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TROUBLESHOOTING WEB SCRATCHES

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Introduction

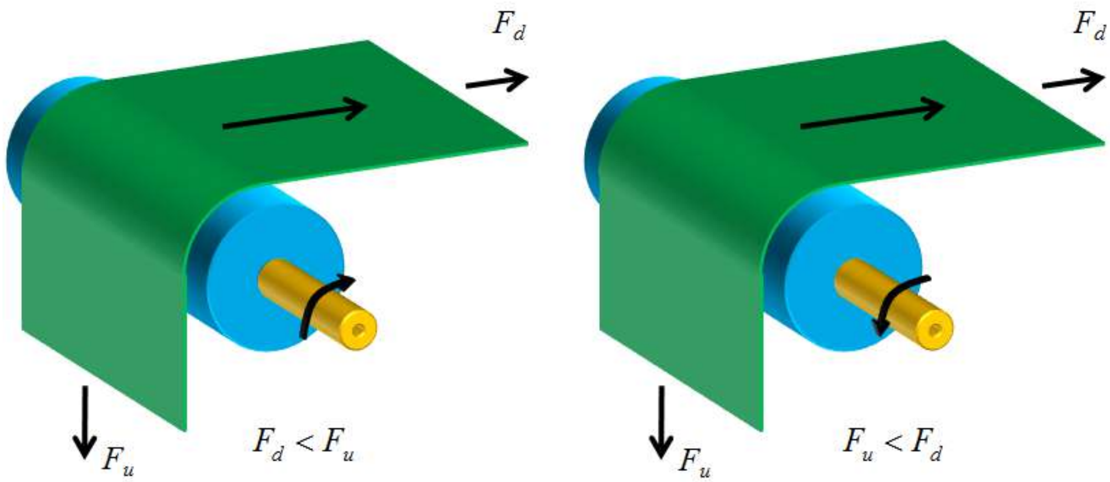
Roller conveyance deals with transporting a continuous web over rollers. Successful roller conveyance is achieved when this process does not damage the web. One defect that can be caused by an improperly designed or malfunctioning roller conveyance system is the formation of intermittent scratches. The purpose of this paper is to develop and present simple equations relating roller velocity and wrap angle in terms of scratch length, scratch pitch and web speed. It will be shown how the equations can be used to diagnose potential roller candidates that might be possible sources of scratches. In addition, troubleshooting guidelines will be outlined for the systematic elimination of scratches.

Roller Traction

A web is defined as a structure which is long, thin and flexible. Common web materials include paper, film, foil, nonwovens and textiles. Web handling is defined as any process that seeks to transport and handle a web while maintaining and preserving all of the web's properties with minimum web damage. Web converting is any process that takes one or more webs and permanently alters them in some fashion. Examples of web handling include unwinding, splicing, roller conveyance, air conveyance, lateral control, tension statics and dynamics, roll starts and winding. Examples of web converting include extrusion, drafting, tentering, surface treatment, coating, drying, slitting and laminating.

Successful web converting depends on successful web handling. In turn, successful web handling depends on successful implementation of several key web handling processes. One of the most important of these is tension control since tension is one of the key process factors impacting web handling. Tension control is the art and science of placement and control of motors and drives within a conveyance line so that optimum maintenance of tension throughout the line is assured.

Tension control consists of many subcomponents. A key one of these is the pull roller. Operationally, a pull roller is a conveyance component that can either be driven (e.g., motored) or braked so as to either remove or impart tension into the conveyance line (Figure 1). This capability is often required to satisfy web handling scenarios. A case where motoring would be required is after a long sequence of idling conveyance rollers. In this situation, tension is rising as the web progresses downstream due to the cumulative effect of air and bearing drag, inertial and possibly elevation changes. The presence of a motor driven pull roller will serve to lower tension downstream of the pull roller thereby eliminating the possibility of tension becoming excessively high. A case where braking would be required would typically be upstream of a winder. Here, tension typically needs to be higher than in the central portion of the machine; hence, the pull roller must act in a braking mode.



Part a: Motoring Part b: Braking

Figure 1: The Pull Roller Function

Regardless of which case is considered, the question arises as to how large this tension difference can be. For a plain pull roller, the *Capstan Formula* gives the answer. If the web slips at known tension values of F_H and F_L (where "*H*" stands for "high" and "*L*" stands for "low" tension), at a given wrap θ (radians), the coefficient of friction, *f*, may be calculated for this situation.

$$\frac{F_H}{F_L} = e^{f\theta} \; or \; f = \frac{1}{\theta} ln \frac{F_H}{F_L} \tag{1}$$

Corresponding values of the high and low tension limits depend on whether the pull roller is motoring ($F_H = F_u$, $F_L = F_d$) or braking ($F_H = F_d$, $F_L = F_u$).

Equation (1) likewise will also apply to the maximum tension difference that an idling conveyance roller can carry prior to slip. In this case, during normal operation at constant speed, the behavior of the idler would generally be equivalent to the pull roller operating in braking mode due to idler bearing drag. Under conditions of high deceleration, the situation could reverse due to inertial forces acting between the idler and web. In any case, for successful tension control, it is important to avoid conditions that result in slip whether we are talking about pull rollers or idlers.

The coefficient of friction at zero conveyance speed is equivalent to the static coefficient of friction and for plain pull rollers or idlers can easily be computed by performing a simple experiment. First, clamp the roller with its rotation axis horizontal to prevent it from rotating. Wrap a web around it and then load both ends of the web with known weights equal to F_L. Increase the load on one end gradually, until the web slips. The weight at that instant is F_H. Plug the data into equation (1) and obtain *f*. This is the "coefficient of friction at zero web speed, f_0" or static coefficient of friction. Figure (2) shows a schematic of this experiment.

Once the coefficient of friction is known, equation (1) can be used to compute the maximum tension ratio that a roller can sustain prior to web slippage. For example, for a typical value of a static coefficient of friction of 0.3 and a wrap angle of 180° or π radians, the maximum tension ratio is approximately equal to 2.5. Of additional importance is the fact that the coefficient of friction is not a constant in practice. At zero conveyance speed, the coefficient of friction is equivalent to the static coefficient of friction between the web and the roller. However, as conveyance speed increases, this will no longer be the case.

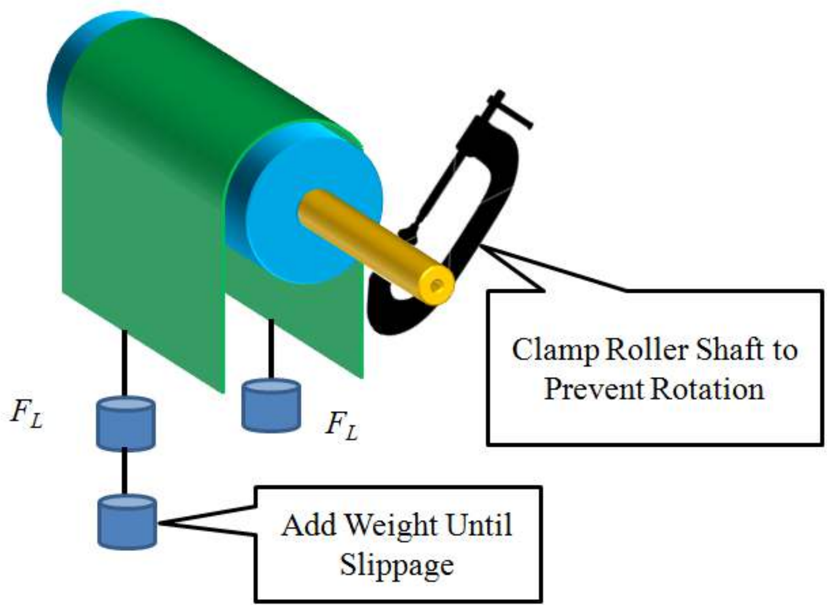


Figure 2: Measurement of Static Coefficient of Friction

In this paper, we are not interested in the details of how the coefficient of friction changes as a function of speed or as a function of the details of the surface of the roller. Additional discussion on these subjects can be found in reference 1. Instead, we are interested in the question of what happens when the tension change around a pull roller (or idler) exceeds the "*traction capability*" of the web/roller system. Roller traction is defined as the maximum tension difference that the web/roller system can support prior to "*gross slip*":

$$traction \equiv F_H - F_L \begin{cases} = F_L(e^{f\theta} - 1) \ if \ F_L \ is \ specified \\ = F_H(1 - e^{-f\theta}) \ if \ F_H \ is \ specified \end{cases} \tag{2}$$

and

$$(F_H - F_L)_{actual} \begin{cases} < traction \rightarrow microslip \ or \ creep \ will \ occur \\ \geq traction \rightarrow gross \ slip \ will \ occur \end{cases} \tag{3}$$

As long as the actual tension difference across the pull or idler roller is less than the traction, the system will be *controllable* and *stable* with at most, very minimum relative displacement between the web and the roller during transport over the roller (e.g., microslip or creep). By controllable and stable, what is meant is that there is a one-to-one correspondence between the roller angular position and web machine direction position and that at most; there will only be a very small amount of machine direction relative displacement between the web and roller. This results from the change in machine direction strain in the web as it progresses around the roller consistent with the tension change. If linear elastic behavior is assumed, it can be calculated and is only significant for very large tension changes, large wraps and very stretchy materials (reference 2). It should be noted in passing that equation (4) from reference 2 has a simple typo; the correct expression for the relative displacement requires that the right hand side be divided by the coefficient of friction.

The behavior of the system; however, will be different when the traction limit is exceeded. In this case, gross slip will take place and depending on the nature of traction forces being transferred between the web and the roller, can cause a range of different responses. In the case of an idler roller in a machine running at constant speed, the most likely scenario is that the idler will run slower than the line. This situation would be most likely to occur in a location where the tension is lowest (since traction is a linear function of nominal tension). Thus, one area of concern would be idlers immediately downstream of intermediate drives.

In the case of a pull roller, the response would depend on whether it was motoring or braking. In the later case, the response would be similar to the idler. In the former case, if traction is exceeded, the pull roller would run faster than the line.

The defining difference between all these cases and the normal scenario where the traction limit is not exceeded is the magnitude of the relative motion between the web and the roller. When the traction limit is exceeded, the relative motion between the web and roller can become very large. In the next section, an analysis will be presented that calculates the relative motion in terms of many key process and design parameters.

Why does one care about relative motion between the web and roller and how does this behavior manifest itself in the web line? There are several reasons one cares about this motion. First, it can reveal itself by compromising drive control functionality in the case of gross slip on a pull roller. In this case, angular motion of the pull roller is not directly coupled to machine direction motion of the web. This can result in instability in the tension and position control of the line. Second, it can reveal itself by compromising lateral position control of the web. It is well known that roller conveyance can become laterally unstable once traction is lost within the system. The reason is due to the changing nature of the web-to-roller forces, which influence the lateral tracking statics and dynamics.

Third, and most germane to this paper, relative motion can give rise to "*scratches*" on the web. What is a scratch? It is an abrasion or dig embossed onto the web and for it to occur, requires three components: (a) relative motion between the web and roller, (b) the presence of a burr or feature on the roller that insures that the relative motion will induce the scratch and (c) a hardness mismatch between the web and roller feature (the softest surface being the one where the scratch is revealed).

Figure 3 shows a schematic of what will be expected for three cases. First, consider the web as it engages the roller where simultaneously, a burr on the roller comes in contact with the web. This is the upper left schematic. If the web and roller speeds are matched, the burr and web will convey through and exit the contact zone as shown in the upper right schematic. Since the speeds are matched, there be no relative motion and hence, no scratch. There may be an *impression* or *mark* but, if the burr is not too large, this may not be a concern. Now, consider what happens if the web speed is faster than the roller speed (e.g., an idler with excessive drag or a braking pull roller). In this case, as shown in the lower left, the web will move ahead of the roller and the burr will cause a scratch to form in the web. The scratch will have a length and a pitch and further, the abraded material will tend to pile up on the upstream end of the scratch. On the other hand, if the web speed is slower than the roller speed (e.g., a motoring drive), the web will now run slower than the roller and as before, a scratch will form. In this case, as shown in the lower right, the abraded material will now tend to pile up on the downstream end of the scratch. Thus, it is evident that the presence of debris tells us something about what conveyance component might have been responsible for the scratch. Photomicrographs of scratches can often review this type of information and can be very helpful to help diagnose the source of the scratches.

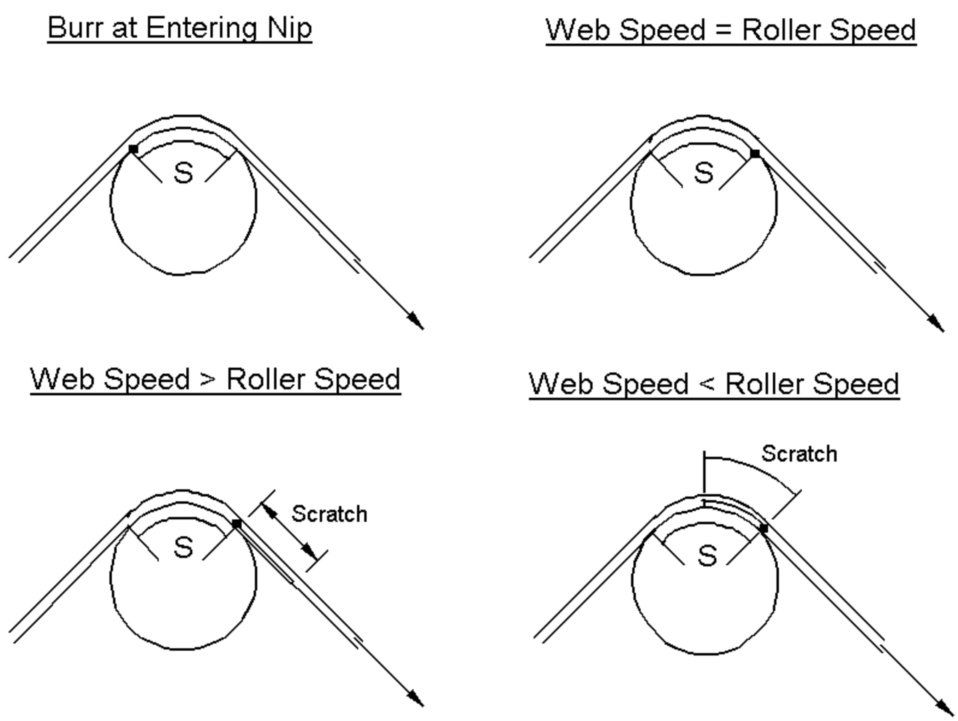


Figure 3: Scratch Formation Mechanism and Orientation

Continuous scratches can also occur in web lines and are differentiated from those caused by traction loss by their continuous and likely spatially fixed location relative to the web line and web edges. For intermittent and repeating scratches, the length and pitch characteristics of the scratches due to traction loss can be used to good effect to diagnose their source on the web line. For that purpose, we will need to develop the mathematical relationships between these features and the product and process parameters.

Scratch Analysis

The objective of this analysis is to derive equations for roller velocity and wrap angle in terms of scratch length, scratch pitch and web speed. These equations can be used to determine potential roller candidates in a conveyance web path running at a known web speed that will be possible sources of scratches with the specified length and pitch. The two important equations are **bolded** in the analysis and are summarized here:

$$\boldsymbol{V_r = \frac{\pi D V_w}{P}} \qquad (7)$$

$$\boldsymbol{\theta_d = \frac{360L}{\pi D - P}} \qquad (14)$$

The geometry of the problem is shown in Figure 4:

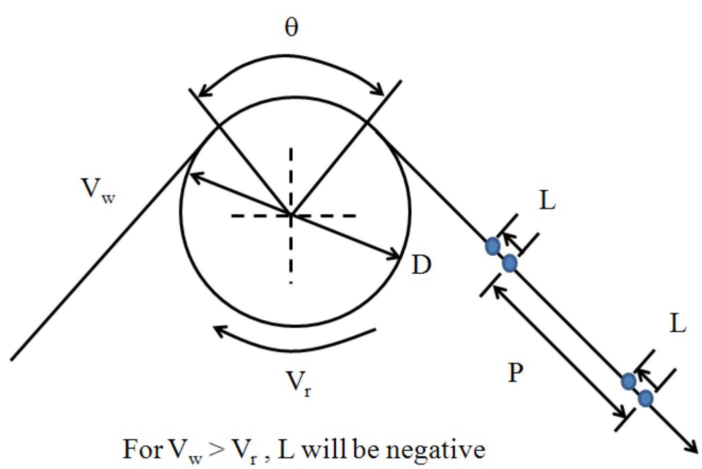


Figure 4: Scratch Geometry ($V_w > W_r$, L shown negative)

The variables are defined as follows:

V_w	web velocity, inch/sec
V_r	roller velocity, inch/sec
D	roller diameter, inch
L	length of scratch (positive when the web moves slower than the roller), inch
P	pitch of scratch, inch
θ	wrap angle, radian
θ_d	wrap angle, degree

Begin by computing the time required for the roller to rotate through one revolution:

$$t_{rr} = \frac{\pi D}{V_r} \tag{4}$$

The distance the roller moves in this time is given by:

$$x_{rr} = \pi D \tag{5}$$

The distance the web moves in this time is defined as the pitch, *P*, and is given by:

$$P = V_w t_{rr} = \frac{\pi D V_w}{V_r} \tag{6}$$

Solving equation (6) for the roller velocity yields the first important equation:

$$\boldsymbol{V_r = \frac{\pi D V_w}{P}} \tag{7}$$

Equation (7) indicates that the roller must travel slower than the web if the scratch pitch is greater than the roller circumference and faster if the scratch pitch is smaller than the roller circumference.

Next, compute the time for the roller to rotate through the contact zone:

$$t_{rc} = \frac{\theta D}{2V_r} \tag{8}$$

The distance the roller travels in this time is simply:

$$x_{rc} = \frac{\theta D}{2} \tag{9}$$

The distance the web travels in this time is given by:

$$x_{wc} = V_w t_{rc} = \frac{\theta D V_w}{2V_r} \tag{10}$$

The length of the scratch, *L*, defined to be positive when the speed of the roller is faster than the speed of the web (shown negative in Figure 4), is equal to the difference in distances traveled by the roller and web:

$$L = x_{rc} - x_{wc} = \frac{\theta D}{2}\left(1 - \frac{V_w}{V_r}\right) \tag{11}$$

Equation (11) can be simplified by using equation (7):

$$2L = \theta D\left(1-\frac{V_w}{V_r}\right) = \theta D\left(1-\frac{P}{\pi D}\right) = \frac{\theta}{\pi}(\pi D - P) \tag{12}$$

Equation (12) can be rearranged to give the following:

$$\theta = \frac{2\pi L}{\pi D - P} \tag{13}$$

Finally, equation (13) can be written in terms of wrap angle expressed in degrees:

$$\boldsymbol{\theta_d = 360\frac{L}{\pi D - P}} \tag{14}$$

Observation of equation (14) indicates that for a particular roller to be responsible for the scratch, the wrap angle must simply be equal to the ratio of the scratch length (numerator) divided by the length of the scratch if the wrap angle was one full wrap (denominator) times 360° (one full wrap). As is evident, the wrap angle will depend on the choice of roller diameter.

Equations (7) and (14) can now be used to determine combinations of roller velocity, wrap angle, and roller diameter that will give measured scratch pitch and length for a given web conveyance speed.

Troubleshooting Scratches

Let's consider the use of the equations presented in the previous section to help diagnose the potential source of scratches during conveyance in a web line.

To begin, the web speed is known and the scratch pitch (distance between repeat scratches) and scratch length have been measured. If it is further known that the scratch is repeating (and not a continuous scratch), it can now be assumed to be caused by a roller moving at a different speed relative to the web. In order to determine possible candidates, one guesses at a roller diameter. To make the troubleshooting process quicker, one would probably select a diameter corresponding to a roller that is thought to be the problem. Equation (7) gives the speed of the roller, V_r, and equation (14) the wrap angle in degrees required to yield the measured scratch and pitch. Does the roller diameter selected have a corresponding wrap as computed by the equations? If not, perhaps there are other rollers with the same diameter that do have the computed wrap angle. If so, then any of these matching rollers are possible scratch generators. If the calculated wrap values do not correspond to those of actual rollers, move on by selecting another roller diameter.

To further aid in diagnosing which roller is causing the scratch, the analysis indicates which direction the scratch is forming. If the roller is slower than the web then the scratch will be plowing back upstream (in which case the scratch length is negative), if it's faster the scratch will be plowing downstream (in which case the scratch length is positive). Of course, this frame of reference assumes that the surface of the roller is harder than the surface of the web; otherwise, the frame of reference reverses. The direction should be clear from microscopic examination and gives another clue as to which roller is faulty; especially since it would be known a priori which rollers are idlers (likely to cause drag leading to scratches plowing upstream) and which rollers are driven (can cause scratches in either direction depending on whether the driven roller is motoring (leading to scratches plowing downstream) or braking (leading to scratches plowing upstream).

Let's consider an example to demonstrate how this would work. Consider a situation where the pitch of the scratch is 12 inches. This would have been determined by averaging over a large number of scratches. Next, the scratch length has been measured to be 0.25 inches in length; again, averaged over a large number of scratches. Photomicrographs have not been examined to see if the length is positive or negative (e.g., roller faster or slower than the web respectively). Further, it is known that the web line is conveying the web at a speed of 880 fpm. This would b known from encoders located within the line. The question is: what roller in the line is likely to be the problem? Figure 5 presents the results from calculations using equations (7) and (14) for a range of roller diameters.

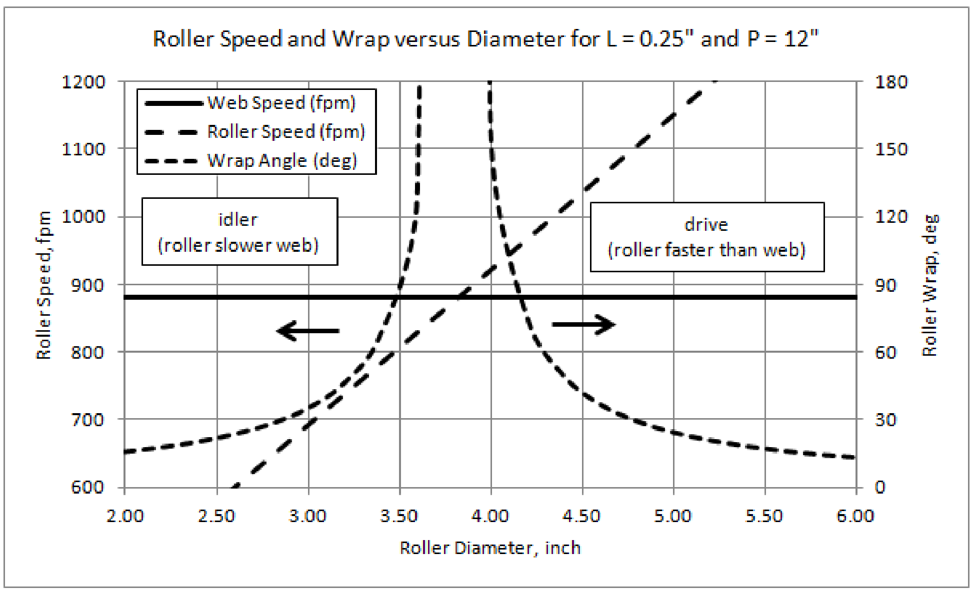


Figure 5: Typical Scratch Analysis Example
Scratch Length = 0.25", Scratch Pitch = 12", Web Speed = 880 fpm

From this graph, combinations of roller speed (left axis) and roller wrap angle (right axis) and roller diameter are shown that will yield the inputted scratch length and pitch. As indicated on the graph, there are combinations that will yield these results for the case of the roller being an idler (roller speed slower than the web speed) and for the case of the roller being a drive (roller speed faster than the web speed). In theory, any of these could be the culprit.

We make further progress by considering the fact that the key variables in the troubleshooting process are roller diameter and wrap angle along with knowledge of which are idlers and which are drives since combinations of these will be known for the conveyance line. For example, let's assume that in this conveyance line, idlers diameters come in three sizes: 2.5 inch, 3.0 inch and 3.5 inch. Further, assume that in all cases that the wrap angles are 60° or more. Lastly, assume that the drive rollers are all 5 inch and have either 90° or 180° of wrap. In this case, as shown in Figure 6, we see that the only roller that has the possibility of causing scratches with this pitch and length is the 3.5 inch diameter idler. At this point, we have been able to narrow down the suspected roller to the subset of idlers that are 3.5 inch in diameter with a wrap of 90°.

Diameter (inch)	Roller Speed (fpm)	Web Speed (fpm)	Wrap Angle (deg)	Roller Type
2.5	576	880	22	idler
3.0	691	880	35	idler
3.5	806	880	90	idler
5.0	1152	880	24	drive

Figure 6: Typical Detailed Scratch Analysis Example

This analysis can be readily incorporated into a simple calculator. For that purpose, the author is indebted to Professor Steven Abbott, creator of AbbottApps (reference 3). Professor Abbott is an independent scientist, consultant, training and technical software author on a range of subjects including, but not limited to, web handling. Professor Abbott has created an App named SLC (Scratch Length Calculator), which is available on-line for public use on any device that accesses the internet.

To use the App, choose the units of measure as either Metric or US. As you enter the key values you get instant feedback on the key outputs in the blue boxes. Some users prefer to use Text entry (it's more precise). Others tend to prefer Slider entry (especially on smaller devices). Feel free to choose whichever is most useful. An example from the App is shown in Figure 7 for the third row from Figure 6.

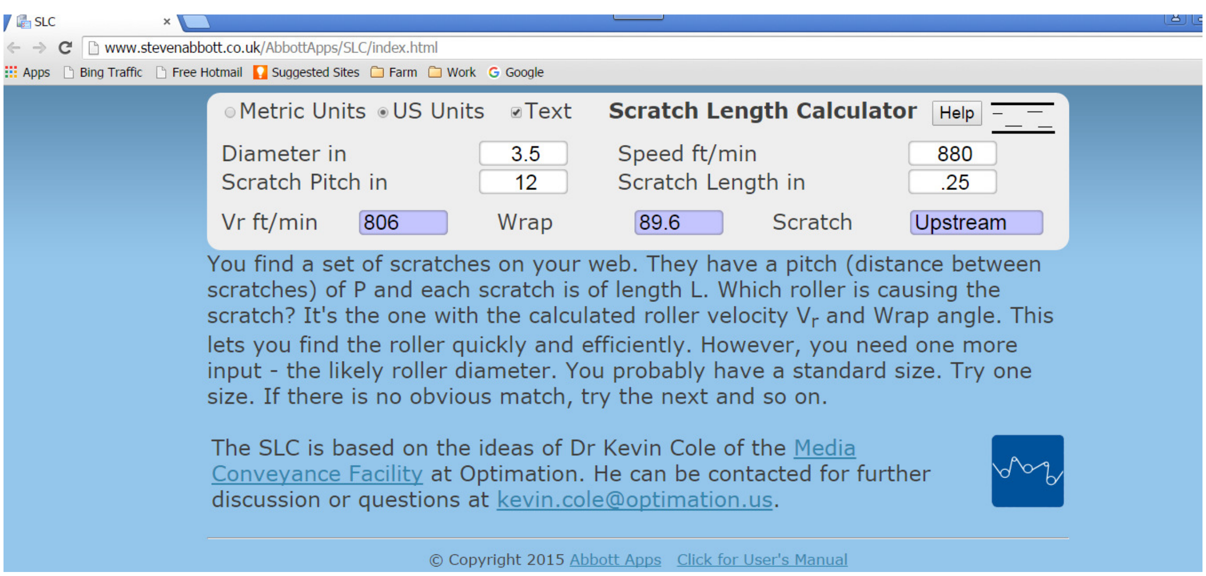


Figure 7: AbbottApp SLC Output

In addition to using the scratch length and pitch information to identify potential candidates responsible for the observed scratches, there are a number of additional troubleshooting questions that should be asked and steps that one should take when seeking to understand and eliminate web scratches:

- Is the scratch continuous or intermittent?
- Which side of the web is the scratch on?
- For a coating process, is the scratch coated over or not?
- Is the machine set up properly (e.g., tensions, vacuums, torques, etc.)?
- Is the orientation of the scratch purely in the machine direction or does it have an angular component?
- What has changed in the operation, process and product – cleanliness, environmental conditions such as humidity and temperature, roller wear, new or modified product, etc?
- Is the scratch length and pitch variable (e.g., might indicate problem occurring during acceleration/deceleration)?
- Can a stop test be performed?

By first progressing through this list, we will be able to identify the type of problem we are dealing with, where in the line the problem is likely to be occurring and whether or not the problem is due to special causes or is due to normal operation. Once these facts have been established, we can then proceed to use the scratch analysis to hone in on potential roller candidates responsible for causing scratches.

Conclusion

Machine direction relative motion between rollers and webs can occur during web conveyance due to the lack of adequate traction. In the presence of roller surface imperfections, such as burrs, this relative motion can give rise to broken scratches. These types of scratches will tend to have a repeatable pitch and length. In this paper, it was shown by analysis how this information can be used to identify possible conveyance roller candidates that might possibly be responsible for the observed scratch characteristics. The key equations from the analysis presented herein have been integrated into an Abbot App™ and that App, along with other troubleshooting tips described here, will enable web handling practitioners to more quickly isolate and eliminate sources of scratches in their conveyance equipment.

References

1. Cole, K.A., "Pull Rollers: Plain, Vacuum and Unported," *Proceedings of the International Web Handling Conference 2015*, Oklahoma State University, Stillwater, OK, June 2015.
2. Zahlan, N., Jones, D.P., "Modeling Web Traction on Rollers," *Proceedings of the International Web Handling Conference 1995*, Oklahoma State University, Stillwater, OK, June 1999, pp. 156-171.

3. Professor Steven Abbott (n.d.), [app SLC for analyzing scratch pitch and length information], retrieved September 7, 2015 from http://www.stevenabbott.co.uk/AbbottApps/SLC/index.html

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