However, it does not have the flexibility that a general stretch ratio based law, such as Ogden-Hill, to fit the highly nonlinear behavior of some elastomers. See Diehl [1995] for an analysis of the applicability of various hyperelastic laws to nip mechanics.

THE EFFECTS OF POISSON'S RATIO, ENGAGEMENT AND MEDIA TENSION ON MEDIA SPEED

Poisson's Ratio and Media Speed

To study the effect of Poisson's ratio on media speed, we will assume that the media is being driven by a plane strain roller with no applied media tension. The engagement of the roller and the roller stiffness will be held constant, and the effective Poisson ratio of the material will be varied from 0.0 to 0.475. These cases were computed with a roller having an outside radius of 1 inch, an inner radius of 0.25 inches and an effective engagement of 20%. The stiffness of the material will be held constant as well, with $\mu_0 = 10.0$ psi. The roller to media friction coefficient was 2.0 (a reasonable number for most roller materials).

Figure 3 shows the media speed ratio versus the effective Poisson's ratio of the roller material. Similar results were shown in Stack [1995b] and are given here for completeness. As we would expect, the media speed increases with larger Poisson's ratios. A larger Poisson ratio leads to more bulging in the nip, and therefore larger hoop strains. For Poisson's ratio less than 0.3, the speed ratio is less than 1. Therefore the media is moving slower than the nominal speed of the roller surface away from the nip. For Poisson's ratios greater than 0.3, the media is overdriving. Referring back to our material classes, rubbers and polyurethanes will overdrive, while open cell foams will underdrive. Foamed rubbers on the other hand are in the middle region (0.2-0.4), and depending upon the specific material values, their speed can be either greater or less than the nominal roller surface speed.

It is interesting to note that roller stiffness has little or no effect on media speed *if the engagement of the roller is kept constant.* The strains in the nip will change very little for varying stiffnesses even though the stresses in the nip will change substantially. Therefore without any tension in the media, speed ratio is relatively independent of roller stiffness. However, if the engagement of the roller changes with stiffness (the nip is spring loaded for example) then the engagement will change and so will the media speed, as we will see in the next section.

Roller Engagement and Media Speed

As one could imagine, as the engagement of the roller changes, the strains in the nip will change as well. Depending upon the roller material, these changes can lead to faster or slower media speeds. To understand these effects, we have computed the media speed for varying engagements for all three material types. Table 2 shows the material parameters used for the three rollers. Each of these cases again used a roller that had an outside radius of 1 inch and an inner radius of 0.25 inches. To compare engagements, we will use the "effective engagement", which is the actual engagement of the roller divided by the difference in outer and inner radii.

Material Class	Stiffness μ_0 (psi)	Poisson's Ratio
Polyurethane	25.0	0.45
Foam Rubber	10.0	0.25
Foam	5.0	0.0

Table 2 - Roller Material Parameters

$$\mathrm{eng}_{\mathrm{eff}} = \frac{\delta}{r_0 - r_i} \qquad (5)$$

Figure 4 shows media speed versus roller engagement for a polyurethane roller, a foam rubber roller and an open cell foam roller. Similar results were shown in Stack [1995b] and are given again for completeness. The polyurethane roller produces media speeds that increase with engagement. This is intuitive, in that as δ becomes larger bulging increases, leading to positive hoop strains and overdrive. The open cell foam roller on the other hand produces media speeds that slow down as engagement increases. The hoop strains on the outer fiber of the roller are negative, therefore the material particles travel a shorter distance. As engagement is increased, the hoop strain becomes more and more negative, leading to slower media speeds.

The foam rubber case is interesting in that as we first increase the roller engagement, the media underdrives slightly, but from about 5% engagement to 25% engagement the speed of the media is unchanged. This corresponds to the hoop strain not changing as engagement is increased. This is due to the geometry of the roller and the effective Poisson ratio. The Poisson ratio and the engagement effects cancel one another out, leading to a relatively constant hoop strain. We will find later that this is a very desirable effect when shaft misalignment is present.

Media Tension and Media Speed

The cases that were computed previously did not include the effects of media tension. In most situations, the media will be under some level of tension, usually to increase its effective stiffness to avoid wrinkling. However, tension will affect the speed that the media will travel at. Referring back to figure 1, if the media is tensioned and the rollers are driven, a forward tension will increase the strain in the nip leading to faster media speeds. Back tension on the other hand will decrease the strain in the nip, leading to slower media speeds.

Table 3 shows the nip materials used to study how tension affects media speed. Both materials are polyurethanes but have very different stiffnesses. The first material has an elastic modulus of 145 psi (the durometer of this material was 45 Shore A). The second material has a modulus of 560 psi (I am unsure of the exact durometer of this material, but I believe it was about 80).

Material Type	Material Stiffness μ_0	Poisson's Ratio
Polyurethane - 45A	25 psi	0.45
Polyurethane - 80A	189 psi	0.45

Table 3 - Roller Material Parameters

Figure 5 shows the effects of media tension on media speed. Looking first at the 45 durometer material, when Tf is greater than Tb (Tf - Tb is the difference between front and back tension), the media speed is increased significantly. As expected, front tension leads to faster media speeds while back tension leads to slower media speeds. However, for the same tension range, note that the stiffer roller material does not have a significant change in media speed. Because the material itself is stiffer, the tension has little or no effect on the strains, therefore the media speed is unchanged.

This is a desirable attribute for many systems when keeping constant media speeds is crucial, such as imaging or coating. Imagine a coating process that does not maintain constant tension, but instead uses constant winding torque. As the tension changes, the time that the media spends underneath the coating nip will change, leading to variations in coat density, etc. The same is true in any imaging application, from thermal printers to copiers to laser printers. Changes in tension can be caused by any number of sources, such as changes in media friction from material variation, changing nip loads or simply constant torque winding. In imaging systems that require multiple passes to produce color output, small changes in media speed can severely degrade the output quality of the image.

AXIAL VARIATION IN MEDIA SPEED - MEDIA SKEW

All of the results thus far have dealt with plane strain rollers. We now would like to investigate some of the effects of axial variation in nip transport systems. In this case, the axial variation that we are talking about comes from the shafts of the rollers being misaligned, or trammed. Figure 6 shows the geometry of the system. Shaft misalignment such as this can cause a variety of media handling problems, including media wrinkling and media skew. Media skew is becoming one of the fastest growing problems in imaging devices because of the inability of OCR and OR to handle skewed images. A rule of thumb is that one degree of document skew is unmanageable from a OCR or OMR point of view.

A designer of media transport systems for these devices would like to insure that even if the shaft becomes slightly bent or misaligned, the media will not skew. To investigate this effect, we will model a system again with one roller. However, this model is three dimensional rather than plane strain to account for axial variation. The shaft of the roller has been skewed by one degree, and the outer and inner radii are again 1 inch and 0.25 inches respectively. The roller engagement δ is 0.125 inches, and the roller length is 1.25 inches.

Positive skew is defined as a sheet that skews towards the side of the roller with more engagement, as shown in figure 6. We can now draw some analogies back to figure 4. We can think of the roller skew as causing more or less engagement to various portions of the roller. And we can expect the local media speeds to vary down the axis accordingly, just as it did before due to changing engagements. *Therefore the media must skew.* We will now compute the motion of the media with a shaft misalignment of one degree.

Figure 7 shows the rotation of the center of the media as a function of roller rotation. For ease of explanation, we will assume that the media is a cut sheet. The roller nip materials correspond to those in table 2 and figure 4. The polyurethane roller causes the media to skew away from the side of the roller with more engagement. This makes intuitive sense because we know that polyurethane overdrives, and therefore the side with a larger engagement should move faster.

Foam on the other hand skews the opposite way for the same roller misalignment! This is because foam underdrives and causes the speed of the media to be slower with larger roller engagements. This produces the opposite velocity distribution down the axis of the roller and leads to positive skew. This effect can be easily shown with some simple experiments.

Foam rubber is, from the designers point of view, the most desirable roller material to use for reducing document skew caused by shaft misalignment. Stack [1995a]. Because the media speed from foam rubber does not change over a large range of strains, the effect of varying engagement down the axis of the roller is nullified. This results in little or no document skew, which is the answer to the designer's challenge. Figure 8 summarizes the amount of sheet skew for 1 revolution of the roller.

SUMMARY AND DESIGN TRADEOFFS

Three popular classes of materials, rubbers, open cell foams, and foamed rubbers were studied to understand their media transport characteristics. It has been shown that rubber and polyurethanes will have the tendency to overdrive, while open cell foams will normally underdrive. The Poisson ratio of the material was demonstrated to be the driving factor behind how a particular nip material behaves. The effect of media tension on media speed was also investigated, and was shown to be significant for softer nip materials. When the shaft of the roller became misaligned, the media began to skew. Rubber and polyurethane rollers will skew media away from the high engagement side, while open cell foam rollers will skew the media towards the high engagement side. Foamed rubber rollers were found to produce little or no document skew, due to their ability to have a constant media speed over a large range of engagements.

When a designer is tasked with developing a media transport system using elastomeric transport rollers, there are a number of tradeoffs which he or she will have to make. Figure 5 showed that changes in tension can drastically change the speed of the media. If changes in tension are present, then stiffer nip materials will reduce media speed changes. However, stiffer nip materials often lead to larger amounts of axial variation both in pressure (see Diehl, Stack and Benson [1993]) and in media transport speed. Most stiff nip materials are rubber or polyurethane, which have been shown to produce a great deal of document skew for rather small shaft misalignments. Foamed rubber produces very little document skew, but would be susceptible to changes in media tension. These are two of the many design tradeoffs that a person must make when developing a nip transport system, and the authors hope that these case studies will help the designer make informed choices about nip materials.

ACKNOWLEDGMENTS

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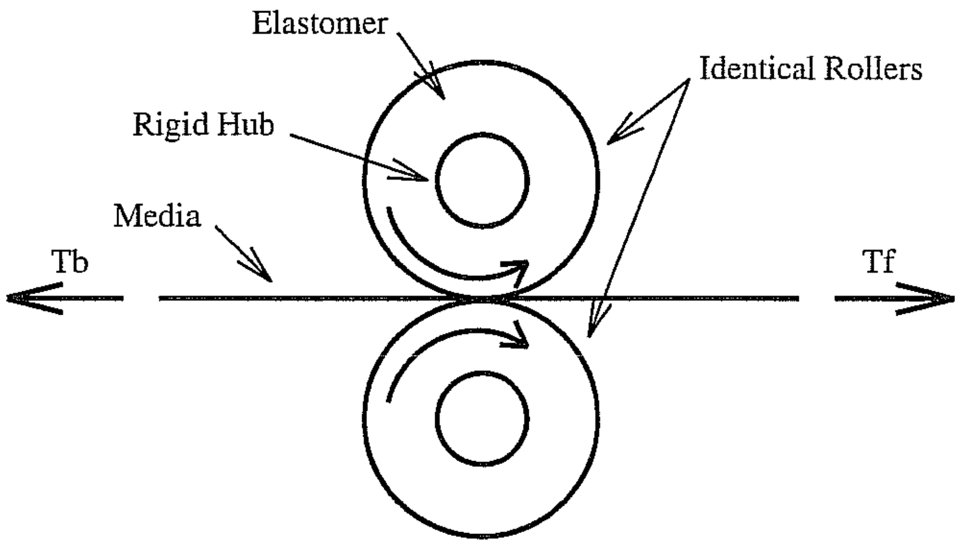
Two Elastomeric Transport Rollers



Symmetry Condition

One Roller And Frictionless Floor

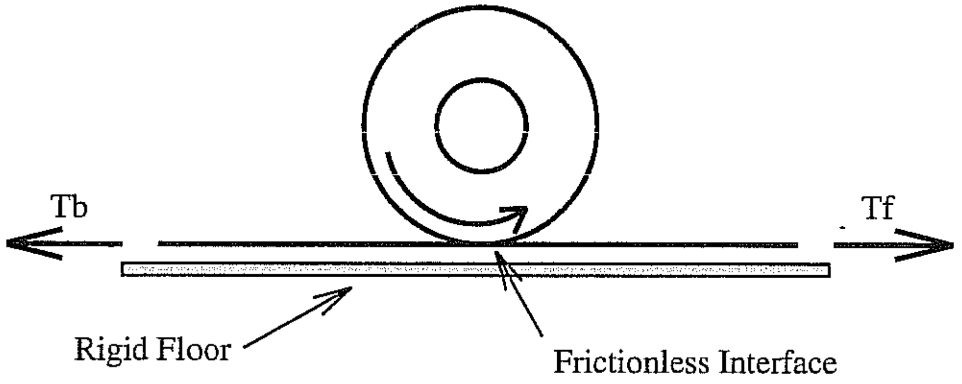
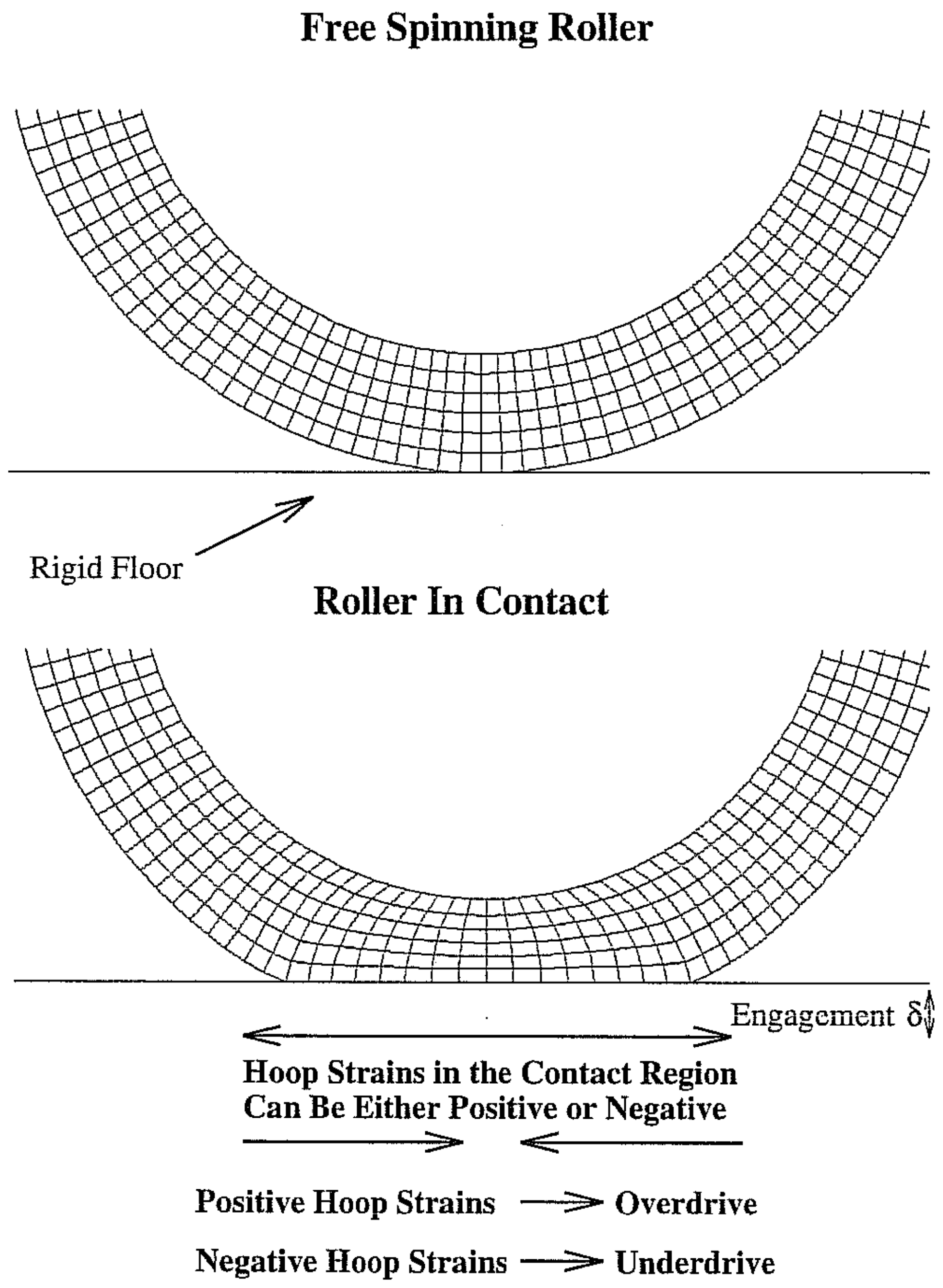


Figure 1a and 1b - Geometry



Free Spinning Roller

Roller In Contact

Figure 2 - Strains in the Nip

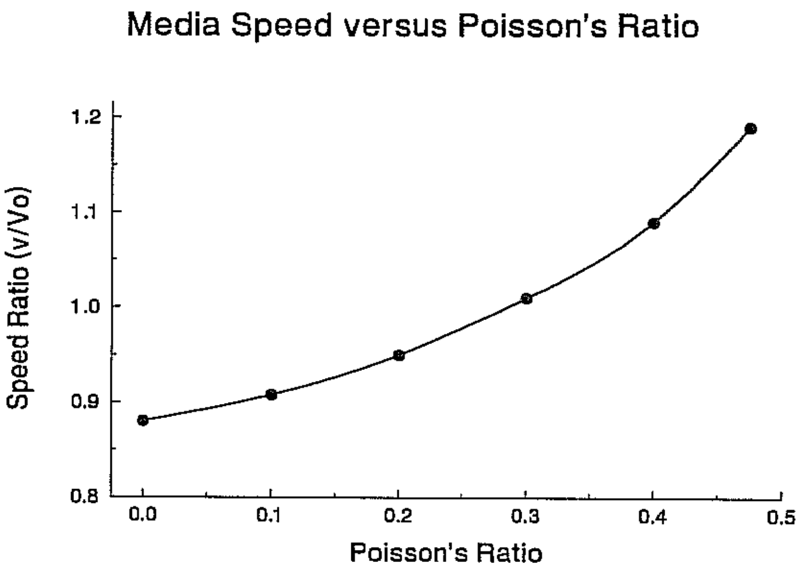


Figure 3 - Speed Ratio versus Poisson's Ratio

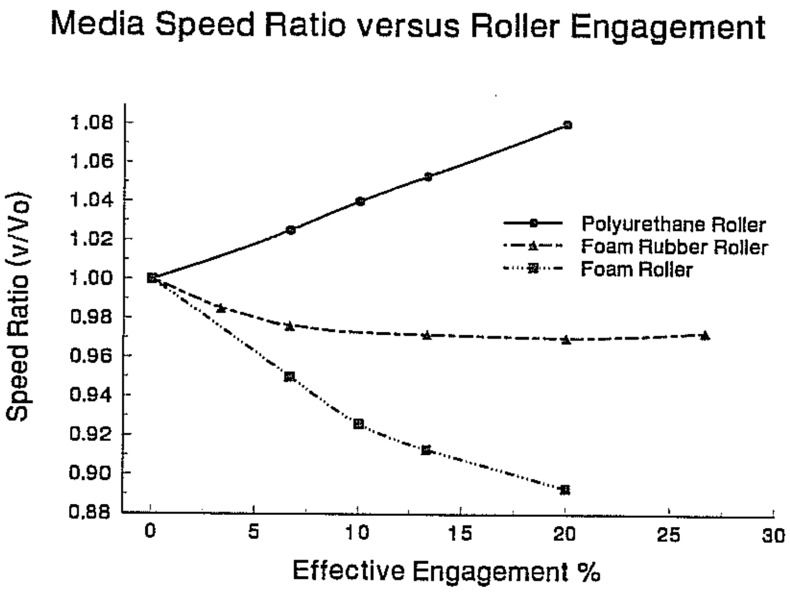


Figure 4 - Speed Ratio versus Roller Engagement

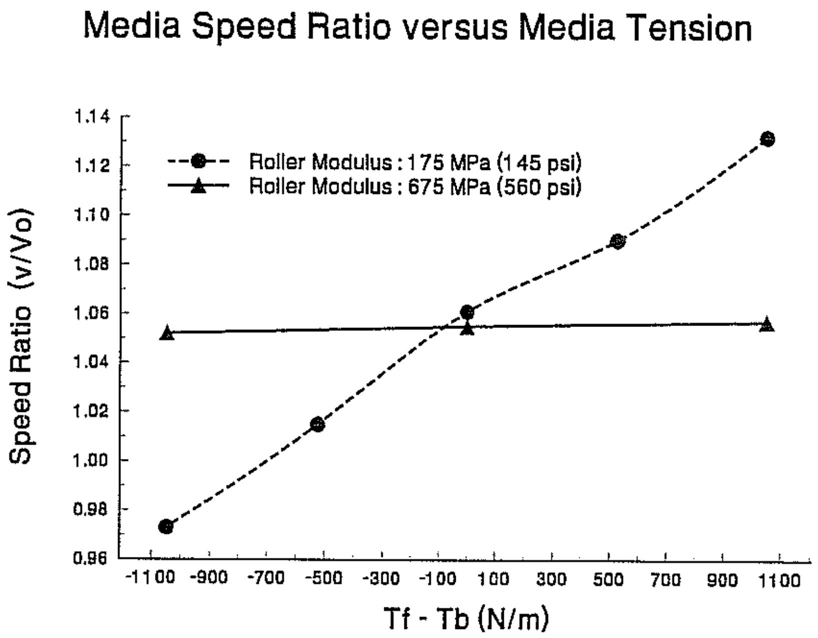


Figure 5 - Media Speed Ratio versus Media Tension

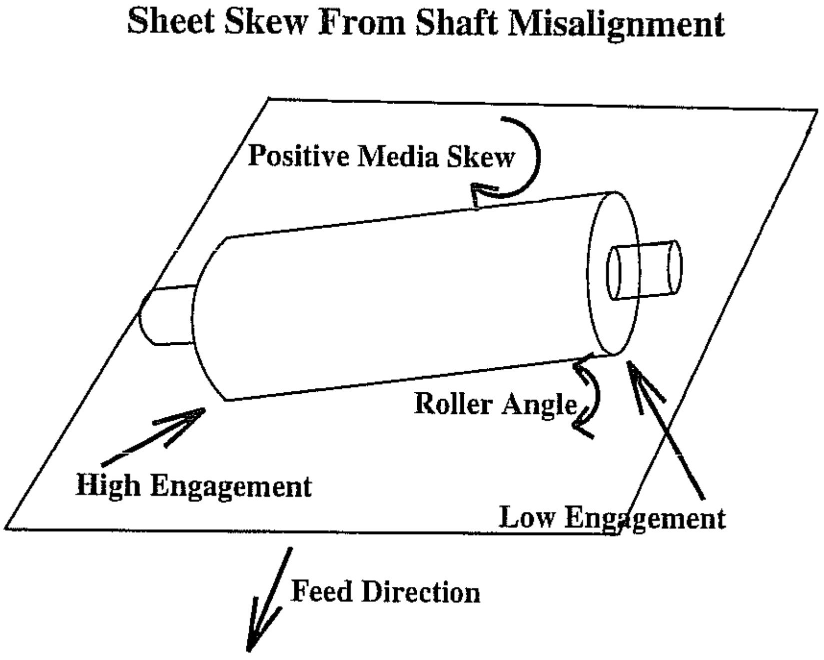


Figure 6 - Shaft Misalignment

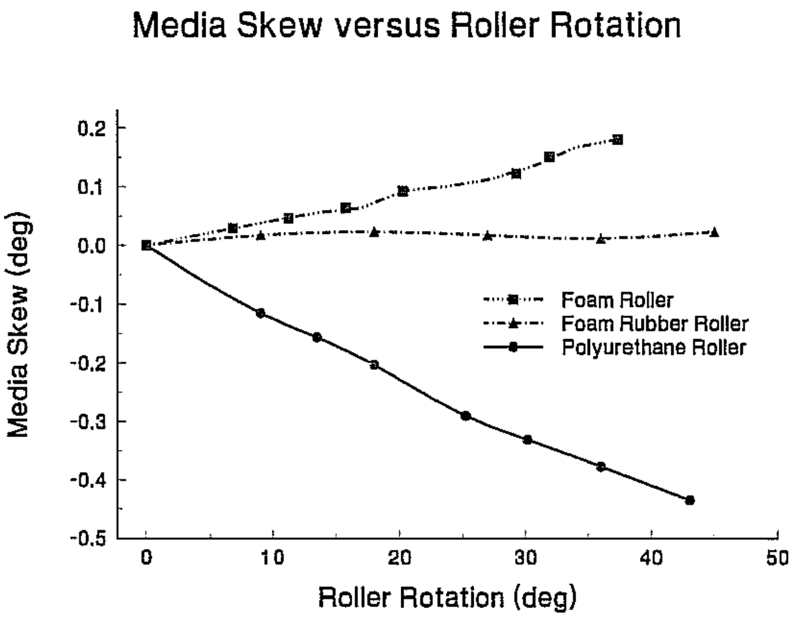
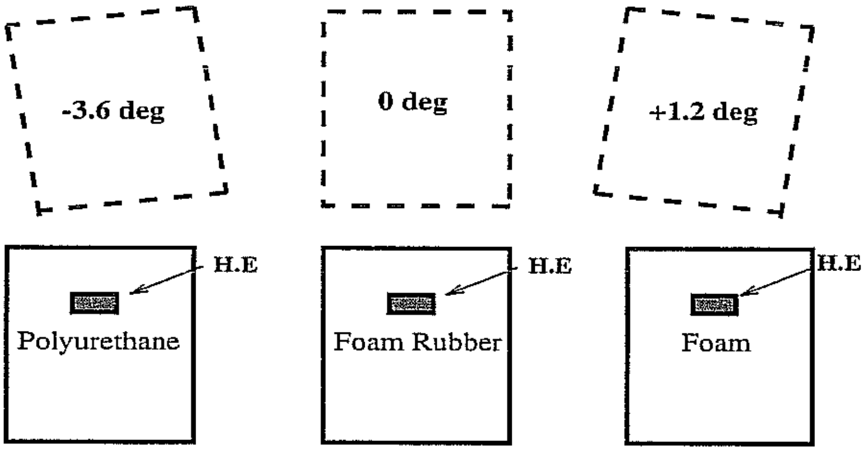


Figure 7 - Media Skew versus Roller Rotation

Different Materials Have Different Skew Directions !

Media Skew After 1 Roller Revolution



H.E. = High Engagement Side

Figure 8 - Media Skew After One Roller Revolution

Stack, K.D.; LaFleche, J.E.; Benson, R.C.
Nip Materials and Media Transport
6/21/95 Session 6 9:25 - 9:50 a.m.

Question - Ken, I'm unsure of what you're really modeling. You have a Figure 1A and 1B. What are you modeling?

Answer - Those results show that it turns out that for two identical rollers and a single roller with a sheet underneath it in a frictionless floor, they're exactly the same for the two models mathematically.

Question - You've got hard data that proves that this is frictionless.

Answer - Absolutely, in fact, there's a great paper of T.C. Sun of Xerox that really goes into this deeply. We've got tons of experiments that shows this very well. Because the two rollers are of exactly the same materials, when you push them together and you get a perfectly flat contact profile. But, yes, you can show that in experiments.

Question - You didn't identify Poisson's Ratio. You didn't show the materials. In Figure 5.

Answer - Web tension? Okay. They are both for polyurethane's. The ratio is .45. Tension is mostly just a stiffness effect. So when tension is concerned, you're really concerned with the stiffness because the stiffness is what keeps the nip from moving around off that nominal.

Question - When you consider material like rubber and elastomers, there's a lot of material histories involved. In fact, in the second picture with the static indentation with the nip, the contact profile around the contact region is no longer symmetric because the histories and everything upsets the symmetry in motion. What do you think is going to happen under such circumstances? How does propose to take the histories in addition to the Poisson's Effect?

Answer - That's a great question. Material histories is really important. And even more important with things like foam, because I've seen foam do a load and unloading curve like this and these two curves are actually different. What you can do is literally put into the code a load and unloading curve. Now, histories effects are actually very complicated. The thesis by Ted Diehl really goes into this stuff in real detail. There's viscoelastic effects literally from the material itself. There's air effects, especially in foam pushing all kinds of air out. The only way to include this in a formulation like this is to use a load and unloading curve that are different. And that, I think, can get most of it. In terms of actually modeling viscoelastic models and stuff, you can do it. You're probably familiar with papers by Podovan . I think that the trend, in general, are about the same. The curve, itself, may be offset due to the histories.

Question - But are your theoretical predictions still valid under the cases because histories losses can range as much as 20 to 40% or even higher?

Answer - For the materials that we talked about, in fact, Ted Diehl really goes into detail on this, material histories effects in terms of speed ratio are %. They were definitely measurable, though, because you can take two rollers, put two straight lines in them and turn them at 90 degrees. You expect those two rollers to line up, but they don't. And that, you see, is a good, quick measurement to see if there is a lot of material histories or not. For the material that we use, they certainly didn't line up perfectly straight, but they were really close. That effect was small.

Question - In your work, you bring the two rollers together . Do you have a force that brings them together? Is it a fixed shaft? Is it a loading force? If the loading force varies, is that going to change your results?

Answer - Absolutely. All the results that I've shown in the paper are from forced engagement of the shafts and are so far apart, then we compute a reaction, of course. If though, we just compute a load and the shaft starts to bend, that's another reason for things like sheet skew axial variation, because, again, what that gives you is engagement differences down the axis. What we do is literally force the engagement in the rollers and back out what the force was to push them down, because mathematically and numerically that's a lot easier than actually loading them up

Question - I wanted to point out some earlier work by the Technical Association of the Graphic Arts Industry in the late 60's where they found a neutral speed ratio through the nip by using a belt design. They were able to achieve a neutral speed ratio all the way through the nip. It was important not to smear the dots. And, I wondered about your amount of sheet rotation versus the deformation of the engaged rollers. What was the percentage of deformation? Was this a measurement that was an actual effect or a computer simulation?

Answer - The results were a computer simulation for one degree of shaft skew. And that is a higher end for a lot of photocopier problems when things become misaligned, especially due to things like humidity variations to the photocopier. Photocopier service calls go up by 90% in August because of all the humidity variations. For a lot of these things, one degree of shaft skew is not unheard of. That is the high end.

Question - Was it measured or simulated?

Answer - These results are all simulations. What's really nice, though, is you can take a really simple measurement with different rollers, cock the shaft, and watch the sheets go one way or the other. It's amazing to just watch it. It's very counterintuitive.

Question - On your Figure 30....

Answer - It's not completely independent of geometry. As you start to change the radius, the thickness changes, but that's not necessarily true. But, in general, that's really close. Hitting a speed ratio of one, even if you use very large rollers or thin rollers , the effect of the Poisson Ratio to do that would probably go between 0.25 and 0.35. That's about as big as you can get. Again, the big thing is not the speed ratio, because we set up the machine to compensate for that. The big thing is how that speed ratio changes.

Thank you.