Secrets of a Level Process and Product

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ABSTRACT

We strive for a level profile across the width of our web products to improve their quality and runnability. Profile is commonly taken to mean caliper, but can also be used for basis weight, density, moisture or any other property of interest. Profile is affected by incoming raw material, web manufacturing such as die and slice lips, and web converting such as coating, laminating and printing. Unfortunately, a level profile can be difficult to obtain, in part because some processes will object to variations that are below the threshold of common measurement techniques such as scanners and laboratory bench tests.

This paper describes why we usually desire a level profile, as well as a few cases where variation may be tolerated or even desirable. It also describes the types of profile variations and their associated risks. The thrust of this paper is, however, a compilation of the means of detecting profile variations. Here, we will stress the importance of the wound roll as both a most sensitive customer and a most sensitive measure of profile variations.

KEYWORDS

Baggy_Web, Basis _Weight, Caliper, Moisture, Measurement, Profile

WHAT IS PROFILE?

What is meant by profile depends on whom you ask. Perhaps the most common definition is the variation of gage (i.e. caliper or thickness) across the width of a web. However, the papermaker will also include basis weight and moisture along with caliper as a measure of profile. Some will say that a web with baggy lanes has a poor profile. Bagginess is a variation of MD tension across the width, perhaps due to variations of manufacturing, converting or uneven yielding during web handling. Thus, it appears the profile could mean the variation of any measurable property across the width. Sometimes the profiles are connected. One example is when gage variations stack up during winding to create ridges that stretch the web into baggy lanes. Another is common on paper where wet streaks tend to be baggy. For these reasons, it is necessary to be precise by specifying what property we are referring to when communicating with others.

PROFILE SAMPLING

Another complication is that profile measurements could be sampled in a variety of ways. Perhaps the most common is to cut evenly spaced samples across the width of a roll just after it has been wound as seen in Figure 1. These samples are then sent to the test lab for measurement. Here, the intent is that the samples on the outside tail of the roll are somehow representative of the entire roll, series of rolls or lot. However, this common sampling technique makes many assumptions. First, that the number of samples at any point or CD position is sufficient to resolve variations at a fine enough level for the need. The resolution of the test method is something that can only be determined by statistics and sometimes not even then. For example, if there is no independent measurement method of the same variable that has even greater resolution, it can be difficult to tell whether variation belongs with the material, sensor or both. Second, that the number of sampling points is sufficient to capture features as narrow as required by the application. For example, samples 6” apart will have little to say about a 1” wide defect. Third, that the magnitude of MD variation is small and stable compared with the CD variation over the course of one roll. While this is often true, the assumption also needs to be verified for each specific application.

Another approach is to use on machine sensors that sample in one of three ways as shown in Figure 2. The first is a fixed single point sensor. While the sensor might be moved sideways, it would be obviously more capable of capturing MD variation than CD variation. The second is a traversing single point sensor, which is the most common type of ‘scanner’ in the web industries. Here, the path of the sensor is a zig-zag. The raw data from this sensor is manipulated inside a computer with filters, averaging and so on. The display may show profile across the width on a single scan, or fixed time interval average, or roll average. The time interval allows heavy averaging to help minimize the effects of variation in product and sensor so that patterns begin to emerge from the noise. The third sampling is to use a sensor that can scan the entire width at the same time, such as some of the high end imaging systems can do. Again, however, the sensor will have a minimum resolution at any point (bin) and a minimum spatial resolution in both directions. MD resolution involves both processing time and machine speed.

What we would like to do, if it were practical, is to construct a three-dimensional topographical map of the web. This map would be the width of the web and the length of the roll (or lot). This map would have elevation contours, perhaps color coded, corresponding to the minimum resolution of the sensor. The vertical and spatial resolution of this map would be sufficient to resolve a pile of construction dirt anywhere on earth, such as military and scientific satellites can do. With data of this detail, you could answer pretty much any question about profile you wished to ask. In the real world, however, we can’t afford such resolution for our webs. Then, what you can or can’t conclude based on more limited sampling of a roll can only be answered by statistics. Paul Frost has an excellent treatment of this vital quality control subject that I urge all of you to read (1).

THE IMPORTANCE OF A LEVEL CALIPER PROFILE

In this paper, we will focus on detecting caliper variations, even though the principles can be also extended to include basis weight, density and, on occasion, other properties such as bagginess. This may not be so limiting as it might first seem. First, if caliper varies, it is near certain that other factors also vary. In some cases, the root cause of caliper variation also causes something else to vary as well. In other cases, the caliper variation itself causes other properties to vary. For example, in paper making a thick/heavy lane will also likely be a wet streak because there is more total water to dry off there than in neighboring positions. The relatively thicker lane entering the calender will leave the calender relatively smoother, denser and/or more highly bonded than neighboring positions. In film, the thick lane will very often have different optical properties, such as being less transparent and having a different gloss. In coating, a variation of raw material caliper on the ingoing side will usually result in a variation of coating on the outgoing side. Coating variations, in turn, may cause lanes that do not dry as completely, increasing the risk of blocking on the winder for example. Second, caliper is a most commonly measured web property. Many suppliers and customers will reject on average caliper, or variation of caliper. The intense interest in this particular property is based on processibility and useability. An uncountable number of problems in the industry occur due to poor control of caliper.

In this paper, we will focus on variation across the width, rather than with MD position or time. There are two practical reasons for this. The first is sheer laziness. Adding information about the second dimension increases the costs and efforts by orders of magnitude. The second is because, as stated previously, many machines are much more stable with time than they are across the width. Thus, it is not uncommon that the basic profile or fingerprint of a machine is recognizable for hours, days or even years. An example is baggy edges that tend to be a permanent feature of many machines.

The premise of this paper is that we need a level caliper profile to be successful. If not, our internal rejections and thus waste will rise. If not, the customer might complain, return material and perhaps even leave us. However, as we will see, the fussiest customer is not always the one we sell to. Rather, it is often the wound roll. Many times the end customer can process caliper varying material, provided it was not further damaged during winding.

CALIPER MEASUREMENT IN THE LAB

The most common measure of thickness in film, paper and many other web industries is TAPPI's T411 which was written in 1926, and revised a dozen times since (2). This method has been accepted as written or modified slightly by dozens of other organizations both inside and outside of the paper industry. It defines thickness as the distance between a flat pressure foot of 5/8" diameter and a parallel anvil with a single ply of the web sandwiched in between. The effective pressure of 7.3 psi is applied for 3 seconds before taking a reading. The rest of the three page standard describes details such as calibration, resolution of the micrometer, mechanical precisions, specimen size and lab conditions. The test unit is a small lab benchtop device available commercially from several sources.

While the TAPPI standard does permit a manually rather than automatically actuated pressure foot, it does not allow for a handheld version. Thus, those more plant-floor convenient devices will measure differently and are not generally supported by standard. However, there are other caliper standards in common use that are variations of this principle. For example, TAPPI's T 500 measurement for book bulk differs in several key respects. First, a stack is used instead of a single ply. Second, the pressure foot has a much larger area. Third, the pressure is much less. For these reasons, it should not be surprising that measurements using T500 give a noticeably greater caliper than by T411. The ISO version of T411 suggests pressures twice as high as TAPPI, probably to decrease the scatter. However, any of these pressures are so great that delicate materials like foam, nonwovens and tissue could be crushed by the measurement. Thus, these webs may be measured by lighter loads, often without the guidance of a standard.

Indeed, one large company I worked for had no less that a dozen distinctly different standards for defining and measuring web thickness, each yielding slightly different numbers. Thus, the obvious care needed here is that we are specific about which method or device was used when communicating caliper to outsiders. When selecting a method for a particular application, we usually are looking for a good combination of convenience and resolution. While one can't convert from one system to another, except by calibration on a specific web, the relationship is almost always monotonic. That is, a thick area by one measure will also be thick by another measure, provided that it is within the resolution of both.

CALIPER MEASUREMENT ON THE MACHINE

Measuring caliper in the lab has many obvious disadvantages. First, the small sample size means we can't resolve true variations as accurately. Second, the test lab is usually more labor intensive. However, the most serious shortcoming of the test lab is the delay. By time samples have been tested on one roll in the lab, at least one more has already been produced. This could make it very time consuming and difficult to home in on machine adjustments to bring caliper into spec. This also means that we could not use any form of automatic controls to regulate caliper. Because of the limitations of the lab, online caliper measurement may be worth considering.

Basis weight has been measured on-machine for many decades in the paper industry and is based on the absorption of nuclear products. Moisture profiles were also measured early and were based on the absorption of infrared or radio waves by water molecules. Some of the first commercial efforts to measure caliper on-line appeared in the early 70's (3, 4). The practical challenges were and still are formidable. The principle of operation is similar to the lab test version. The distance between a puck, instead of a pressure foot, and a platen defined thickness. However, one challenge with paper is that the puck can't touch the web else it may scratch or tear it, especially at speeds of thousands of feet/minute. Thus, most designs are air floated so that any variation in air film height would be mistakenly read as a caliper change. The sensor also poses challenges, if one want to resolve a 0.003" thick web to a few percent, the gage must have resolutions and accuracies of far better than 1/10,000." Several sensing principles have been used, but magnetic reluctance is one of the more common. However, the more severe challenge was the frame that held the anvil. It also could not move by similar amounts due to forces such as thermal distortion. To compensate, the frame 'profile' may be measured by an independent sensor and factored out.

For the first decade or so, the triad of measurements (basis weight, caliper and moisture) were only used to monitor the process. It was only after trust in the measurements and understanding of the process grew to the point that closed loop control of profile was attempted. The experiences are similar in other web industries because the principles were similar. While metal foils might be touched by a probe, the material might be stiff enough so that contact is not guaranteed on the anvil side. Other measurement principles can also be used. For example, film thickness (gage as they call it) might be measured by changes in capacitance. Many have used laser position measurement of one or both sides of the web. No matter how it is done, however, scanning systems are very expensive. This has prompted many do-it-yourself inventions, which are almost invariably a wasted effort. Finally, one should not be surprised that even though costing 100-1,000 times as much, scanners seldom have resolution as good as test lab methods. Indeed, the accepted best practice is to regularly calibrate and check the scanners against the test lab.

THE WOUND ROLL AS A MEASURE OF CALIPER PROFILE VARIATIONS

Hundreds, thousands and sometimes even tens of thousands of layers are built up to make a wound roll. If the caliper is relatively higher at one CD position, microscopic differences can add up to huge results. The wound roll has a substantial advantage in sample size compared with the lab and on-line caliper measurements. This is because the outside of the roll may reflect the stackup of caliper variations of many, many layers. Thick areas will build larger (or stiffer as we will see) because the material has nowhere to go. Due to the stackup of caliper variations, it should not be surprising to find that the wound roll can be a very sensitive measure of profile. Indeed, it is often far more sensitive than the lab or online scanners.

There is the common misperception that the stackup of layers is proportional. In other words, 1000 layers of 0.0001” thicker caliper would cause the radius to be 0.1” larger there. In reality, however, it will be less because the relatively thick area also winds tighter so that it winds more compactly and vice versa. In this sense, the roll has a built-in tendency to level itself. In materials with a very stiff stack modulus, such as some films and dense coated/calendered paper, the buildup in nearly proportional. A stiff stack modulus is easy to detect by striking the roll with a stick. If it cracks or rings, it is stiff. However, wound roll diameter will respond very little to caliper variations on materials with a low stack modulus, such as nonwovens and tissue. In any case, however, thick areas will stack up to larger diameters because the material has nowhere else to go.

There are three primary measurements of the wound roll that can detect basis weight and/or caliper variations (5). These are as a variation of diameter, hardness or density across the width. In turn, there are several techniques for making each of these primary measurements as described below. You must evaluate the alternatives to select the most appropriate for any particular situation. The best will be easy to use on the plant floor, and have the greatest or at least adequate resolution as determined by statistics (6).

Variations of diameter across the width can be measured in a number of ways. The simplest is to place a straight edge along the top of the roll so that caliper ridges and valleys will stand out better. However, this is nonquantitative and will not detect the conical portion of roll cylindricity error. A better approach is to measure diameter variations using a flat tape about the roll’s circumference. While this is accurate, it can be time consuming and unwieldy, especially if you want to capture narrow defects. The roll may need to be upended or suspended by the core so that the tape can be fitted around the outside. While there have been other instruments invented for profiling diameter across the width, they appear cumbersome. One technique to detect very fine variations is to rub a chalked flat board or equivalent across the periphery of the roll. This is similar to when, in kindergarten, we traced the delicate pattern of a leaf with crayon on paper. Variations of diameter work very well with film and are often written into rejectable specifications.

Variations of hardness across the width were first measured in the paper industry a century ago striking the roll with a ‘backtender’s stick’. This is ideally similar to a blackjack or nightman’s stick used for self defense, although most any pipe or stick of similar size will work. This technique is very sensitive in the hands of the experienced and quite simple to do. The club rebounds more on the thick/tight/hard areas, and the sound of the impact is louder and has a higher pitch. This stick is nonquantitative, and thus limited. This prompted the invention of several instrumented versions of this principle which includes the Beloit (now Millpro) Rhometer, the Schmidt Hammer and the ParoTester. All of these are common in the paper and film industries. Variations of hardness work well with harder materials. Customers and suppliers in both the film and paper will occasionally reject on hardness variations. While maximum overall variation across the width is the most common, the most predictive of some defects is the maximum station-to-station variation across the width. In other words, the gradient of or slope of caliper variation would correlate to troubles such as corrugations and narrow web camber.

Variations of density across the width can only be measured if the web is cut into smaller width rolls. In that case, the roll density is calculated as simply roll weight divided by roll volume. The roll weight is measured on a scale with sufficient accuracy and the core and packaging weight subtracted out. The volume is measured with a tape measure. Variations of density are an extremely sensitive method for compressible materials such as foam, nonwovens and tissue. The only issue is that density reflects both incoming caliper variations as well as tension variations. Thus, a lane could be smaller at an equivalent caliper if there were more tension there (7).

WHICH CALIPER MEASUREMENT METHOD IS BEST

The three fundamental methods for determining if a process is level are, in order of decreasing frequency of usage in the web industries are: lab test, scanner and wound roll. However, which is best is often the subject of heated debate. Many like the simplicity of the lab test, and the fact that it is well supported by standard. Many like the scanner because it provides much more information, often with less labor. However, I most often prefer the wound roll because it is usually the most sensitive. The sensitive reader may detect a bit of bias in these preferences. The Q/A manager, of course, will favor standardized measurements. The scanner is favored by those who love instrumentation and technology. The wound roll, of course, is favored by the winder guru. Fortunately, we need not yield strictly to opinions and judgments. Statistical testing can keep up from fooling ourselves by determining which is the most sensitive (6). However, it can be even simpler than that.

Let me illustrate this bias with a common situation I run into. I will observe a roll with a bulge in it such as shown in Figure 3a. I will then tell the operator “you have a gage problem with the web.” He might then say “let me check the scanner.” Wrong answer! You don’t need the scanner to determine there is a gage variation. You can see the ridge. You can feel the ridge. You can hear the ridge (when struck with a stick.) The web is thicker there as given by three different and independent ‘measurements.’ However, if you did check the scanner, you may see a gage profile like Figure 3b. Here, people tend to be very creative and try to map one of the spikes in the profile, to the ridge in the roll. (This is easy enough because there are plenty of spikes to choose from and you will always find something that appears to line up.) This is a fallacy (error in rational thinking) to try to fit the data to the problem. Alternatively, you may see a gage profile like 3c, whereby manufacturing will claim the process is level. This is usually because someone complained about the noisy profiles like 3b, and turned down the gain on the display. By the way, 3b was created by a random number generator, not too unlike the results of some instruments which have not been independently tested for sensitivity.

Some people become so attached and vested in their instruments that they may not see the obvious. One of my paper clients had a hard time believing that their million dollar scanner was incorrectly showing a level profile, when the wound roll set had a 1” diameter variation. The rolls came off looking like footballs! This makes it harder to convince people of manufacturing or gage variations that are subtler. A classic example is the wound roll corrugation that occurs at an abrupt change in caliper (7). Here, test labs and scanners usually don’t have the sensitivity or CD resolution to pick up the errors in gage that are the root cause of this well-known defect. Caveat emptor.

CLASSIFYING CALIPER PROFILES

It is useful to classify the shape of the more common types of gage profile variation for at least two reasons. The first is so that we can communicate the essence of a variation in a few words, instead of being limited to columns of numbers or their graphical representation. The second is that shape is a useful tool problem solving (9). The shape tool states that the "shape of the problem must match the shape of the cause." Thus, we could eliminate machine misalignment as a cause of ridges because misalignment has the shape of an even taper front to back, while the shape of ridges varies abruptly with CD position. Ridges might, on the other hand, be caused by tiny nicks in a die lip.

On a coarse scale, the caliper profile could be a frown, smile or taper. The corresponding wound roll shape would be barreled, belled or coned respectively. These are shown in Figure 4. In some cases, the coarse scale is the most important consideration. A winding example is telescoping which can be greatly exaggerated by a tapered profile. In most cases, a level profile is preferred. However, in the case of wound roll wrinkles, a bell shaped roll acts like a concave spreader roll and thus might be advantageous in unusual circumstances, if judiciously done. However, in the case of wound roll air entrainment, a football shaped roll can sometimes allow air to escape from the edges gracefully rather than being trapped inside the roll.

On a finer scale, the caliper could be a ridge, valley or step as shown in Figure 5. The fine scale can be more important for defects such as coater streaks that are more visible when the variation of property is abrupt with CD position. Also, as discussed earlier, the wound roll corrugation is most sensitive to abrupt variations, the worse being a narrow high-low-medium thickness variation pattern. In most cases, a level profile on a fine scale is also best. However, the world is full of exceptions to general rules, though no good one comes to mind at the moment.

Few profiles are as simple as these shown here. In the real world, profiles are usually the superposition of two or more of these features, each of which should be separated out for problem solving purposes. For example, you might have a ridgy, barrel-shaped roller. In this case, the causes for the ridges are quite possibly entirely different than the cause of the barrel. They merely have the same outcome; caliper variation. This is not unlike having a headache that can be caused by any number of root causes singly or in conjunction.

OSCILLATORS AND RANDOMIZERS

Gage will never be dead level, no matter how we might wish otherwise. The thickness variation itself could be a problem for next machine or customer, in which case we must level it or live with it. However, sometimes the more serious affect of gage variation is on the wound roll. For example, the thicker position will wind larger, which may stretch the material into a baggy lane. This problem is common on many grades of film and paper. Also, the thicker position will wind tighter, causing increased interlayer pressure, which increases the risk of blocking on some materials. This problem is common with grades that are coated, printed or perhaps just have surfaces that have an affinity to each other. If there is a bulge in the roll, the web may be gathered there due to the concave spreader principle, causing the bulge to build larger, causing a greater gathering force in a vicious snowballing defect that is not uncommon on thin film, and occasionally seen on other materials such as paper. Sometimes a bulge on the edge, such as raised edges on slitting, can destabilize the roll because it prevents the rest of the roll from winding tight enough. To accommodate these gage variations, i.e. to not make the problem worse, we may use oscillators or randomizers.

We can shift any forming element sideways in a reciprocating fashion to keep the pattern from building up. A classic example is doctor blade oscillation which improves the life of both the blade and the roller, and perhaps product and runnability in turn. We can also oscillate the unwind or winder to keep narrow gage variations from exacerbating wound roll problems. The two parameters to control are stroke and speed. The stroke must be similar or greater than the width of the defect one is trying to avoid. Thus, a 2" stroke might be quite significant for a 2" wide gage feature which is causing a ridge or corrugations, but of no use on a 6" wide baggy feature. The speed must be sufficient so that the layers are oscillated within the influence region of winding. This is a princess and the pea type of problem such that if oscillation is too slow, the gage variations will build up sufficiently to cause problems. With many common rolls, the influence region of winding is an inch or so on the radius. However, one can't oscillate too quickly or you may have diagonal shear wrinkles in the web path as well as edge disturbances in the wound roll, even if taking a trim.

The randomizer is pretty much unique to tubular products such as blown film. Here, the die itself may rotate 360 degrees in one direction, and then reverse in a reciprocating pattern. While this smudges out variations caused by things at or upstream of the die lip, it does nothing for variations caused downstream in the collapsing frame or nip. The more effective approach, as judged by the industry, is to randomize the web after the collapsing nip by using a pair of rotating turn bars.

The source of gage variation is sometimes easier to pinpoint in some cases of oscillation. Let's take the example of a roll-to-roll converting process with an oscillated unwind. If the moves in synchrony with the unwind, then the source of the variation is in the raw material. If the problem is stationary with respect to CD position, then the problem is with the process in between. In the case of the oscillating blown film die, defects that move in synchrony belong to elements at or upstream of the die. The stationary defects belong to elements at or downstream of the collapsing frame.

SUMMARY

We all desire a uniform product. In order to achieve this, we need to have our basis weight, coating weight, caliper and so on level across the width. While we might measure these with lab instruments and scanners, I propose that you also consider the wound roll as a profile indicator. If the roll is not uniform, it is unlikely that the manufactured web is either. Your challenge, is to find a method for checking profile that is easy to use and not prohibitively expensive. However, you are also obligated to make sure that whatever method you use, it is sensitive enough to satisfy the requirements of all of your customers, including the wound roll.

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Figure 1 – Roll Sampling

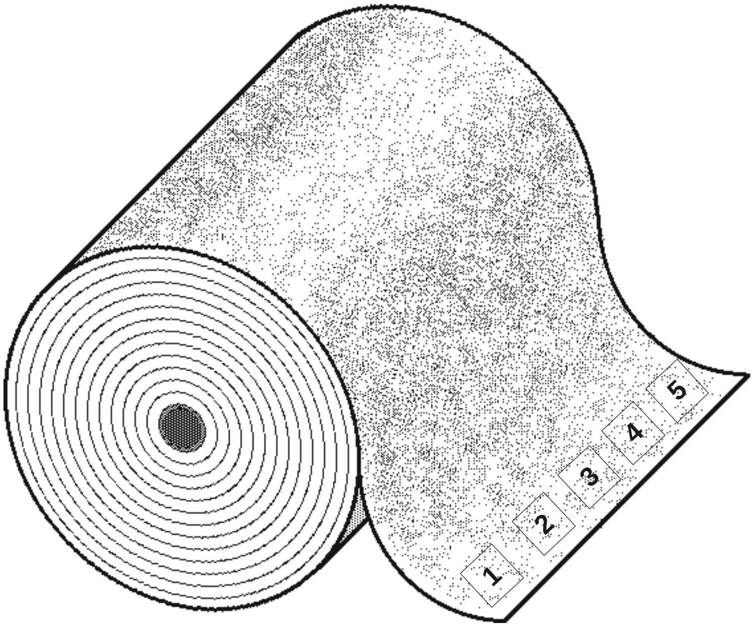
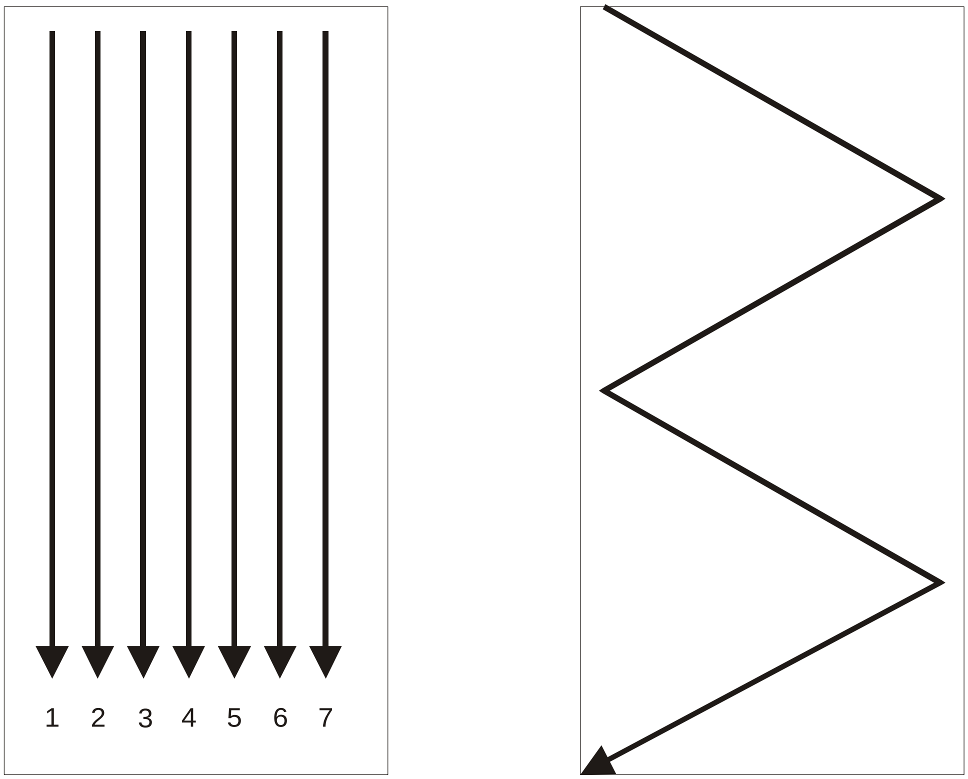


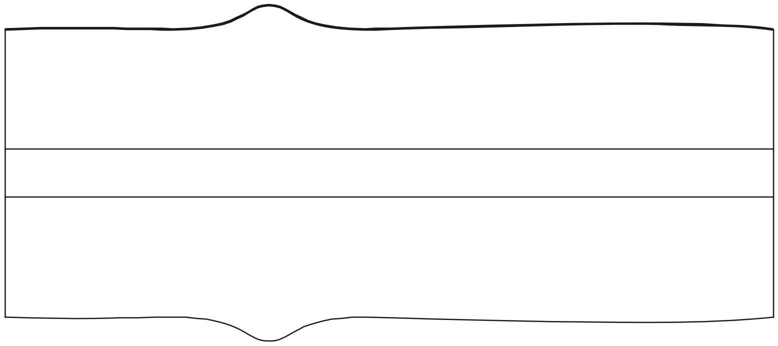
Figure 2 – Scanner Sampling


Fixed Position

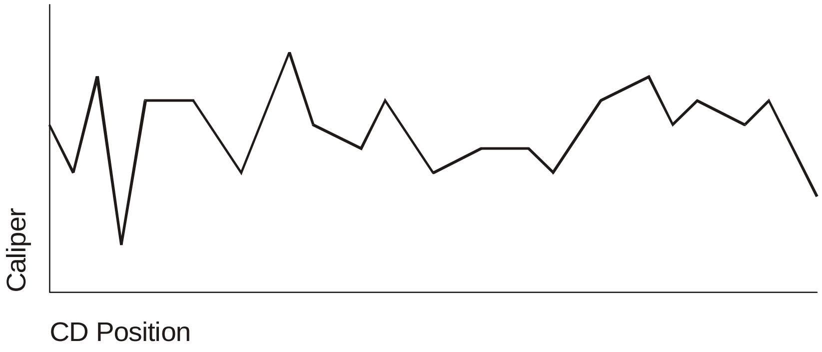
(Zig-Zag) Scanner

Figure 3 – Roll with a Bulge

A - Wound Roll With a Bulge



B - Scanner I Output



C - Scanner II Output

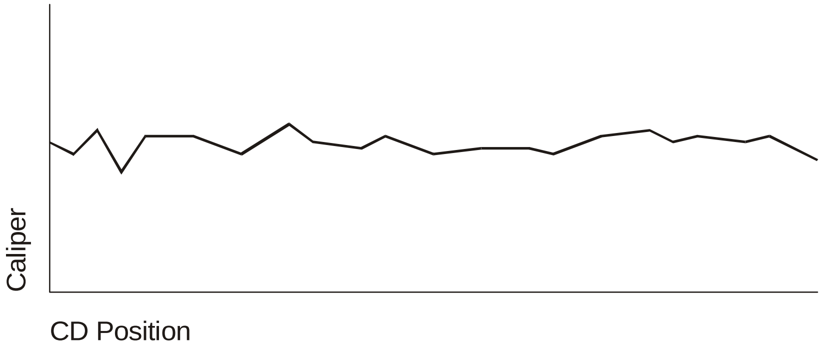
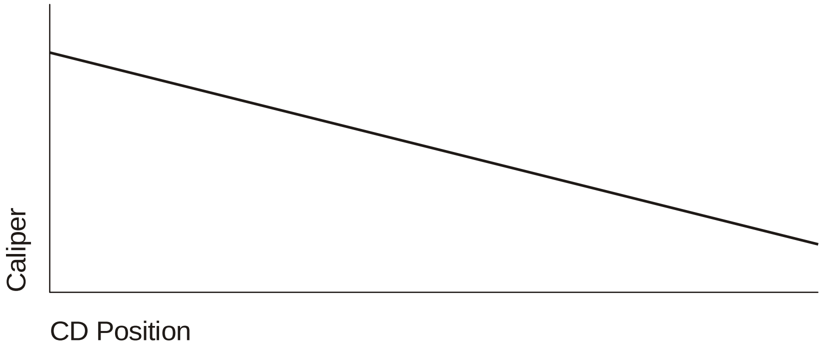
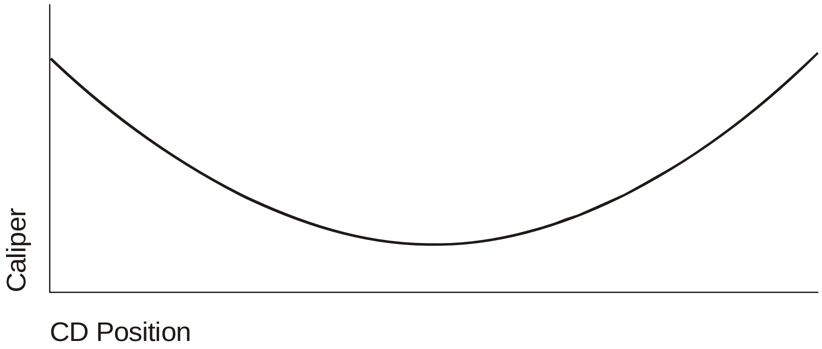


Figure 4 – Profile Categories – Coarse Scale

A - Taper



B - Smile



C - Frown

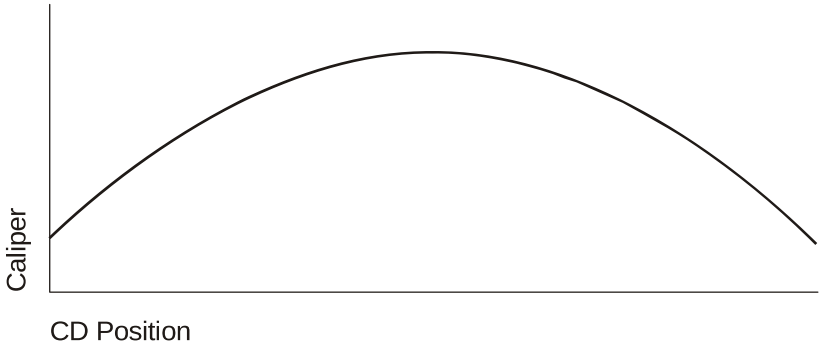
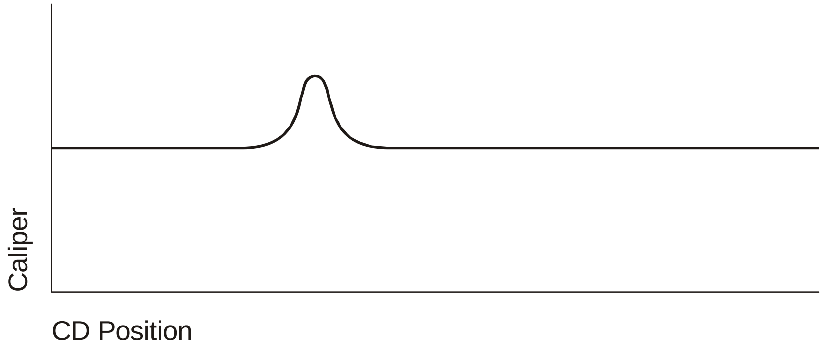
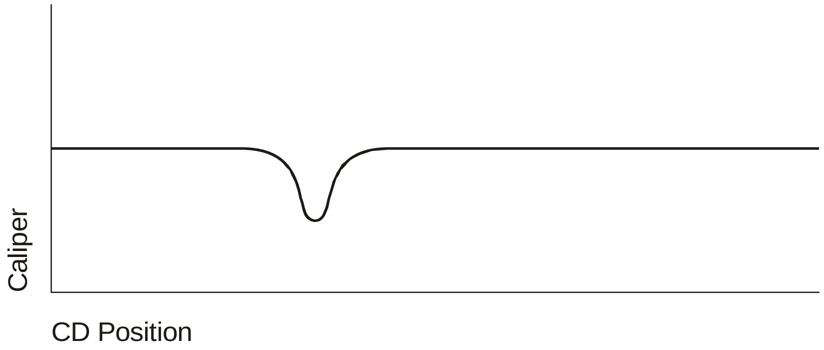


Figure 5 – Profile Categories – Fine Scale

A - Ridge



B - Valley



C - Step