THE 10 COMMANDMENTS OF WEB MACHINE DESIGN

by

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ABSTRACT

This paper describes the most important aspects of roller design, selection and maintenance necessary for a smooth running web process. Included are discussions of alignment, deflection, geometry, surfaces, traction, and tension control. Design criteria for sizing and tolerancing rollers will be given which are based on web handling mechanics. Also given are simple field checks for a quick evaluation of existing machinery.

INTRODUCTION

Rollers are the foundation of all web manufacturing and converting processes. They allow us to economically manufacture our products continuously instead of in batches. Despite their ubiquitousness, however, rollers are often poorly understood and appreciated. They may be dismissed as trivial and uninteresting components because of their deceptively simple appearance.

However, rollers are neither simple nor unimportant. Their complexity is such that an entire handbook can (and is) being written to describe their behavior.[1] They are so vital that they can be the most important aspect of web processes. While raw materials are also important, the material's interaction with rollers can largely affect quality and productivity. With few exceptions, webs are formed, converted and transported principally on rollers and related elements. Thus, it is appropriate that all machines first conform to good roller design practices. After which, other aspects of machine design such as safety, access, operation, cost and so on can be incorporated as required by the uniqueness of the product or process. In this article, we will merely highlight some of the most important roller considerations. The guidelines given here will be suitable for most applications.

DO NOT USE EVEN A SINGLE ROLLER MORE THAN NECESSARY

The best machines often have the fewest parts, and rollers are no exception. The more obvious reasons to reduce roller counts are to reduce initial costs, maintenance, machine floorspace, as well as threading and cleanup time. However, as will become more apparent shortly, rollers can damage webs.

Rollers serve one of two primary functions. Transport rollers merely carry the web through the machine as opposed to modifying the web, and are often supplied in excess. Indeed, one may be able to judge the skill of a machine designer solely by how few transport rollers are used. Justifying transport rollers by arguments such as to orient a web run and to reduce a span length are usually weak. One can often improve existing processes merely by threading around rollers that do not serve an essential function. Process rollers, on the other hand, are usually required by the application and are seldom supplied in excess.

DO NOT ALLOW A ROLLER TO DEFLECT EXCESSIVELY

Perhaps the most common design error is to select a roller that is too slender. Rollers with undersized diameters will deflect excessively under the combined forces of gravity, tension and nips. Some of the many problems that can result are: machine direction trough wrinkles,[2] wrinkling through a nip, process variations in a nip,[3] and tension profile variations. Slender rollers also are susceptible to being bent and are difficult to balance. Roller deflection can be quite serious. In one instance, for example, a single undersized $1K lay-on roller caused $1M in waste.

Specifically, as given in Table 1, one should allow no more than about 0.00015 x width as a maximum deflection for most rollers. The deflection of rollers, shown in Figure 1, can be calculated from beam bending equations. As a very rough rule of thumb, however, properly sized rollers will typically have slenderness ratios (length/diameter) of 10-15 for nipped rollers and 15-20 for lightly loaded transport rollers, and are relatively insensitive to shell material or wall thickness.

Cantilevered machines, common in narrow web converting, also must abide by deflection standards. Unfortunately, cantilevers have two handicaps not shared by their larger machine cousins. First, the roller component that resists deflection is the shaft of the dead shaft roller, which is much smaller than the shell. Second, mounting and framework compliance adds to the effective differential deflection.

NEVER ALLOW A WEB TO SLIP ON ROLLER

The three states of web/roller interaction include floating, sliding and traction. Traction can sometimes be lost on rollers so that the web slides across part or all of its width. Factors that aggravate slippage are lightly wrapped rollers, slippery web and roller surfaces, air/fluid entrainment and high inertial or drive torques. If an idler roller can't be configured to avoid slippage, it must be driven. If a driven roller slips, it must be reconfigured or the drive strategy changed.

The obvious result of slipping may be roller surface wear and web marking (of some grades). However, a more serious universal result is the loss of web control. When a web transitions between floating, sliding or traction on even of portion of its width, there will be both a tension and edge position upset. This becomes particularly debilitating with processes that require registration, or have those with tight tolerances for length, width or position. About the only common exception to the no-slip rule is a coating process roller that may be driven at a different speed than the web to induce fluid shear.

The band-brake equation can be used to calculate whether a roller will slip. Specifically, this equation predicts the maximum tension ratio that can be sustained across a roller as a function of wrap angle and coefficient of web/roller friction. The major application difficulty is obtaining the friction coefficient. For cases where air/fluid entrainment is negligible, the friction can be obtained by simply dragging a weighted strip of web with a force scale over a locked roller as seen in Figure 2. Even at high speeds, however, the reduction of traction due to air/fluid entrainment can be made negligible with proper surface texturing or grooving.

Unless a roller is in a state of gross slippage, it is actually quite difficult in practice to determine the extent of slippage if it occurs sporadically and/or over part of the wrap or width. Indirect evidence can be obtained by how quickly a (bluing or original machining) mark is removed from the roller surface, or the absence of a patina on metal rollers, or the presence of glazing on roller covers. Direct evidence can be obtained by tachometer or laser measurements of web speed compared to roller speed if it is sufficiently sensitive.

AVOID HIGH TENSION DIFFERENTIALS ACROSS ROLLERS

There is a tension difference across every roller determined by three components. The first is drag caused by bearing friction, windage, and nip rolling resistance (if present). Drag can be measured by a coast down test using Torq=Iα. Bearing drag can be simply checked in many cases by making sure an idler roller will coast for at least 10 seconds after a sharp hand spin. The second component, only seen on speed changes, is roller inertia because the torque to accelerate or decelerate the roller's mass is supplied by a tension difference across the roller. The largest factors in inertial tension are the roller's diameter (machine width) and the machine's acceleration rate. Though some relief can be obtained by using 'low inertia rollers', reducing roller count should be the first step. The last component, only seen with driven rollers, is the torque applied by the drive mechanism.

There are a few situations where a high tension differential across rollers is needed, and will generally be across a driven roller. One is where the web undergoes a large change in strength, and thus requires a different tension setpoint in that zone.[4] Another is where tension must be stepped up or down from zero, such as on a threading or sheeting operation. As a general rule, however, tension should not vary more than about 10% through a tension zone due to drag or helper drive error and not more than about 15% for inertial tensions. This effectively determines how many non-driven rollers can be used. Figure 3 illustrates this concept with a simple tension control section.

REDUCE CLEARANCE AND COMPLIANCE

Rollers and the mountings can have excessive clearance and compliance. The resulting problems include compromised alignment and machine vibration. Bearings can have more clearance than the few ten thousandths of an inch needed for proper operation. An extreme example is some self-aligning bearing styles that may have many mils (0.001") of clearance, even when new. More often, it is a pivoting or sliding roller mounting that has excessive clearance. However, even a tight bearing and mounting can be compromised if it is attached to a flimsy framework, such as a cantilevered beam. In general, the total system clearance and framework deflection under applied loads should be much smaller than values for allowable deflection or misalignment.

ROLLERS MUST BE ALIGNED

Misaligned rollers can easily wrinkle light weight webs,[5] and can contribute to a loss of traction on stiff webs. Furthermore, a misaligned roller will skew the tension distribution as seen in Figure 4. It is not unusual for misalignment to cause the web to go baggy on the loose side, and yet be so tight on the other side as to damage or break to web. The only cure for these and related problems is to periodically realign every roller in a line. Alignment is degraded with time due to subtle stress-relaxation of framework, foundation movements, and roller rework. The alignment tolerance could be calculated by as the in-plane angle that causes wrinkling,[6] the angle where web tension is skewed by say 10%, or where traction is lost on one end.

As a practical matter however, alignment tolerances must be tempered by what is practically achievable. While optical alignment should bring a roller in to less than 10 mils in a single move, it may be difficult to consistently achieve alignments less than 2 mils. Unfortunately, the cost of optical or laser realignment can exceed the costs of some rollers, giving yet more impetus to reduce roller counts. The more common response is, unfortunately, to attempt alignment using machinists levels or Pi tapes. However, the desirable tolerances for alignments on most machines is <u>far</u> tighter than can be obtained by hand tools.

ROLLERS MUST HAVE TIGHT CYLINDRICITY TOLERANCES

Webs will steer toward the high diameter portions of a roller. Thus, a bulge on one end will cause a web edge offset, while a bulge in the middle can cause a light web to gather or wrinkle there. More seriously, rollers in nip are extremely intolerant of roller geometrical imperfections and result in product and process problems too diverse and numerous to mention here. To avoid these roller induced disruptions of web stress, the roller must be machined and maintained to tight tolerances.

Figure 5 shows the common measures of roller cylindricity errors. Radial runout is the deviation from circularity in a particular plane (CD position) and is often called TIR (Total Indicator Runout). Maximum diametral variation, and equally important, station-to-station diametral variation are the other two important measures. In general, most rollers should be machined to about a 2 mil tolerance by those measures. However, hard process rollers, particularly those in nip, may need tighter tolerances of about 0.2-0.5

mil. Covered rollers, on the other hand, can and need only be machined to about 1-5 mil tolerance. With time, rollers will wear and may need to be reground when their outgoing tolerances reach about 2-4x the ingoing specifications.

MOST ROLLERS NEED TO BE BALANCED

Roller imbalance is the primary cause of machine vibration,[7] and can be a major contributor to web tension surges. Thus, nearly all rollers need to be balanced after machining, and in some cases after re-machining. Only applications with very heavy webs running at very low speeds may not need roller balancing. At low speeds (10-100 FPM), a simple static balance may be adequate. Static imbalance can be checked on some rollers with very free bearings as the tendency pendulum to the heavy spot. Intermediate speed (100-1,000 FPM) applications will require a 6.3 class balance, while a 2.5 class may be desirable for very high speeds (1,000-10,000 FPM).

ROLLER SURFACES

The previous roller design and maintenance criteria are fundamental to all rollers, webs and applications. Only after these are taken care of do we need to look at application dependent considerations. Of these, we will merely note a few common roller surface options.

Some rollers are coated with a thin metal such as anodize, chrome or tungsten carbide. This additional treatment is often for one of two principal reasons. First, coatings are much harder than the base metal, which makes the roller more resistant to abrasion or other damage. Second, coatings allow a greater control over surface roughness, which can vary from a mirror smooth polished chrome to a very gritty tungsten carbide. Smoothness may be desirable to avoid web marking or enhance web or material release from a roller. Roughness may be desirable to increase roller traction. An interesting recent development is Teflon impregnated tungsten carbide which can grip the web while being resistant to fouling.

Some rollers are covered with one of a dozen or more common polymer options. The most common motivation for covering is to reduce the intensity and improve the uniformity of a nip. Also, covered rollers usually have a higher web traction than smooth metal.

Whether plain, coated or covered, rollers are sometimes grooved or machined with a bewildering variety of patterns. Sometimes these patterns are given near mystical attributes. The most common fallacy of which is the ability to spread webs. Unfortunately, the reality is that grooving or raised topology tends to contract rather than spread the web.[8]

The principle reason to groove a roller is to allow a fluid (air or liquid) to pass around the roller, instead of lifting the web that will reduce traction. Thus, grooving should be considered for light nonporous webs traveling at moderate or higher speeds. Unfortunately, many common grooving patterns are not well engineered for this purpose. In general, the groove pitch is far too large, and the groove width and depth greater than needed or desirable. The required cross-sectional area of the grooving is such that the air film height that would have been pumped between the web and roller[9-10] can be passed through the grooves instead. Another very important constraint is that the width be no more than 10-20 x web caliper to avoid pulling it into the grooving. If one goes through this quantitative design exercise, they will find that the optimal grooving may be similar in character to the grooves on a phonograph record.

CONCLUSIONS

Rollers are the foundation of all web manufacturing and converting processes.

Follow their design rules or be prepared to answer for the potential consequences.

ILLUSTRATIONS

Fig. 1 - Deflection of Simply Supported and Cantilevered Rollers

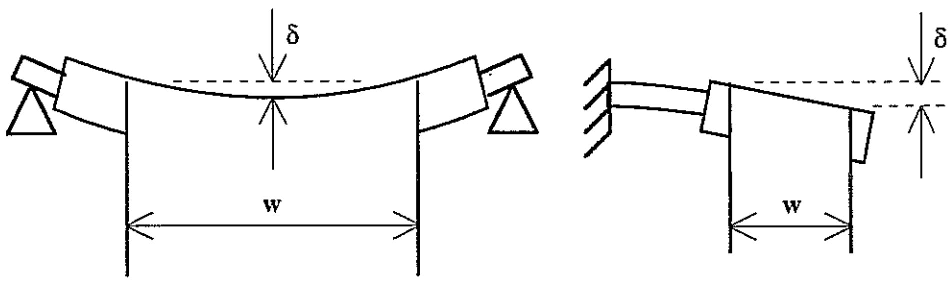
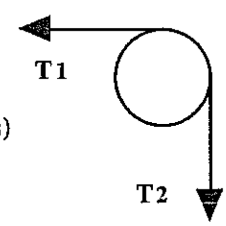


Fig. 2 - Band-Brake Equation for Web/Roller Traction

$$\frac{T_{hi}}{T_{lo}} \leq e^{\mu\theta}$$

θ = wrap angle (radians)
μ = coef of traction



Measuring Traction
1. lock roller
2. weight web strip
3. pull wgt up, back calc μ
4. let wgt fall, back calc μ
5. traction is avg of 4 & 5

Fig. 3 - Tensions Through a Control Zone

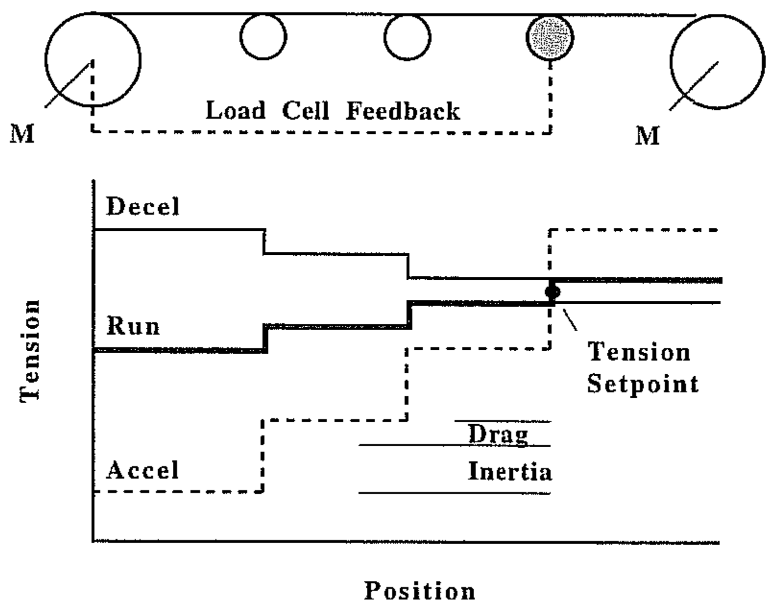
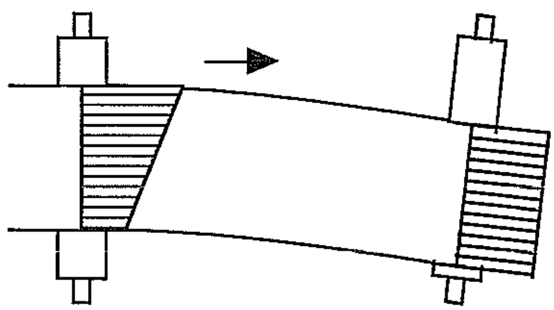


Fig. 4 - Tension Variations Upstream of a Misaligned Roller

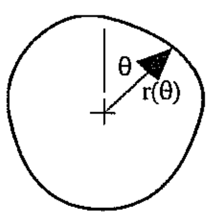


Alignment Guidelines
(0.001"/100"width)

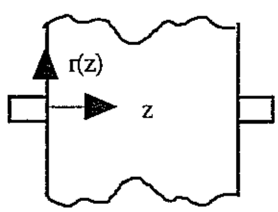
2 - most applications
5 - extensible or l/w > 10
10 - extensible and l/w > 10

but not < 0.002" or > 0.020"
regardless of face

Fig. 5 - Roller Cylindricity Errors



Radial Runout
measured with a
dial indicator



Diametral Variations
measured with a
caliper

TABLE

Table 1 - Allowable Roller Differential Deflection Across Web Width

Class	Deflection	Application Examples
Class A	< 0.00008 x width	precision or nipped applications
Class B	< 0.00015 x width	most rollers
Class C	< 0.00030 x width	flexible or thick materials
Class D	< 0.00060 x width	conveyors, spreaders, wind shafts and cores

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APPENDIX

Mechanics of Rollers - Table of Contents

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Roisum, D.R.
The Ten Commandments of Web Machine Design
6/21/95 Session 6 10:40 - 11:05 a.m.

Question - I appreciated you comment that all rollers should be optically aligned and on your slide you also said they should be around one or two thousandths. I'll give you the opportunity to turn it over to a thousandth per inch of face of measurement because it's the angle and not the
thousandth that counts, especially on narrow machinery.

Answer - This is very much true. The web is affected by angle. I suggest a design criteria whereby one end of the web has no more than ten percent tension difference than the other side of the web. It truly is an angular discussion. It turns out that if you do the calculation, our paper industry is actually aligning to tighter tolerances than they need to be. But what about you film people who don't align at all; what about the narrow web converters where alignments are almost unheard of? We not only have to have the angular tolerance and that's all in my book, but there's also a criteria of practicality. The two to ten mils is a practical recommendation where ten-thousandths is easy to make with one move and under two-thousandths is enormously difficult to achieve. So yes, you're right. It was just a practical constraint on what the web would prefer.

Question - Relative to this alignment, if you're working with a web which is a relatively compliant, then you probably could be a little bit more casual in your tolerances and get away with tape measure type stuff. Just because you use a tape measure, in any craft there are people who do a great job, but when we start to get into narrow webs that are stiff, then even optical alignment may not be adequate and it may be appropriate, if not necessary, to go to laser technology and things of that sort , because if you try to set up a machine that's 350 inches wide, you can get by with ten-thousandths alignment tolerances in many cases that would be more than adequate. But if you do an 80-inch wide machine and suddenly it starts to get borderline on the limits of doing it with optical alignment, if you were to tear the optical equipment down and set it back up again and try to get exactly the same results. As you suggested with your converting equipment, starting with a 40-inch wide machine and 20-inch wide machines, you can't get there with optical alignment.

Answer - The best thing they can do is to align as close as possible and let it slip on the roller like a slip clutch to relieve the abuse a little bit, if alignment is not good enough.

Question - What is your view on people who use adjustable rollers on the line to compensate for a fault on the web?

Answer - Compensating for what?

Question - A fault in the web, such as baggy edge or baggy center.

Answer - That might be okay to do on occasion if very strategically placed in front of a nip, for example, and it's only useful where the camber or some other error varies linearly from front to back. If you want to get another degree of adjustment, you can use a bowed roller, again, often right in front of a nip. But often people have too many adjustable rolls. If you put adjustments in a machine you'd better take the knobs away from the operators, or they may cause more problems than they solve

Question - Optical alignment is fine and can be pretty accurate and it makes it now hard to do levelness measurements. Do you have any suggestions on how to make level measurements with a high degree of accuracy?

Answer - No, I don't, not beyond the optical alignment which is good to about one-thousandth of an inch.

Thank you.