MYTH BUSTERS: WEB HANDLING AND THE POWER OF MODELING

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ABSTRACT

Web handling is filled with myths and folklore about things to do and not to do, about how to design web paths, and about how to handle specific situations. The folklore and myths are often industry specific and many web handlers rely on their industry's folklore to do their work. In 40 years of web handling, the author has heard many of these myths. We have all heard the myths from, "Every driven roller needs to run faster than the last," and "Idlers add tension to a web," to "It ain't rocket science." Folklore is not always wrong and not every myth is busted. Some have a grain of truth or apply only in very specific situations. This paper discusses several of the more common web handling myths and uses simple formulas and logic to explain their origins and understand their validity.

NOMENCLATURE

D_n	idler drag, ΔT across an idler at nominal running velocity, N
E_w	web modulus = $\Delta T/\Delta\varepsilon$, N (Tension, modulus and drag are in force units)
T_h	web tension force on high tension side of an item contacting a web, N
T_l	web tension force on low tension side of an item contacting a web, N
T_n	web tension force in indicated span, N
T_{ref}	web tension force in reference span, N (Usually with dancer or load cell)
V_n	web velocity in indicated span, m/s
V_{ref}	web velocity in reference span, m/s (Usually the pacer or master roller)
ε_n	strain in indicated span
ε_{ref}	strain in reference span
θ	wrap angle, radians
μ	coefficient of friction

Subscripts

BAR	bowed axis roller
h	high
l	low
n	span index number, increases in downstream direction
ref	reference

INTRODUCTION

The development of web handling science is a recent event in the long history of web handling. In addition, through most of that history, web handling consisted of making and converting paper and tissue, materials that are not well understood, even today. Equipment and practices were developed by trial and error - guess and test methods. Successful things were remembered and repeated; unsuccessful things were remembered and avoided. The folklore and myths of web handling grew out of this early history and continue today to be the guidance that many engineers and operators rely on. This paper discusses several of the more common web handling myths and uses simple formulas and logic to explain their origins and understand their validity.

FOLKLORE

Idlers Add Tension to a Web

I have heard this many times and I have seen cases where people have added idlers to a web path in an attempt to solve a low tension problem. If you have low tension in a web path, adding idlers will not make it higher. The extra idlers are never good and they usually will make the low tension situation worse. Tension in a series of spans is controlled by a dancer or load cell and the velocities of the downstream driven rollers. Two formulas govern the relation between roller velocities, idler rollers, and tension. First is the strain transport formula,

$$\frac{V_{ref}}{1+\varepsilon_{ref}} = \frac{V_n}{1+\varepsilon_n} \qquad \{1\}$$

The second is the idler drag formula,

$$T_{n+1} = T_n + D_n \qquad \{2\}$$

Substituting the modulus formula,

$$T_n = \varepsilon_n E_w \qquad \{3\}$$

into formula {1}, and solving for T_n, we get formula 4,

$$T_n = E_w\left(\frac{V_n}{V_{ref}}\left(1+\frac{T_{ref}}{E_w}\right)-1\right) \qquad \{4\}$$

If we look at the web path in figure 1,

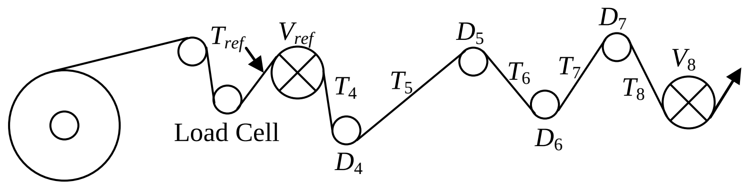

Figure 1 – Typical Web Path

we see that tension, T_8, depends only on the two roller velocities, V_{ref} and V_8, the reference tension, T_{ref}, and the web modulus, E_w. The tension, $T_{8,}$ does not depend on the number or drag of the idlers between V_{ref} and V_8.

The tension in spans upstream of T_8 is reduced by the drags of the idlers. T_7 will be less than T_8 by the drag, D_7, of the idler in between. Tension T_6 will be less than T_7, T_5 will be less than T_6, and T_4 less than T_5. Adding additional idlers between V_{ref} and V_8 will not increase T_8, but will lower T_4. Similarly, adding idlers upstream of the load cell or dancer idler will not alter T_{ref} since this tension is controlled by the load cell or dancer.

I think this myth originates with our experience of pulling an item with a rope. If we add more weight or drag to the item, or add more items to the rope, we have to pull harder on the rope. It would seem logical by analogy that adding more idlers and their drag in the web path would require more tension to pull them. However, web paths do not work this way. Other common analogies that do not work are higher pressure needed to overcome higher resistance to flow in a pipe, and adding rail cars to a train requiring more engines.

In the web path, the quantity of web entering span 4 in a unit of time is unchanged by adding an idler downstream of span 4. Necessarily then, the quantity of web exiting span 8, in the same time, must also remain unchanged, else web will accumulate or deplete in span 8. Since V_8 remains constant, ε_8 and T_8 must therefore also remain constant. The only way to satisfy this requirement is for T_4 to decrease.

The only glimmer of truth to the myth is if one adds an idler between the load cell and V_{ref}. The load cell control will maintain the load cell at its target tension. Consequently, the increased drag between the load cell and V_{ref} will result in a higher T_{ref} approaching V_{ref}. This will increase all the tensions downstream of V_{ref}. This alters the process in ways that are invisible to the load cell and the people managing the process. The same result could have been achieved more honestly, reliably, and at lower cost by increasing the set point tension of the load cell.

This myth is busted.

We Must Control Tension

Not always! Sometimes we want to control strain. Tension is a force and is an important factor in how the web interacts with the things it touches. For example, if you have a slot coating application, tension is the force that pulls the web against the applicator and is a major variable in the coating process. Here, the tension must be controlled in the coating span to manage the coating application. However, if you control tension, strain will vary inversely with modulus. Strain is a dimensional variable and sometimes dimensional stability of the web is more important than tension. In a multicolored printing press, you need a specific strain at each print station so that the length of the print pattern from the previous stations exactly matches the plate length of the following stations. Controlling tension would cause variation in length and result in print problems.

Some webs, like tissue paper, have wide swings in their stress-strain properties. They are also easily deformed and this makes them very sensitive to strain. With a variation in stress-strain properties, controlling tension would result in variations in strain and deformation causing undesirable variation in the final product. Any web that deforms easily is going to be strain sensitive. Lamination is also sensitive to strain. Ideally, the webs are at equal and low strain at the point of combining.

Many web paths will establish an initial reference tension with a load cell or dancer, as in figure 1 above. From the strain transport formula, we can see in formula 5 that the lower the reference tension, the less variation there will be in the combining strain due to modulus variation.

$$\varepsilon_{combining} = \frac{V_{combining}}{V_{ref}}\left(1 + \frac{T_{ref}}{E_w}\right) - 1 \qquad \{5\}$$

If the reference tension was zero, the combining strain would be insensitive to modulus. There are several schemes, like slack loop feed controls, that essentially provide a zero reference tension.

I think the myth that tension must be controlled at all cost derives from the fact that we can measure tension, but we can't measure strain. There is an old adage, "What is important gets measured," and its corollary, "What is measured, becomes important." It is the corollary that causes the trouble. If there is a tension measurement and readout in a web path, somebody will want to control the tension, if it is the right thing to control or not. What we need is a way to measure strain directly in a moving web.

As a general rule, this myth is busted. It can even lead you astray if strain is the important variable in your process.

High Friction / Coefficient Of Friction Adds Tension

I have heard people suggest lowering the coefficient of friction on a roller surface to lower the web tension. I think their mental image is one of dragging a block of stone with a rope. If the coefficient of friction between the stone and ground is increased, friction increases and you will have to pull harder. But, this is not how a web works in a web path.

Most of the time, it is desirable for a web to be in full traction with a roller, i.e., no relative velocity between the web and roller surface. If it is a driven roller, full traction enables the driven roller to control the velocity of the web, the whole purpose of driving the roller. If it is an idler roller, full traction allows the web to transmit the necessary force to the idler's surface to overcome the idler's drag, *D*, and keep the idler's surface moving at the web's velocity. In either case, driven or idler, full traction with the roller is good for tracking stability, tension control, and to reduce scratching and dust.

A higher or lower coefficient of friction on a roller's surface will not change tension. As long as the web is not slipping on the roller, changing the coefficient of friction does not change the web's velocity. High friction on driven rollers and idlers is good to avoid slip.

The capstan formula for a roller,

$$\frac{T_h}{T_l} < e^{\mu\theta} \qquad \{6\}$$

tells us that the maximum ratio of tension possible without slip across the driven roller depends on μ, the coefficient of friction. If the coefficient of friction is low enough to allow the web to slip, then you might see some change in tension due to a change in the web's velocity. If the upstream tension is the lower tension, the upstream tension will increase, and if it is the higher tension, it will decrease.

On sliding surfaces such as turn bars, folding boards, glue heads, etc, low friction, and therefore low coefficient of friction, is good. The capstan formula for sliding contact,

$$\frac{T_h}{T_l} = e^{\mu\theta} \qquad \{7\}$$

says that the tension upstream of sliding contact will decrease with increasing coefficient of friction. A higher coefficient of friction between the web and the contact surface will result in more drag, and therefore more of the web's tension will be lost to friction with the surface. In the web path in figure 2, T_6 is controlled by the T_{ref} and V_{ref}, by idler drags D_6 and D_7, and by V_8. Increasing the coefficient of friction in the sliding contact item, D_5, will lower the tension in spans 5 and 4. The other spans will be unaffected as long as no rollers slip.

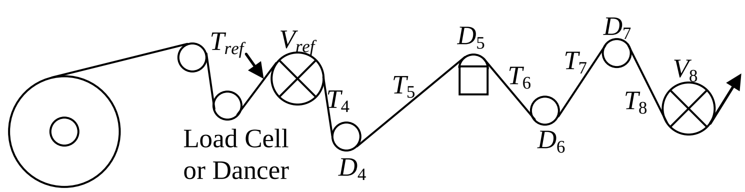

Figure 2 – Typical Web Path

The exact response to a change in coefficient of friction depends on the situation. With increasing coefficient of friction, tension may go down in some spans if it forces the web into traction with a high drag idler, or it may go up or down if it forces the web into traction with a driven roller depending on the rollers velocity.

Busted again! As long as the coefficient of friction is sufficient to maintain traction, nothing will change with an increase or decrease. I think the only thing that can be said is that, if changing coefficient of friction makes a difference, something is probably slipping, and that generally is not good.

<u>You Have to Increase the Velocity at Every Driven Roller</u>

I think this myth gets its start from web paths with too many idlers and too few drives. If you do not have a good understanding of how the web behaves, and you are trying to save money, this is the mistake that gets made.

Imagine you start unwinding at the parent roll with the minimum tension needed to pull the web from the roll. You then have a few idlers followed by a load cell followed by a few more idlers, and then a few more idlers before the first driven roller at the end of span 7. A plot of the tension so far is shown in figure 3.

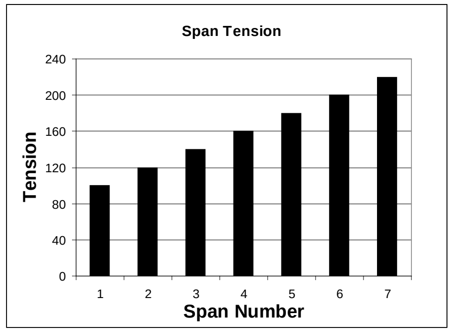

Figure 3 – Tension Plot by Span Number - First Seven Spans

If we duplicate this pattern of six idlers and a driven roller at the same velocity, we get the tension profile shown in figure 4.

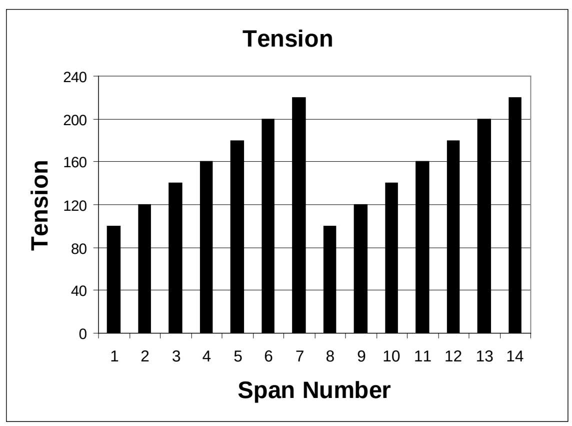

Figure 4 – Tension Plot by Span Number - Two Driven Rollers

This is where the problem starts. Many kinds of webs do not like to take large tension drops across driven rollers. The drop ratio from span 7 to span 8, T_h/T_l, equals 2.2. For wide webs, this large of a drop ratio can result in parallel trough in span 8 that wrinkle on the following rollers. The troughs form when web that is necked down by high tension in span 7 is released into the lower tension span 8. As the web tries to widen in span 8, it buckles. The only solution in this path is to increase the tension in span 8 by increasing the velocity in span 14. More idlers between span 7 and span 14 would lower the tension in span 8 making the drop ratio larger and the problem worse.

The better solution is to take smaller tension drops across the driven rolls. If we add a third driven roller and divide our idlers evenly between the driven rollers, we get the span plot in figure 5.

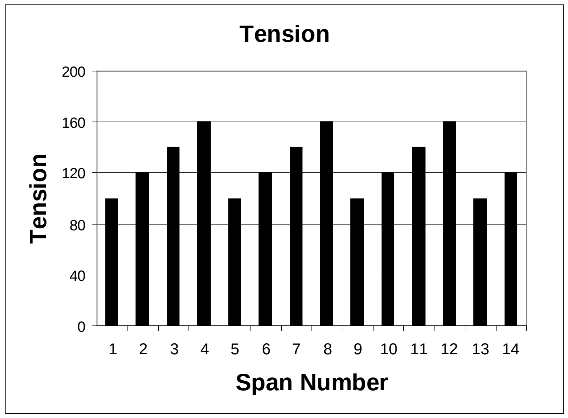

Figure 5 – Tension Plot by Span Number - Three Driven Rollers

The third driven roller allows reducing the drop ratio to 1.8. A fourth driven roller would look even better with drops of 1.6.

I think this myth comes out of old tissue paper lines where there were too many idlers and not enough driven rollers. If you have too many idlers, you have to have high tension at the driven roller to overcome their drag. This can damage a paper web and make the web even weaker as it enters the next zone of rollers. This problem is solved by pulling even faster at the next driven roller, causing even more damage. This pattern goes on and on, driven roller after driven roller. If you design the web path to not pull hard and damage the web in the first place, you don't have to pull faster and harder at the next driven roller to overcome the damage and wrinkles from the previous driven roller.

This myth is again busted! We will see in the next section that it is desirable to keep all driven rollers at the same velocity.

Low Modulus Causes Low Tension

There is variation in everything. It is a common belief that below normal modulus results in lower than normal tension and above normal modulus results in higher than normal tension. Lets look at the strain transport formula,

$$\frac{V_{ref}}{1+\frac{T_{ref}}{E_w}} = \frac{V_n}{1+\frac{T_n}{E_w}} \qquad \{8\}$$

If we solve for T_n, we get formula 9,

$$T_n = \frac{V_n}{V_{ref}} T_{ref} + E_w \left(\frac{V_n}{V_{ref}} - 1 \right) \qquad \{9\}$$

The first term, $(V_n/V_{ref})T_{ref}$, is always positive and does not vary with modulus. The term in parenthesis will be positive if $V_n > V_{ref}$, negative if $V_n < V_{ref}$, and zero if $V_n = V_{ref}$. Look at the web path in figure 6 with tension control in the first zone and draw control in the zones that follow.

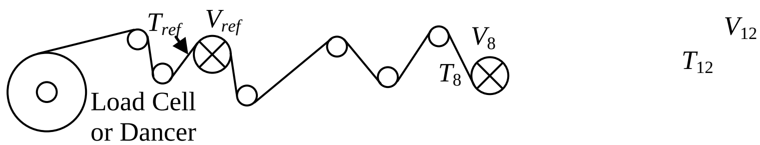

Figure 6 – Typical Web Path

Formula 9 tells us that if V_8 is slower than the V_{ref}, a decrease in modulus will result in an increase in T_8. In the same path, if V_{12} is faster than V_{ref}, the lower modulus will result in a lower tension. If there was a V_{16} the same velocity as V_{ref}, there would be no change in T_{16}. Conversely, if the modulus increases, T_8 will decrease, T_{12} will increase and, T_{16} would again remain unchanged. In the same web path, we could see some spans get tighter, some get looser and some not change at all. For this type web path, the myth is busted.

If we look at a pure draw control web path, without the load cell or dancer, we will see a similar result, except V_{ref} is the surface velocity of the parent roll and we don't know T_{ref}. T_{ref} will be the wound in tension at the outer wrap of the parent roll as each wrap is uncovered and enters the path. We can expect T_{ref} to vary throughout the parent roll based on the winding tension profile and the parent roll storage conditions. The T_n's will respond to T_{ref}, increasing or decreasing based on the ratio of their driven roller's velocity to the parent roll's velocity. For this kind of web path, variation of T_{ref} may be more significant than variation of E_w. Lastly, if the web path is all tension controlled, tension will remain constant. Strain will vary of course, but we can't see that so there are no myths about strain variation with modulus.

Generally, this myth is busted, unless you follow the myth saying every driven roll must be faster than the last, in which case it is true. (Is this Myth^2?)

Bowed Axis Roller Velocity

Bowed axis rollers have been around for a long time. How they work is well understood, and the requirements for the amount of bow, direction of bow, wrap angle, and approach and exit span length are described in detail in the thousands of pages written about them. Traction is required for them to work as intended, but most written material just assumes this is the case and provides very little guidance on how to achieve traction. No rules are given for determining the surface velocity of the bowed axis roller. I have heard several different "rules" for setting the velocity of a driven bowed axis roller, assuming that it is even driven. These range from matching the velocity of the upstream roller to +/-some% of nominal web velocity.

To work properly, the roller must be in traction with the web. Since the web is friction driven, it must satisfy the requirements of the capstan formula to avoid slip,

$$\frac{T_h}{T_l} < e^{\mu\theta} \qquad \{10\}$$

The best tension ratio to avoid slip is 1, where the upstream and downstream tensions are equal. At this ratio, there is no tendency to slip under any conditions of coefficient of friction and wrap angle. From the strain transport formula,

$$\frac{V_{BAR}}{1+\frac{T_{BAR}}{E_w}} = \frac{V_{Next}}{1+\frac{T_{Next}}{E_w}} \qquad \{11\}$$

we see that the strain and tension approaching the bowed axis roller will equal the strain and tension approaching the next roller when the roller velocities are equal. This is the ideal case. If the next roller is a driven roller, the bowed axis roller should equal its velocity.

$$\frac{V_{Idler}}{1+\frac{T_{Next}-D_{Idler}}{E_w}} = \frac{V_{Next}}{1+\frac{T_{Next}}{E_w}} \qquad \{12\}$$

therefore,

$$V_{BAR} = V_{Idler} = V_{Next}\left(\frac{E_w + T_{Next} - D_{Idler}}{E_w + T_{Next}}\right) \qquad \{13\}$$

For higher modulus webs, if we assume a nominal strain of 0.002, ($T_{Next} = 0.002E_w$), and a nominal idler drag of $D_{Idler} = 0.1T_{Next} = 0.0002E_w$, we then find $V_{BAR} = 0.9998V_{Next}$. For lower modulus webs, assuming nominal strain of 0.01 and nominal idler drag of $0.2T_{Next}$, we find $V_{BAR} = 0.998V_{Next}$. Both of these estimates are very close to matched velocity with the next driven roller.

There are two additional questions about bowed rollers, "Do we need to drive the roller", and "What affect does the bow have on velocity?"

We can go back to the capstan formula to answer the drive question. When the bowed roller is an idler with D_{BAR}, the downstream tension is T_h, and the upstream tension, T_h - D_{BAR}, is T_l. Substituting these into the capstan formula and solving for the ratio of D_{BAR}/T_h, we get formula 14,

$$\frac{D_{BAR}}{T_h} < 1 - \frac{1}{e^{\mu\theta}} \qquad \{14\}$$

For a wrap angle of 60 degrees, ($\pi/3$ radians), and a coefficient of friction of 0.3, the D_{BAR}/T_h ratio must be less than 0.27. This is possible for webs running at higher tension, but can be a problem with webs at lower tension. However not all of the available friction can be used to drive the roller, since some must be used for stretching the web in the cross direction. I have not seen a study of bowed roller drag and can go no farther with this. As to the direction of bow, at the point of contact with the roller the web has the same speed across its width and will have the same strain to satisfy the strain transport equation.

It Ain't Rocket Science

Well it is too! We both follow the same rules and use the same tools. $F = ma$ describes how rockets fly and how webs interact with idlers. Timoshenko's models work for wings and webs equally well. Made from rolled aluminum sheet or carbon fiber cloth, airplanes and rockets are made of webs. The snapback of a cut elastic thread follows the same model as a broken tethered satellite cable. Structural FEA models first developed for NASA have grown into a tool used to look at all aspects of web handling. In the US each year, we spend more money on toilet paper than we do on NASA.

I wouldn't want to fly in an airplane built using rules of thumb or folklore handed down from past generations. While generally not life threatening, the consequences of a failed web path can be life altering for the engineer or company that built it. In our highly competitive businesses, we need to optimize material costs, production speed and reliability to squeeze a few more pennies per product out of costs. Trial and error methods got web handling through the first 200 years, but won't get us through the next ten. It is not enough to roll gun powder in a paper tube and light it off. Our ongoing success and growth depends on replacing myth and folklore of yesterday with fact and knowing generated by experiment and models. Our products are only as good as we know how to make them. The days of getting by with myths and folklore are over.