A STUDY OF OSCILLATION

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ABSTRACT

There are many reasons to consider oscillation. Most fall under the overall desire to smear out streakiness in web caliper (basis weight, gage, thickness etc) so that it doesn't build up on some downstream process; most particularly winders. Bagginess and corrugations are just a few of the many 'winding' defects that may be helped by oscillation. However, many defects are too wide to be economically remedied by oscillation. This is because most oscillating systems will require an additional trim loss. This forces an economic tradeoff between defect waste (and/or customer complaint) by not going *far* enough and trim waste by going *too* far. Exceptions are blown film because it oscillates the entire width (circumference of the bubble). Yet here we run into another limitation of oscillation that blown film suffers more than most. That is it may not be oscillated nearly *fast* enough to avoid caliper buildup damage. This paper reviews the motivations in detail as well as the common machinery of oscillation. The paper also reviews the literature on the subject that is, in a word, nearly nonexistent. Next, a simple model is presented that can help guide the process designer in selection of oscillation stroke, speed and shape. Finally, the model results are compared to the nearly nonexistent application guidelines.

KEYWORDS

Oscillation, wind, unwind, displacement guide, steering, guide, bagginess, corrugations, gage bands, trim, waste, defect.

MOTIVATION TO OSCILLATE

There are many reasons to consider oscillation. Even so, nearly all fall into the umbrella desire to smear out streakiness in web caliper (basis weight, gage, thickness etc) so that it doesn't build up on some downstream process; most particularly winders. The streakiness of paper, in particular, has been formally studied in book-length detail [1].

The conclusion is that profile (across width) variation tends to be far higher than down-web variation. Indeed, a fingerprint streakiness may persist for hours or days or even be largely an ever-present shape since the machine was commissioned (particularly with regards to edge effects). This streakiness is also a characteristic of nearly all webs. Sometimes by intention (print or seal lanes, selvedge edges on textiles, etc), but most often unintentionally.

It is well documented that winding up gage bands is one of the largest causes of **baggy webs** in general as seen in Figure 1. A landmark study on paper grades showed that a 10% variation in thickness, equivalent to about a 1% variation in roll diameter profile, was way beyond commercially acceptable tolerance for shipping rolls [2]. In film and foil you can be almost certain that the root cause is winding a web with a thickness profile (variation across the width) problem. Unfortunately, the scanner or test lab often can't 'see' the web streakiness well enough. Inadequacies of profile measurement are common enough either because its spatial resolution or especially the thickness resolution is not good enough to pick up the damaging gage bands, especially on thin materials. The typical 'threshold of pain for thickness' is 1-10% variation. At 1% you have no (or few) problems and at 10% you have no (or few) customers. (Note, foil needs to be better than that while blown film can easily be 2-4X that because it is oscillated 360 degrees). In the many cases where the test lab and scanner are not adequate, you may instead try to look at hundreds of layers using roll hardness [3,4]. Unfortunately, test lab, scanner and roll hardness alike may not work well (be predictive) for many soft webs, such as nonwovens, textiles and tissue. Still, whether you can or can't 'see' the variation or whether it is the best your process can do is totally besides the point. Caliper variation buildup beyond a certain point will not be tolerated by the winder without defect.

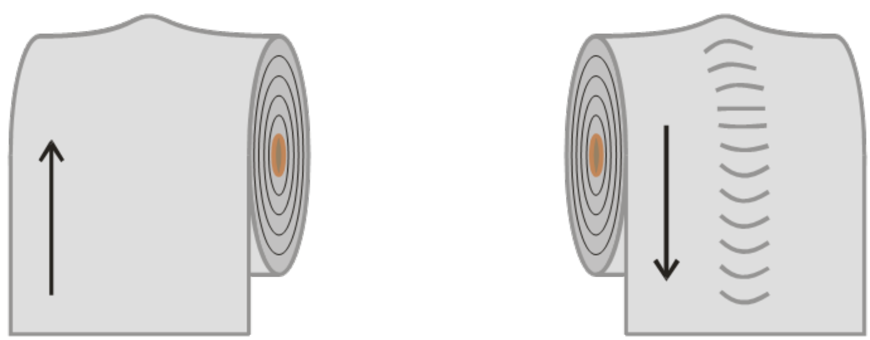

Figure 1 – Baggy Web Caused by Winding Gage Bands

The motivations to oscillate are not limited to bagginess as epidemic as that set of problems are. **Corrugations**, as seen in Figure 2, are common on all but the thickest webs. In virtually all cases the corrugation is at a low spot, especially if there is a narrow high-low-medium pattern. Yet, the benefit goes beyond the corrugation that is one of scores of tight winding defects. In principle, oscillation may also help with ANY **tight** OR **loose defect** by widening the window between tight and loose defects (in the same roll) so that setting *average* winding tightness by the TNT's is more effective

Figure 2 – Corrugation Caused by a High-Low-Medium Caliper

Raised edges due to slitting can occur when a cutting device stretches the edges into ‘ruffles’ that build up almost as if the layers were thicker. This slitting lip can exceed 2 cm (1 inch) in height in especially egregious cases. The irony here is that typically the *gage band* causes the baggy lane whereas with raised edges from slitting the *baggy lane* causes the ‘gage band.’ This edge may be severely blocked (layers stick together) and the wound roll may not sit well on its bilge. Fortunately, the stretched edges are so narrow that the oscillation stroke need not be large. Still, we have the challenge of stagger wound roll edges or trim loss in the next operation.

In netting and some **coarse textile weaves, the warp (MD strands) can misbehave** if they are stacked on top of each other during winding. There are even occasions where oscillation is to protect processes other than winding. Sometimes an unwind may be oscillated to **protect downstream calender rollers** from being marked by edges or persistent high caliper areas. Occasionally the unwind and winder are oscillated in synchrony to protect either the calender rolls (if the incoming web is streaky) or the winder (if the calender rolls make streaks) while still avoiding both staggered edges and trim loss. Although not directly studied here, the winding of yarn, ropes and wires on sheaves and traverse winding of ribbon-like materials also employs similar considerations.

The motivations for *this* study would be to improve our understanding of the applications and limitations of oscillation. Certainly the need is there because until quite recently the subject had virtually no mention in the literature [5]. This disconnect between what was suspected, known and/or practiced and what was published is large. This was exacerbated by a recent challenge to explain why blown film oscillation was so slow [6]. In other words, **blown film damage** is clear because so many extra thick lanes of thousands of layers accumulated on the winder before the oscillator moved the web sideways very far. The primary defect in blown film and its subsequent products (such as laminated packaging) is what is termed as **‘ring stars’** where rings of starring defect had no readily discernable pattern on rolls or even between one side of one roll and the other side of that same roll. Here we will discuss methods of oscillation and then follow with a simplified analysis of the benefits for certain classic gage band errors.

HOW TO OSCILLATE

A guide can move the web sideways. The most common applications are to correct the path of the web at the unwind (to start the web in a consistent CD location), winder (to wind straight edged rolls) or in between (steering guide for long entry paths or displacement guides for short paths). Each has its own design limitations such as how fast (maximum correction rate) or how far (stroke) the web can be moved. These limitations are primarily for guiding as oscillation tends to be less demanding. Almost any of the guide types as shown in Figure 3 can be made to oscillate. In addition to guides, a quickly moving **side-shifting roller** can move the web, but only a very small amount and thus is confined to applications such as coarse textiles and nettings to keep the MD strands from aligning.

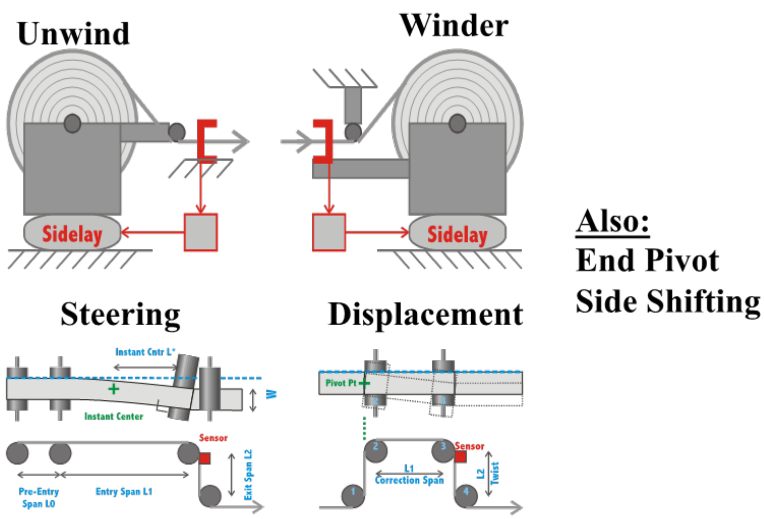

Figure 3 – Common Guides Used for Oscillation

Oscillation is particularly easy for digital controls because all one needs to do is superimpose a stroke magnitude and stroke speed (or cycle time) upon the steady state part of the command that may be either fixed or following the web's edge (or center). Both magnitude and speed for oscillation are typically well within the mechanical and control response capabilities of most guides. In fact, the speed of oscillation tends to be slower or much slower than the guide response needed for good edge guiding. Even non-digital guides can be made to oscillate using a cam (sine wave) or limit switches (bang-bang) to shift the guide.

The control decisions for oscillation include shape, stroke and speed. The three 'shapes' of oscillation are: zig-zag (bang-bang), sine wave or full 180 or 360 degree oscillation (blown film, traverse wound and sheaves only). Of these zig-zag is the easiest as all that may be required is limit switches on each end to switch motor direction or switch valves for hydraulic direction. However, bang-bang may be rough on the equipment as the acceleration and 'jerk' (first derivative of acceleration) and thus forces are quite high. Sine wave does reduce jerk to near zero, but reduces cycle time slightly when the system is rate limited. A full 180 or 360 degree oscillation is used at the bottom or top of the blown film extrusion tower. At the bottom, the die may be rotated 360 degrees. Just after the primary tower nip roller the web can be oscillated by a turntable assembly. In either case, the blown film oscillation is far slower than the other methods; something we will revisit later in this paper.

LIMITATIONS TO OSCILLATION

While oscillation can, in principle, nearly eliminate certain chronic troubles such as bagginess and corrugations, there are many limitations that can mitigate or even preclude oscillation benefit. They fall into the categories of stroke and speed. The **stroke** of a web upstream of the wound roll will require either accepting stagger wound rolls or taking a trim loss. Stagger wound rolls, such as seen in Figure 4, do not handle or ship as well (such as storing on end) and require that the customer de-oscillate or take trim in their process. The progressively spaced rings are the fingerprint of a periodic motion of some sort up stream of the winder. In this case, it is an oscillating guide. The length of material in one ring is equal to the amount of material transported in the time of one cycle; i.e., length / speed. Note that other cyclic processes such as pump and tension oscillation can also make progressively spaced rings; so the mechanics are not unique to oscillation. All we can conclude is that the source is periodic and upstream of the winder. The web length in a cycle is the primary clue to diagnosing the periodic source and is

$$L = \frac{\pi}{4t}(D^2 - d^2) \qquad \{1\}$$

where

L = length of one cycle (m)
t = thickness of web (m)
D = diameter of outer edge of ring (m)
D = diameter of inner edge of ring (m)

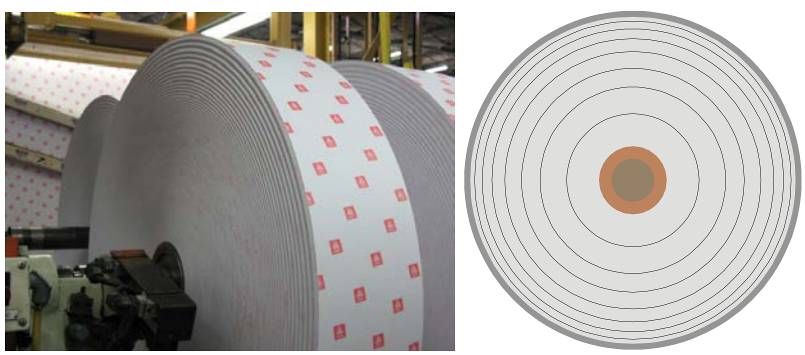

Figure 4 – Oscillation Offsets in a Wound Roll

The other option is to oscillate and then take extra edge trim. Here, the amount of trim loss is increased precisely by the amount of oscillation. Thus, if you oscillate 1 cm or 1 inch, you will lose an *extra* centimeter or inch of material as trim loss. If you stroke too much, you cost your company money by trim loss (or loss of customers who don't want stagger wound rolls). If you stroke too little, you cost your company money by (presumably) extra rejects for bagginess, corrugations, roll appearance, tight and loose defects or customer complaints for the same issue. Readers who have followed my work would immediately recognize this is where one would apply economic optimization to find the best compromise between the costs of too much and too little oscillation.

With regard to speed we have limitations on both ends of the range. At the slow end we might not avoid the buildup damage on the winding rolls. At the fast end, we can induce diagonal strain wrinkles nearly equivalent to in-plane misalignment (except that the web is sheared instead of bent sideways). Also, you will often see oscillation marks on the winding roll, even if the edges are trimmed.

HISTORICAL BEST PRACTICE OSCILLATION AND LITERATURE REVIEW

Best practice recommendation in oscillation are essentially absent in the literature. However, you will occasionally hear of the following heuristic. The stroke needs to be similar to the width of the defect you are trying to reduce. Thus, if it is a strand of coarse textiles or sometimes netting you may not need it because 'nature' will randomly oscillate the path a bit for you. If you have a 1 cm or 1 inch wide defect, the sweet spot of oscillation, that value would be a starting point guide for stroke. However, if you had a 1 meter or even 1 foot wide defect the economics of stagger wound and trim loss would preclude any net benefit here. The speed has even less guidance; very occasionally you will hear that the cycle needs to be completed before 1 inch of buildup on the radius. We will use and check that parameter as part of the 'model' for oscillation. Still, it makes intuitive sense that ultra-slow oscillation will do no good because too many layers build up in nearly the same location so in the limit it must certainly be true.

A public domain literature search of oscillation indicates only a pair of articles that are peculiar to blown film [7]. There are many things admirable about this study. First, it appears to be a first attempt in modeling of oscillation of gage bands. Second, it uses real caliper data (or at least one example of such) in the model. It 'rotates' the caliper data in a fashion similar to what a blown film oscillator does. Still, there are many limitations. The first is that while blown film can effectively oscillate many meters sideways because the bubble can be rotated entirely, almost all other processes can oscillate at most a few centimeters. The second is because the data is real instead of using elemental shapes, it is difficult to draw any general conclusions that might go beyond that particular data set example. The third is perhaps the most serious. That is there is no accounting for the vastly different influence of an extra thickness 10 layers deep versus 100 or 1000. Thus there is no way to make any conclusions about the *rate* of oscillation. This is the most important parameter of blown film oscillation and that analysis technique is incapable of making any suggestions to avoid such defects as the ubiquitous 'ring star.' In the next sections I attempt to address those issues.

OSCILLATION ANALYSIS METHODOLOGY

The first thing we need to do is to decide which elemental shapes of thickness error are most important to study. We can begin by noting that low lanes (corrugations and diamond wrinkling excepted) do not cause anywhere near the amount of trouble as high lanes do. Next, we note that a high lane might be located in the middle (simple gage band or ridge) or the edge (raised edge due to slitting). Finally, we give a simple shape to these elementals as seen in Figure 5. The gage band is modeled as a sine wave and the raised edge is modeled as an exponential. (We will see later that precise shapes have almost no effects on the results.) Now we need to decide on a height of the error. Wide experience with many materials indicates that the range of error tends to vary from 1% (no problem) to 10% (no product) with respect to basis-weight/caliper/thickness. (Diametral variations are perhaps 1/10th that). Metal foil can tolerate a bit less, nonwovens and blown film maybe a bit more. Of course, this is a grey-scale where the defect rate goes from negligible to uneconomic so that exact numbers should not be taken too literally. Also, customer and customer's processes vary greatly in their 'threshold of pain.'

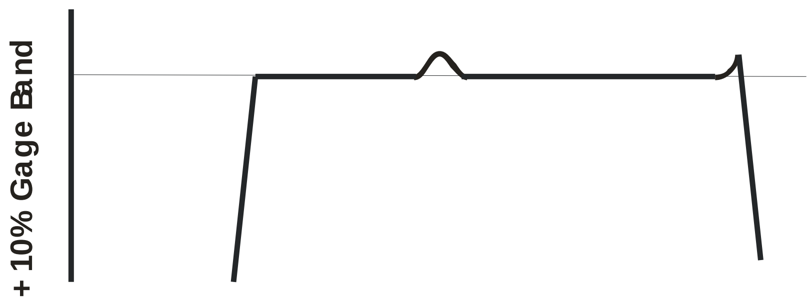

Figure 5 – Gage Band and Slitter Lip

Next we need to decide how we are going to 'oscillate' the thickness data and note effects. FEM would be too clumsy and limiting for winding. Winding models would be extremely difficult to construct as they would need to oscillate 3D models instead of the far more common but still complicated 2D axisymmetric models. Thus, any results would be totally specific to the case presented and totally unavailable to the general practitioner as a tool. That leaves programming of simple computer models or spreadsheets. I chose the latter. Figure 6 shows a portion of the spreadsheet model. While the numbers can't be seen at this scale, you can see both the central sine shaped ridge (columns) and a half cycle of sine wave oscillation. Not seen because they are way off this scale is the left ordinary edge and the right raised edge. More importantly, you don't see the simple addition at the bottom that sums the thickness and divides by the number of layers. In this model the width and layers are discretized. The width of the sine shaped defect was 18 columns and could represent a defect 18, 180 or 1800 mm wide. The rows are layers. One row could be 10, 100 or 1,000 layers. In order to see effects independently, the defects have to be separated by at least the oscillation width otherwise they will combine and tangle impossibly as did using real caliper did for the Worberg.

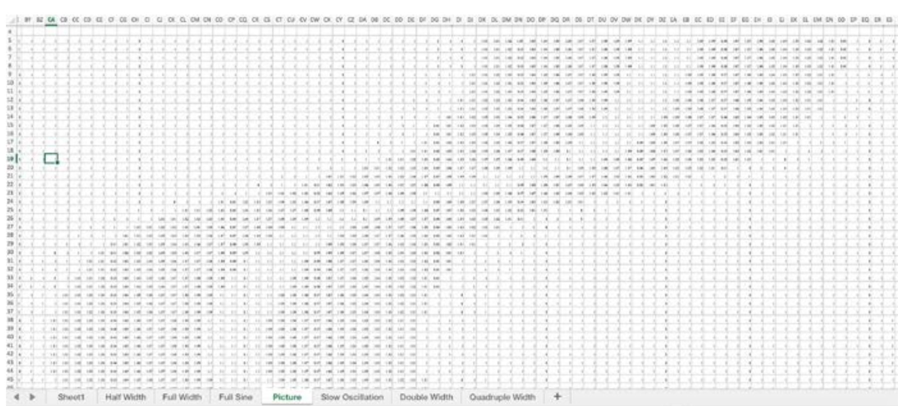

Figure 6 – Oscillation Spreadsheet

While this is exceedingly tedious as far as cut and paste, you can easily see what is going on at any time and place by simply pulling out a graph on a row or column. One variation studied, but not shown here, is zig zag oscillation. This is much easier as each 'layer' is moved over one column on the next row. A bit more complicated is the accounting for depth that is needed to make conclusions about oscillating speed. Here, for that (speed) portion of the study only, the top layers is given 100% strength, the next layer beneath a bit less and the next layer below that even less in an exponential decay. This exponential decay resembles the radial and tangential stress changes in the outer layers. It also resembles and is in fact modeled by several unpublished studies at Beloit R&D where 90% of roll hardness readings were found coming from the outer 1 inch of a paper roll. This was done by measuring 'hardness' of a stack of paper of various thicknesses sitting on a concrete floor. The effect of the floor was indistinguishable when the thickness was much more than 1". A similar result was found by making a step change in TNT's during winding; you could not see it via hardness measurements when that step was an inch or so beneath the surface. So then after much cutting and pasting and graphing we can summarize the results.

RESULTS AND RECOMMENDATIONS WITH REGARDS TO STROKE

Figure 7 shows the salient results of this linear model of the stack-up of caliper variations as a web (or roll) is oscillated sideways. The first result is expected in that the effective defect 'width' gets wider with oscillation.

$$W_{osc} = W_{orig}(1 + O) \qquad \{2\}$$

The second result is also expected in that the 'height' of the defect gets smaller.

$$H_{osc} \approx H_{orig}(1 - 1/O^2) \qquad \{3\}$$

where

W = characteristic width of defect
H = characteristic height of defect
O = oscillation width / defect width

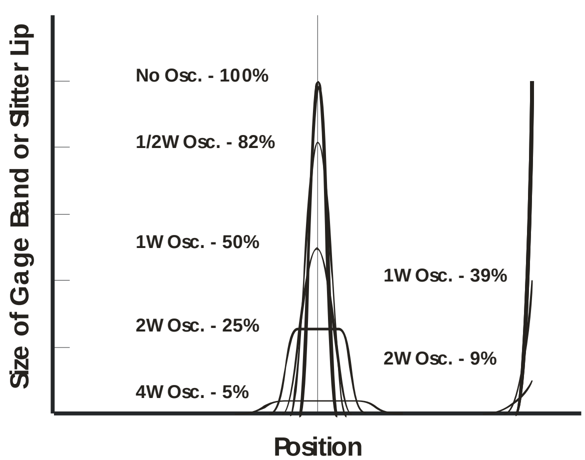

Figure 7 – Oscillation Results

Note that the model results for width are precisely matched by equation 2. However, model results for *height* were up to 10% different than the above fit and that could be an artifact of discretization (18 elements across width) or that the results are not proportional because the defect is not a simple step shape but rather a sine.

So given the above results it appears that the historical guideline of oscillation 1X width may be noticeable, but perhaps not impressive enough. Oscillation of 2X to 4X should do the job, though the economic optimum of defect waste versus trim waste must be carefully considered. Perhaps also as important are several other key findings.

1. The **shape of the defect** is not very important as the sine defect and a step shaped defect would give nearly identical overall results. This should not be surprising because oscillation is a smearing/smudging/averaging process that blurs shape quite quickly.
2. The **shape of the oscillation** is also not very important as zig-zag and sine gave nearly the same results. The sine is 15% less effective because the gage bands 'dwell' a bit longer during the time when reversals in direction are taking place. Still, sine oscillation or at least a soft directional shift should be considered for limiting jerk without any serious regard to any notable loss of the smearing function.
3. The (exponentially shaped) **raised edge** (due to slitting or manufacturing process) is very quickly reduced by even modest oscillations. Here we (typically) have a narrower width to begin with coupled with sending high spots literally off the edge of the roll.
4. The **edges of oscillated rolls** have no support whatsoever. Thus, 'starring' type behavior should not be surprising as one can be readily seen on most webs coming off of a coater (because you can't coat all the way to the edge).

RESULTS AND RECOMMENDATIONS WITH REGARDS TO SPEED

The results of speed are also not surprising, but could very well reflect assumptions built into the model. That is that layers near the outside have more effect (on the current outside of the roll where most damage occurs) than do layers beneath. If the assumption is that the outer centimeter or outer inch matters most, then the results almost perfectly match those assumptions. In other words, the *half* cycle must be completed well before this influence depth. This departs from previous historical recommendations that were for a *full* cycle. Yet, one half of the cycle accomplishes everything a full cycle does as the other half is just a repeat in a different direction.

These assumptions of an influence depth are probably quite sound for materials with high **anisotropy** (E_T/E_R) ratios such as paper. However, it may not be so applicable to materials that are fully compressed such as rubber where layer influence can literally go from the core to the outside. In other words, every layer counts almost as much as any other layer in the roll, regardless of depth.

Of the two most important parameters, stroke and speed, **stroke** *might* be most challenging because the speed to complete a cycle within 1 cm would be trivial for guides. Except, however, oscillation speed is also limited by one other factor. It acts something like in-plane roller misalignment. This is because the normal entry law is not specific to the axis of rotation, but rather more accurately, it is to the vector of the speed that includes the usual forward motion of the web but now also the sideways motion of the web due to oscillation. If we use that criteria (for diagonal wrinkles [8], the oscillating speed / web speed < 0.001 if not a tenth of that for stiffer webs. If we exceed some oscillating speed limit we will see alternating left and right wrinkle patterns near the guide. This can be seen in the field on occasion in the open web runs. (We can see it even more often as tiny offsets in the finished rolls even after slitting, but that is a different issue).

So, how much web is added with those oscillating speed limits? Well, it depends on thickness. If web speed is 100 MPM, the maximum allowable sideways speed might be as little as 0.01 MPM. A 0.1 m wide gage band would be moved over its own width in 10 minutes. During that time 1,000 meters of web would have been added to a wound roll. On a typical thin paper / thick film web on small shipping core, that would more than a 1,000 layers and nearly 10 cm on the radius buildup; 5X what I have proposed above being a 2 cm buildup in one cycle (1 cm per half cycle). Of course, this was a conservative assumption for 'misalignment' limiting oscillation speed that may be more appropriate for the paper to foil people. Also, of course, as the roll gets larger the speed limitation is less important. In short, we may or may not be effectively oscillation **speed limited** by diagonal wrinkles. There are so many combinations of gage band width, web modulus, web thickness and other factors that we will let the reader do the calculations for their own cases using the heuristics suggested above.

If you do similar analysis of **blown film rolls**, you will find that typical oscillation speeds (usually about 4 cycles per wound roll) are **ridiculously slow** for wide thickness defects such as a notable portion of the width of the bubble. This is verified by the ubiquitous ring stars. What is so puzzling is why the oscillation is so slow. The best I've been able to get from many queries and a blog on the subject is that people are afraid of twisting the bubble. While I have never heard of a study of speed versus twist, and have not even seen any twist personally, it is the common belief if there is one with regards to oscillation speed. Spinning the equipment faster is, of course, trivial both mechanically and electrically.

SUMMARY AND FUTURE WORK

The above heuristics roughly support the guidelines of oscillating stroke (though perhaps greater than 1X defect width should be considered) and speed (though perhaps 1 cm of buildup on radius instead of 1 inch). This is also roughly aligned with practice in the field. Oscillation is used for coated grades of paper where streakiness and corrugations are usually both narrow, but not so much for other paper grades as other defect widths can be notably wider. Oscillation of stranded products is very narrow. Still, it only needs to be narrow because the pitch is narrow. Sometimes 'natural' oscillation (random web path excursions) is enough. Blown film is oscillated much more, but far too slowly and thus leaving chronic 'ring' stars everywhere on finished rolls in extrusion and particularly for their customers who laminate (usually with stiffer materials).

Still, the results should be checked as we have tens of thousands of oscillators in the world with little other guidance. The first would be to use simple (program or spreadsheet) models such as above to independently check the methodology and results. Next, one could incorporate oscillation into existing 3D winding models without enormous difficulty. This could be checked by measuring pressures (etc) inside the roll. Of course, these last two steps would only be possible at the masters or Ph.D. mechanical engineering level and then only by spending a good amount of time on the effort.

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