Using Laser Doppler Velocimetry to Increase Profits and Reduce Downtime on Converting Lines

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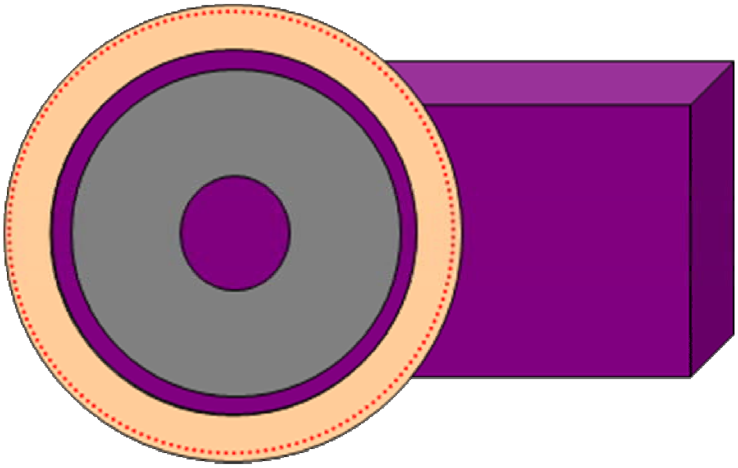
Introduction

Sheet products are manufactured and shipped in rolls and the end customer is frequently paying for the product by the unit length. Although some product may be sold by weight, increasingly length is preferred by customers due to variability in thickness and moisture content. Thus accurate length measurement is required on each process to insure that the customer is not getting more or less than he is paying for.

Problem

The problem stems from the fact that traditional, indirect methods of length measurement are not very accurate. The most commonly used method is a wheel driven encoder in contact with the product. Each revolution of the wheel produces a fixed number of pulses which are counted to determine the amount of material that has passed under the wheel. Unfortunately the connection between the wheel and the surface of the product is not perfect and the wheels inevitably slip. In practice, it is not uncommon to see between 1% - 2% slippage between the wheel and the surface to be measured. Any slippage between the wheel and the product will cause there to more product on the roll than the counter is indicating. Depending on the cost of the material and the amount of material being produced, this could result in shipping a significant amount of extra material out the door for free. It is possible to use softer, stickier, wheels but generally this increases wheel wear (and thus another inaccuracy in the system) and can frequently cause marking of the product. Although a system can be calibrated to compensate for a certain amount of slip, it is time consuming and the calibration can quickly become invalid as the wheel wears.

Figure 1 shows an example of wear on a wheel encoder.



Originally:

D = 3.819”
1 rev = 12”

After 1/32” of wear:

D = 3.757”
1 rev = 11.8”

= 1.6% short!

Figure 1 Traditional Wheel Encoder

Inaccuracy due to wheel wear is another issue faced by the wheel encoder system. As the diameter is decreased due to wear, the encoder becomes increasingly inaccurate. As noted in Figure 1, a mere 32nd of an inch causes a 1.6% error. In this case the error would be in the negative direction. In other words, the encoder says there is 10,000 feet on the roll when there is actually only 9,840 feet. This might be good for short term profits but once the customer realizes he was shorted the resulting cost to customer relations, charge backs, and product returns could be significant. This frequently leads manufactures to put a safety margin on a roll in order to avoid this situation.

Another method for mounting encoders is directly on a roll shaft or on the motor driving the roll. Slippage is still an issue in this case since there can be not guarantee the roll and the product are moving at the same speed. Even a pressure nip will not prevent a certain amount of slip from being introduced. Shaft encoders are also employed but one can’t guarantee that the material is moving the same speed as the shaft. In the end, there is no way to be sure that the product is being measured correctly unless the surface of the material is measured directly.

Laser Doppler Velocimetry

A new technology is needed that is accurate, non-marking and doesn’t need frequent recalibration. This technology exists. Laser Doppler Velocimetry (LDV) is a technology or technique that is often used for fluid flow measurements. However, it can also be used for measurement on opaque materials as well. Devices based on LDV technology can be made cost effectively, provide more accurate measurements than contact methods, are non-marking since they are non-contact and can be permanently calibrated. Due to the accuracy capability and being permanently calibrated they represent a much lower cost of ownership than contact measurement methods.

LDV Theory of Operation

A pattern of light and dark stripes is created and projected on a surface. As surface particles pass through these fringes a time based signal is created and read by a photo cell. This time based signal is proportional to the speed of the product being measured.

Interferometry

The light and dark stripes (fringe pattern) are created by constructive and deconstructive interference of laser light. This is done by intersecting two coherent laser beams that have the same wavelength and same polarity. Figure 2 shows two laser beams of equal wavelength crossing. The light waves constructive/deconstructive interference create the fringe pattern, as shown in Figure 3, on the surface to be measured.

Figure 2 Beam Crossing

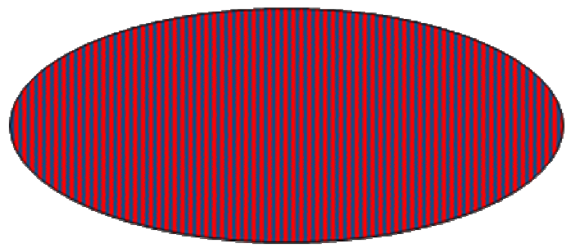


Figure 3 Fringe Pattern

The spacing of the fringes is held constant as long as the wavelength of the laser beams and the angle between them is constant.

The distance between the fringes is derived trigonometrically to be:

Equation 1

$$d = \frac{\lambda}{2\sin(\kappa)}$$

Where λ is the wavelength of the laser beams and 2 * κ is the angle between them.

As particles on the surface of the material pass through the interference pattern, they scatter light. The scattered light is detected by a receive photo cell and further processed. Note: It is the scattered light and not reflected light that contains the speed information.

Different surface textures have different scatter patterns but virtually all surfaces (apart from plate glass and mirrored surfaces) will scatter light. If the surface scatters light, it can be measured.

Processing the Scattered Light

The goal of an LDV device is to convert a time based signal to a measurement. This can be done using various techniques. One simple way is to use the zero crossing method where the system counts the number of times the time varying signal crosses zero. This is a simple technique that does not work well since along with the signal that represents the material speed, there is a noise that can create zero crossings at higher frequencies. Some LDV devices use Fourier Transforms to process the signal since the dominant signal received is the material speed. While it has good frequency resolution it does not have good time resolution.

Autocorrelation is a commonly used technique to detect a periodic signal inside a noisy signal. This works well for LDV systems and has very good time resolution. The better the time resolution the quicker the system can lock on and track the Doppler signal giving better system response.

Mathematically, the equation for autocorrelation is:

$$A(r) = \sum_{k=0}^{N-1-r} X(k)X(k+r) \qquad r = 0,1 \ldots N/2-1$$

This involves a lot of multiplying but since in an LDV system we are only interested in frequency and not amplitude of the signals, a special type of autocorrelation can be used called “Double Clipped Autocorrelation”. Double clipped simply means that when the signal is in its positive cycle it is represented by a one and when it is in its negative cycle it is represented by a zero. This simplifies the math and when using modern digital signal processing hardware, measurement rates of 100,000 measurements per second are achievable. The advantage of taking so many readings is: fast signal tracking which allows for averaging without slowing down signal response to increase accuracy.

Accuracy

The measurement accuracy of a laser gauge is affected by several factors. The most important factors are:

- Laser collimation
- Rotational angle of gauge versus surface line travel
- Perpendicularity of gauge to surface
- Temperature

Collimation is the consistency of the fringe spacing, “d” (from Equation 1), throughout the measurement region or depth-of-field of the gauge. The depth-of-field is defined as the length of the intersection of two laser beams. See Figure 4 LDV D. Collimation is determined by the optics’ ability to make the laser beam wavefronts completely parallel and flat. High quality optics must be used to maintain constant fringe spacing throughout the depth of field of the gauge.

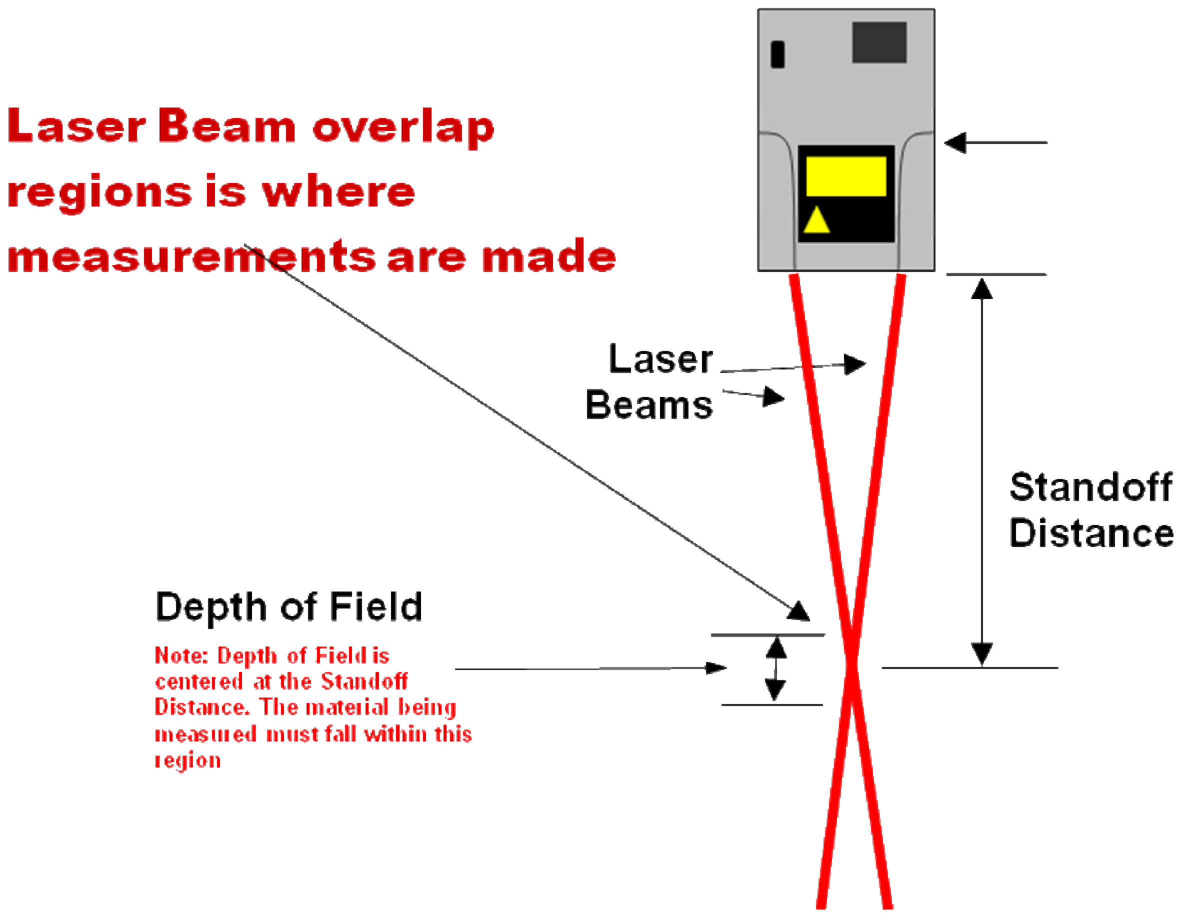


Figure 4 LDV Depth of Field

Movement within the depth of field will affect accuracy if the distance between the fringes changes through the depth of field. Proper collimation is important to allow the system remain accurate throughout the depth of field.

Different depth of fields can be created by changing the beam angle which will also change the standoff distance. The standoff distance is measured from the face of the device to the center of the depth of field. In practice, the surface to be measured should be in the center of the depth of field to allow for movement of the product. Depths of field values from a few millimeters to 300mm are achievable. The product must remain in the depth of field, where the fringe pattern is created in order to be measured.

If high quality optics are used and are collimated properly, the fringe spacing consistency can be maintained.

Rotational and perpendicularity will also affect the measurement accuracy. Rotation of the gauge will create a cosine error. See Figure 5. The resulting error is determined by the amount of rotation. However, a rotation of 1° will only result in an error of 0.015%. A 1° rotation is detectable by the human eye and can be corrected during the installation.

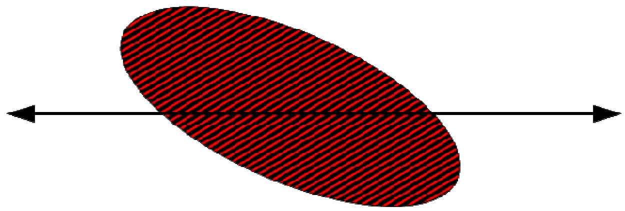


Figure 5 Rotation Error

While rotation of the gauge changes the path to which a particle passes with respect to the fringes, perpendicularity affects the spacing of the fringes themselves. See Figure 6. As with the rotational error, a 1° tilt will result in only a 0.015% error. This can be seen during installation and be corrected.

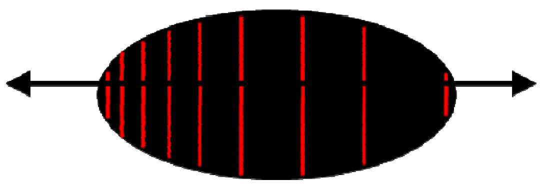


Figure 6 Tilt Error

These errors are additive, however they can be easily overcome. The collimation is done during the manufacturing of the devices and with currently available high quality optics, good collimation is easily produced. Tilt and rotation errors may occur during installation, but even misalignment of 1° would cause a fairly insignificant amount of error. Commonly used tools and even “eyeballing” the installation rarely creates more than a 1° misalignment. Given all this, installed accuracies of +/- 0.05% are achievable. In fact, in practice, 0.05% is worse case!

Acceleration

Since the non-contact technology uses Laser Doppler technology, product acceleration should have no affect on length and speed measurements as long as the signal processor has a fast response time. Laser Doppler Velocimetry is an optical system. Therefore, there is no inherent limit to the response of the system. Therefore, the acceleration rate of the system only depends on the response time of the internal processing of the gauge.

Permanent Calibration

Earlier in this paper we have talked about how the fringe pattern is created and what particular properties affect the fringe spacing. The two principle properties are beam angle and wavelength. While the beam angle is different for different standoffs, it is fixed for a particular unit. Wavelengths can be fixed if a single mode laser is used and a constant laser temperature is maintained. The laser temperature can be held constant using a thermoelectric device. If a single mode laser is held at a constant temperature, it’s mode or wavelength will not change.

During the manufacturing process, the actual fringe spacing can be determined empirically and stored inside the device in non-volatile memory. During the lifetime of the measurement device, the optics and laser temperature can be held constant and so the fringe spacing will be held constant. This means permanent calibration.

Permanent calibration is an important benefit for LDV devices over contact methods as it means lower maintenance and more process uptime. This is good for manufacturers.

Benefits and Applications

At the beginning of this paper we talked about the problems associated with traditional length encoders. Modern LDV devices overcome each of these disadvantages because they:

- are 20-40 times more accurate than a contact wheel encoder
- are non-contact and therefore non-marking
- are permanently calibrated
- have no moving parts, so there is nothing to wear

This translates into profits for anyone replacing a wheel encoder with an LDV device because they are:

- Reduced or eliminated over shipment of product to the customer
- Never accidentally shorting a customer, creating a buy back situation
- Eliminate product marking and associated scrap creation
- Totally eliminate the down time and expense of recalibration

Typical applications in the converting industry are, but not limited to, slitting, rewinding, coating and laminating processes.

To see the value of 20-40 times better accuracy, let's take a rewinding application where an order requires 500ft put on a roll. At 1.5% error, likely with a simple contact wheel encoder, there will be 7.5 extra feet of material given away. With an LDV device there will be no more than 0.25 ft extra material, worst case.

What does this mean after a year of producing rolls?

Production days per year	355
Production hours per day	22
Current accuracy	1.5%
Current linespeed	300 ft/min
Cost of material per foot	$0.08
Length savings per year	1,335,510ft
Cost savings per year	$106,915

Calculating savings in this manner is very straightforward. However, there are further savings associated with maintenance and re-calibration that are more difficult to calculate but are most certainly not an insignificant part of the total cost savings equation.

On a laminating line where two products are laminated together, it is very important to have both materials moving at the same speed. At the start of the run the payoff rolls are typically the same length but will both rolls be empty at the end of the run?

With current contact methods the process could be off by as much as 2%. One feeder roll might have material left over, which becomes scrap.

During the process, if one layer is moving at a different speed than the other, there will be tension between the two layers causing problems such as curling. Without and LDV device one can try to synchronize motor speeds but it is not certain that material will move at the same speed as the drive roll.

The best way to be sure that the materials are laminated without tension and/or that the rolls payoff the same amount is to measure the product directly with high accuracy. LDV devices work very well for this type of application.

Summary

Laser encoders, based on LDV technology are available today and have been proven to increase profits by dramatically improving accuracy and improving uptime by eliminating re-calibrations and frequent replacement costs. With advancements in technology and computer hardware, these devices can be made compactly and cost effectively. Typical payback is within 2 months on material savings alone.