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ADVANCES IN NON-CONTACT LENGTH AND SPEED MEASUREMENTS WITH ZERO SPEED AND AUTOMATIC DIRECTION DETECTION FOR PROCESS AUTOMATION[1]

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Abstract

Precision speed and length measurements are critical for controlling production costs and improving process control for the steel, and nonferrous metals industry. Traditional, contact rollers and tachometers have inherent problems with slippage and mechanical wear. Both of these problem cause increased scrap, increase maintenance costsand reduce the quality of the end product. LaserSpeed® non contact speed and length gauges solve all of the problems of mechanical contact rollers and tachometers.

Key words: Length & Speed measurement non-contact gauge.

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INTRODUCTION

As steel, aluminum, and non-ferrous producers are driven to become more efficient and improve product quality, their ability to measure speed and length with increasing accuracy has become essential. Accurate speed and length measurements are critical to all attempts to improve process control automation.
Traditionally, speed and length measurements were obtained from tachometers and encoders attached to drive rolls, tension rolls, contact wheels, and idler rolls. However, contact measurements are prone to calibration changes due to wear, and they often experience measurement errors caused by slippage between the roll and the material being measured and have high maintenance costs.
Non-contact, laser-based gauges were developed more than 20 years ago. The first non-contact laser speed and length gauges were big, bulky, expensive, and met with limited success in the market. Many technological advancements have been made since then. Laser-based speed and length measurements have become the standard measurement technology for many common manufacturing applications, as well as difficult applications.
Mass Flow Automatic Gauge Control (MFAGC) for cold rolling mills is one application that has been greatly improved by non-contact speed measurement gauges. All major single-stand and multi-strand tandem cold rolling mills in the world today use laser speed measurement gauges to improve the performance of their MFAGC or elongation control.
The new generation of lower cost, higher accuracy gauges, such as the LaserSpeed gauge, is utilized in many applications today. Plate mills, cold mills, hot strip mills, tube and pipe mills, bar and rod mills, temper and skin pass mills, for example, have begun using this technology in the past several years. These lower cost gauges are smaller and much less expensive than gauges previously available, while maintaining the high accuracy and high performance of the older, more expensive gauges. However, the recent technological developments have not offered a suitable solution for applications with line speeds is below 1 to 2 meters/min or when the line stops and reverses direction.
A new gauge has been developed that can measure down to zero speed and also automatically determine the direction of movement. This has been accomplished by adding an acousto-optic-modulator to the new, smaller, lower cost gauge technology. The new gauge with zero speed and direction detection is smaller and much less expensive then older gauges with the same capability. The new gauge is also ideally suited for positioning applications, continuous caster, crop shear, guillotine shearing, process lines, cutting control and many other applications that either stop or reverse direction.
This paper describes the new technology used to develop a compact, non contact speed and length gauge with zero speed and automatically detect the direction capability. The paper also evaluates measurement data utilizing the new gauge technology, and summarizes test results.

DESIRED CAPABILITIES

Typically, laser speed and length measurement gauges are large, bulky and expensive. Recent advances in microelectronics, however, have made it possible to embed the required signal processing on a single chip for a dramatic size reduction of the gauge. These electronic enhancements, along with updated optical designs,

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have enabled the electronics and optics to be housed in a single small, rugged housing. For users, the result is a very compact, low-cost, non-contact length and speed gauge that can deliver measurement accuracy equal to or better than bigger, more expensive systems.

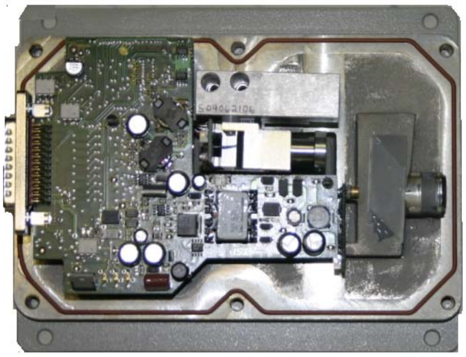

Figure 1. Sample Compact Electronics and Optics. Size = 8″x 6.3″ x 3.2″ Weight = 5.6 lbs

AN EXAMPLE

Beta LaserMike introduced the LaserSpeed® Model 8000 gauge in 2003. The Model 8000 gauge, and it's predecessor the LS200, were the first gauges developed for the metals industry that used new technology to house a complete, laser Doppler based, a non-contact speed and length gauge in a small compact housing. The new technology allowed these small compact gauges to produce equal or better performance than the much larger more traditional gauges. In addition, the cost of the gauge was significantly reduced which allowed a significant price reduction to the end user and allowed the new gauge to be cost effective in more applications.

Figure 2. Compact LaserSpeed Gauge

Figure 3. Beta LaserMike Model LS9000 Model LS9000 & Model LS2100S Introduced 1987.

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OPERATION

The operating principle of this gauge is based on the dual-beam Laser Doppler Velocimetry. When two laser beams intersect, an interference pattern of both light and dark fringes is created. This is called the measurement region and is illustrated in the Figure 1. The distance (d) between the fringes is a function of the wavelength (λ) of light and the angle between the beams (2K). It is represented in the following equation:

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

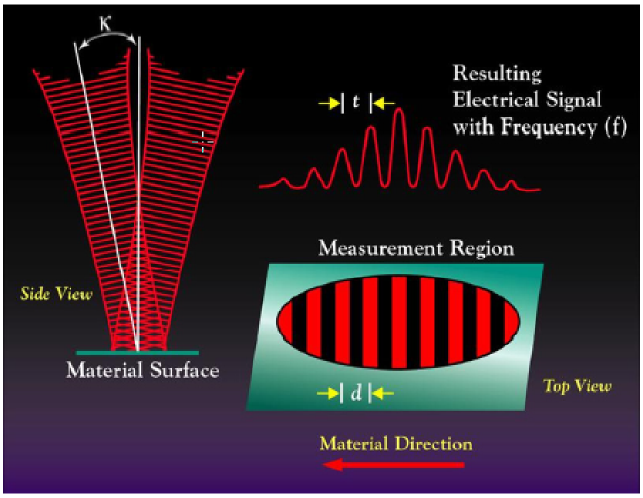

Figure 4. Measurement Region

Nearly all materials have light scattering sites — particle and minute facets that make up the surface microstructure. As a light-scattering site passes through the measurement region, light is scattered every time it passes through a light fringe. The scattered light is collected and converted to an electrical signal that has a frequency (f) proportional to the material velocity (Doppler frequency).
The material velocity (v) is Distance / Time where the Distance is the distance between light fringes and Time is the time it takes to move from one fringe to the next:

$$v = \frac{d}{t}$$

Since the time is inversely proportional to the frequency of the signal, the material velocity can be obtained by multiplying the distance between fringes by the measured frequency.

$$t = \frac{1}{f}$$

Therefore, v=d x f
Having measured the material velocity, the length can also be provided by integrating the velocity information over the total time.

$$L = \int_0^T v\,dt$$

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Essentially, the gauge measures the speed of the surface and integrates the speed, over the total length of the material, to obtain accurate length measurements. As material passes through the measurement region, the frequency of the scattered light is directly proportional to the speed of the material. The scattered light is then collected by receiving optics within the gauge and converted to an electrical signal. Such electrical signals are then processed by a state-of-the-art DSP to obtain frequency information, subsequently measuring speed and integrating it to measure length. The DSP also formats the instrument's user input and output functions.
This technique has two limitations, 1) no light fringes are being crossed when the surface is not moving so no Doppler signal is produced, therefore, zero or very low speeds can not be measured, and 2) the Doppler signal looks the same when the surface is going in the forward or reverse direction., therefore no direction detection is available. It should be pointed out that this type of gauge can measure both forward and reverse speeds but it outputs the absolute value of the speed not speed and direction. A graph showing the relationship between the Doppler frequency and Velocity is shown in figure 4. About 80% to 85% of all the application does not stop or reverse direction and are unaffected by these limitation.

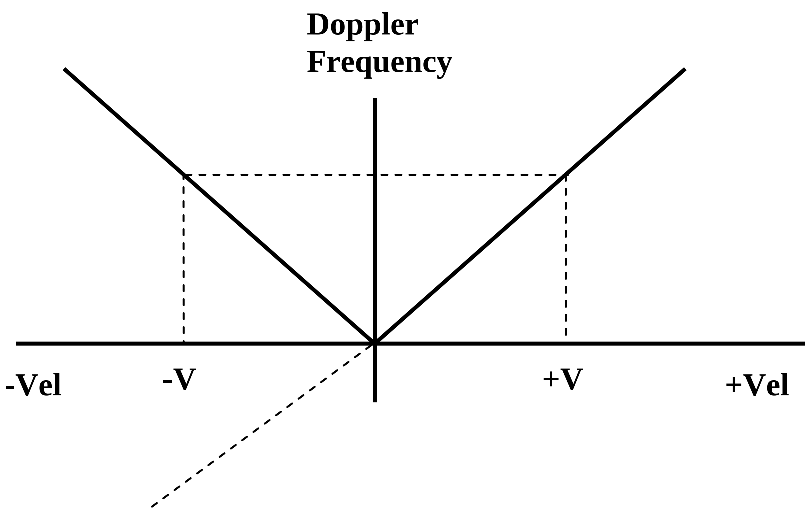

Figure 5. Doppler Frequency vs Velocity

However, 15% to 20% of applications stop and/or reverse direction or move very slowly. To overcome the limitations listed above, a new gauge was developed using the compact gauge technology and an Acousto- Optic Modulator. This allows the new gauge to measure the speed of the surface, determine the direction of movement and to also measure very slow speeds.. An Example of applications where the surface stops and/or reverse is where products have to be positioned for operations like shearing, cutting, marking. Applications like continuous casters require very slow speed measurements, down to a few inches per minute and zero speed. Caster speeds are below the range of the traditional Laser Doppler gauges because the Doppler frequency generated by such slow speeds is below the practicable ability of traditional signal processing methods.

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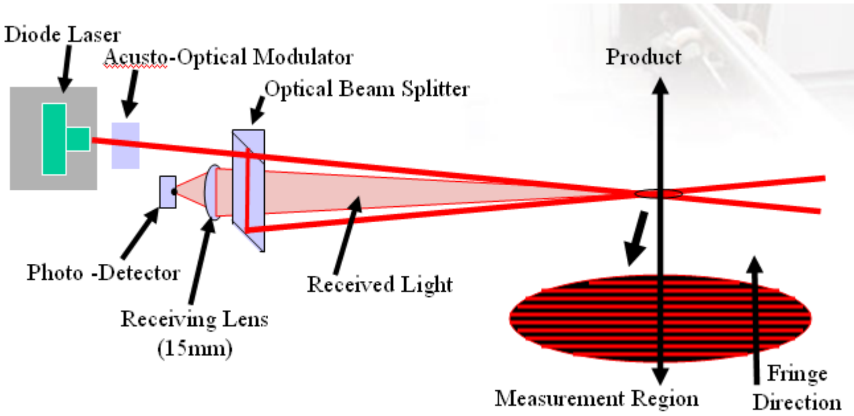

Figure 6. Block Diagram of a Laser Doppler gauge with an Acousto-Optical Modulator.

An Acousto-Optical Modulator is made from a crystal glass (who's index of refraction changes when compressed) and a piezoelectric transducer. The Piezoelectric transducer vibrates at 40 MHz causing a compression wave to propagate through the glass crystal. The traveling compression wave corresponds to a traveling wave of index of refraction changes. The index of refraction of the glass is higher where the glass is under compression and lower where the compression is lower. This acts like a moving diffraction grating to the laser beam that passes through the glass. The diffraction grating causes the Laser beam to be split into two Laser beams. The two Laser beams are called the zero order beam and the first order beam. Theoretically, the power in each beams can be adjusted to be equal to ½ the original Laser input power.

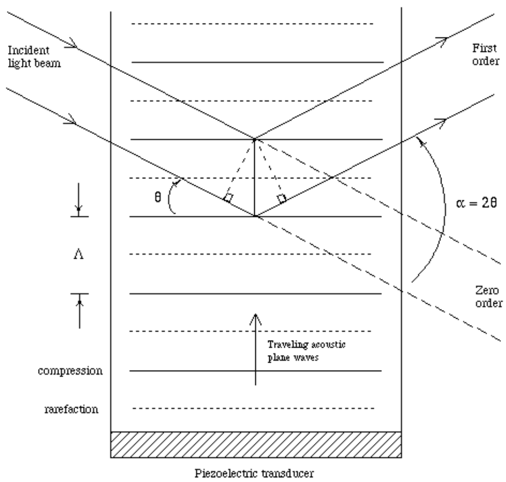

Figure 7. Diagram of Acousto- Optic Modulator

The zero order beam passes through the glass crystal unchanged but the first order beam get frequency shifter by the crystal frequency of 40 MHz. The 40 MHz frequency changes the frequency of the Laser by only 0.000014% and therefore does not change any of the properties of the Laser beam except it's frequency.
Referring to Figure 6, an interference patter will be generated when two Laser beams of the same frequency and phase cross in space. This interference pattern will consist of light stripes when constructive interference occurs and dark strips where destructive interference occurs. When an Acousto- Optical Modulator is used to

generate the two beams one beam is frequency shifter by 40 MHz with respect to the other beam. This causes the optical fringe pattern to move at the rate of 40 million fringes /sec or the same rate as the vibration frequency of the piezoelectric transducer as shown in Figure 7. A new relationship between the Doppler Frequency and velocity is established and is shown in Figure 7.
At zero speed the fringes will be moving past the surface structure at the rate of 40 million fringes per second. This will generate a Doppler signal of 40 MHz. when the surface is at stand still. When the surface moves in the opposite direction of the fringes, see figure 6, the Doppler Frequency will be greater then 40 MHz. When the surface moves in the same direction of the fringes the Doppler be lower then 40 MHz. See Figure 8.
The 40 MHz compression wave effectively adds 40 MHz to the Doppler signal, This is called frequency shifting. A signal processor measures the frequency of the combined signal of the Doppler Frequency plus the 40 MHz shift. The speed and direction of the moving surface can be obtained by numerically subtracting 40 MHz from the combined measured value.

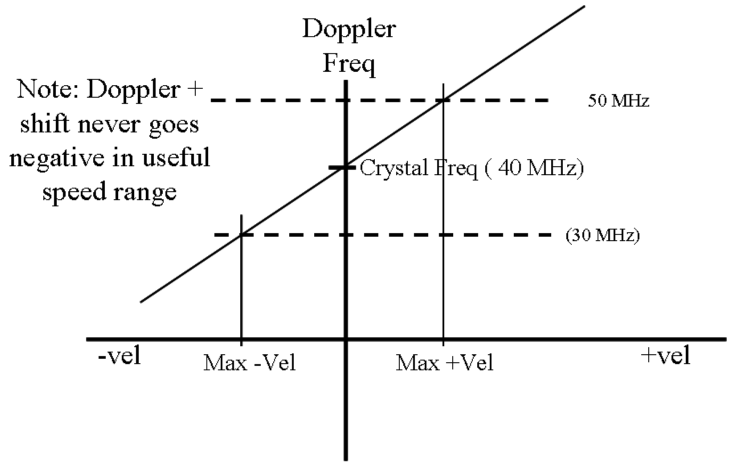

Figure 8. Doppler Frequency vs Velocity with Frequency Shift.

Unfortunately Acousto-optic modulators operate at very high vibration rates, i.e. 40 MHz. This applies a very high shift value to the Doppler frequency. Doppler frequencies can be below 100 Hz for a caster. Measurement resolution and repeatability suffer at slower speeds when such a high shift frequency is used because 40 MHz is added to all Doppler frequencies. That makes it difficult to resolve 0.01% of a 100 HZ when it has be shifted up to 40,000,100. Since the goal of the new gauge is to specifically measure very slow speeds, addition steps must be taken to gain back the accuracy and resolution at slow speeds. Therefore, the same technique of down mixing, used in all cell phones, has been applied. The technique is proprietary and can not be explained in this paper, but effectively, almost all of the 40 MHz shift frequency is removed using the down mixing technique only leaving enough shift frequency needed to determine the direction and to measure the speed at stand still.

REPEATABILITY

Variations in the measurement are affected by the quality of the laser's Doppler signal and the ability of the signal processor to determine the exact frequency from a noisy optical signal. The LS9000 gauge uses the latest in signal processing

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algorithms to extract the most accurate frequency measurement from the optical signal. The Gauge employs a "Double Clipped Autocorrelation" function with 10 to 15 times over-sampling to achieve unparalleled measurement accuracy. Using this algorithm ensures an accurate and repeatable measurement under all conditions. The autocorrelation algorithm is:

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

The Autocorrelation algorithm is the inverse transform of a Fourier Transform and is better suited for extracting the principle Doppler frequency the composite signal received by the photo detector. The algorithm is specifically engineered to operate on large-scale digital integrated circuits and makes 100,000 individual speed measurements per second.

Figure 9 shows a Histogram and Repeatability data using the new LaserSpeed gauge measuring on a NIST- Calibration standard length. Over 600 length measurements were taken and are shown on the graphs. The standard deviation of all the data taken was 0.00067or 0.002% of the mean. As can be seen by the graph in Figure 10, the repeatability offered is better than ±0.01%.

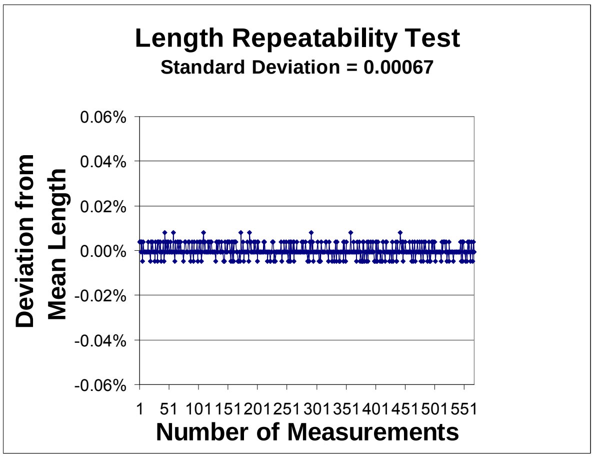

Figure 9. Histogram of Length measurements. Speed: 712Ft/min

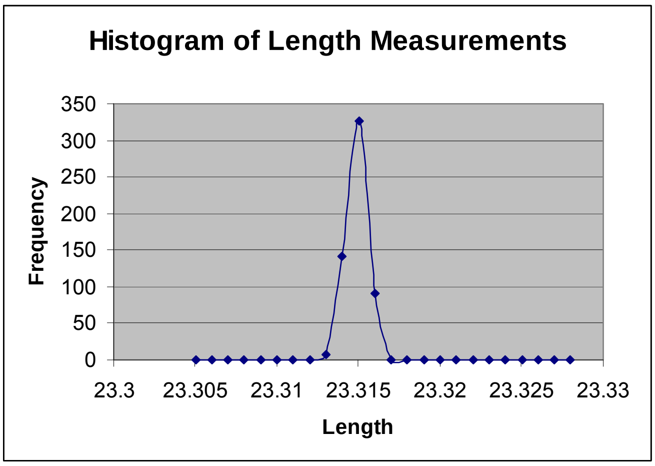

Figure 10.Repeatability of Length measurements Speed = 712 Ft/min

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MEASUREMENT 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", 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 Doppler beams. Collimation is determined by the optic's 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.

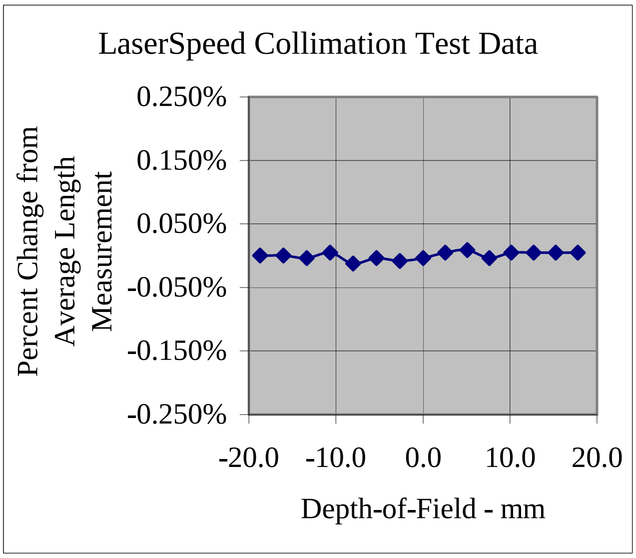

Figure 11. Actual Collimation Test Data

Movement of the surface within the depth-of-field will affect the accuracy of the measurement if the fringe spacing changes along the depth-of-field. Figure 11 shows the effect of surface position within the depth-of-field of the LS9000 Gauge. The test to determine the effects of surface positioning within the depth-of-field is called Collimation.

Different depth-of-field lengths can be obtained by changing the angle in which the laser beams cross and the size of the laser beams. Depth-of-field values can range from a few millimeters to more then 300mm. Different models of the LS9000 Gauge offer depth-of-fields ranging from 35 mm to 200 mm. Depth of field of 300 mm can be achieved.

The standoff distance is the distance from the front of the gauge to the middle of the measurement region or depth-of-field as shown in Figure 6. The standoff distance and depth of field are directly related. The longer the standoff distance, the longer the depth-of-field. Measurements can only be made when the target surface lies within the depth-of-field of the gauge. If high-quality optics are used to collimate the laser beams, the effect of the surface position within the depth-of-field has negligible effect on accuracy. However, if poor quality optics are used, different surface positioning within the depth-of-field can cause measurement errors up to 2% or more.

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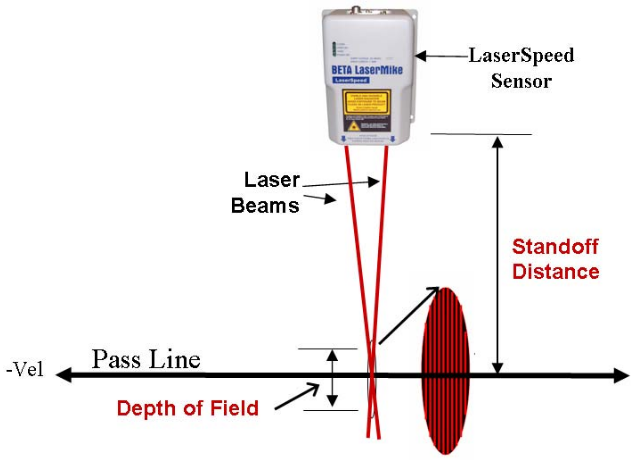

Figure 12. Depth-of-Field and Standoff Distance

ACCELERATION

Since the non contact technology uses Laser Doppler technology product Acceleration should have no effect length and speed measurements as long as the signal processor has a fast response time. Laser Doppler Velocimetry only uses light to generate the optical fringe pattern and the scattered light back to the photo detector also travels at the speed of light, 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 signal processor and post processor. Figure 13 shows the length repeatability to a surface that is accelerating and decelerating and the rate of 2833 ft/min/sec.

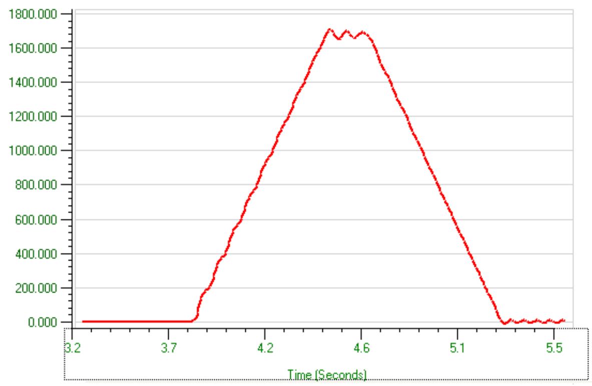

Figure 13. Acceleration in feet/min

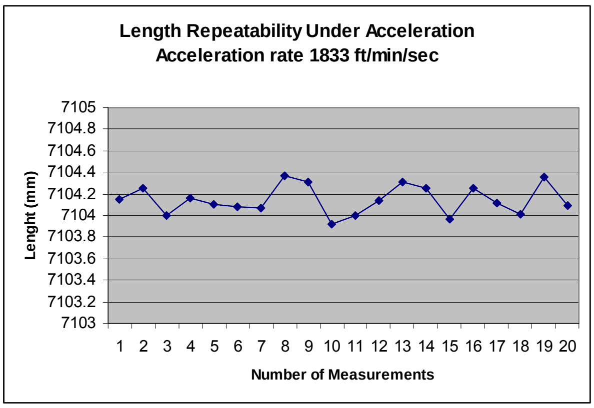

Figure 14. Length Repeatability

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SLOW SPEED OPERATION

Slow speed operation, below 5 ft/min(1.5 m/min) is difficult for Laser Doppler measurement gauges because the frequency of the Doppler frequency is below 1 KHz. Modern signal processors need at least 10 cycles of the Doppler signal to analyze in order to obtain an accurate measure of the Doppler frequency. If the Doppler frequency is below 1 KHz, less then 100 measurements/sec can be obtained. This is typically to low a measurement rate to be uses full. By frequency shifting the Doppler frequency up to 50 KHz, for example, 5000 measurements/second can be easily obtained, thereby improving the performance of the gauge. Therefore, another function of frequency shifting is to improve the low speed operation of the gauge.
A LaserSpeed gauge with a 2 meter standoff distance (the distance from the gauge to the cast) was tested on a Continuous Caster.
Two industrial environmental protective enclosures have been designed to protect the gauge from the harshest environments. The LaserSpeed Model 8000E is housed in a rugged aluminum housing. This combination enables the gauge to be used in almost all metals applications except interstand cold mills and over hot strip mills.

Figure 15. LaserSpeed 8000E with Quick Change Window and Air Wipe

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CASE STUDY WITH SKIN PASS MILL

Two LaserSpeed 8000E systems were mounted on a wet Skin Pass mill for elongation control.

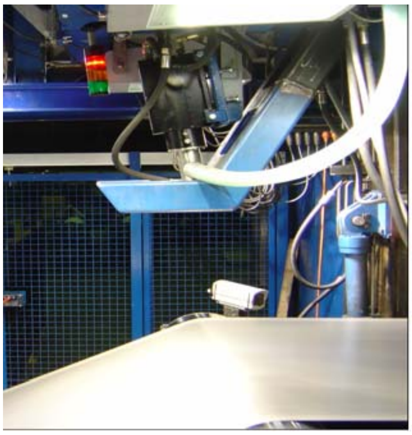

Figure 16. Picture of entry side of Skin Pass Mill

The oil of the skin pass mill caused too much slippage between the tachometer roll and the strip during acceleration and deceleration. Thus tachometers could not be used for elongation control.
Two LaserSpeed gauges were installed to eliminate the slippage problem. The following chart shows the elongation measured by two LaserSpeed gauges and by two tachometer rollers. The mill was controlled by the gauges during the test. There was medium mill coolant applied to the strip during the test.

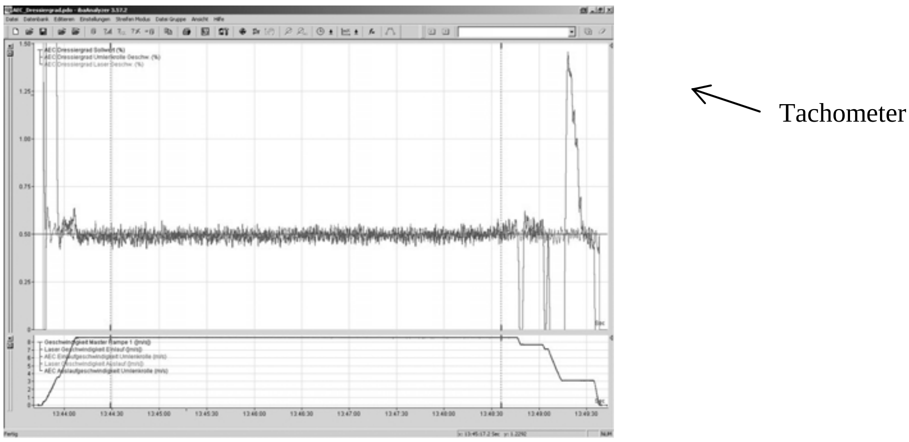

Figure 17. Comparision graph of LaserSpeed gauges vs. tachometer rolls on a wet skin pass mill

The top graph shows the elongation ratio percentage. The bottom graph shows the strip speed in meters/ second. The red-colored graph is the elongation ratio measured by the tachometers, and the green graph shows the elongation measured by the LaserSpeed gauges. The graph shows that more than 1.5% error can occur with the tachometers during acceleration and deceleration, while the LaserSpeed gauges measured accurately over the entire coil.
The LaserSpeed 8000 can also be housed inside a stainless steel housing for applications with extremely harsh environments, i.e., Mass Flow Automatic Gauge Control for interstand measurement in a cold rolling mills.

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Figure 18. LaserSpeed 8000X Stainless Steel Housing with beam path air purge

Figure 19. LaserSpeed 8000 gauge inside stainless steel housing

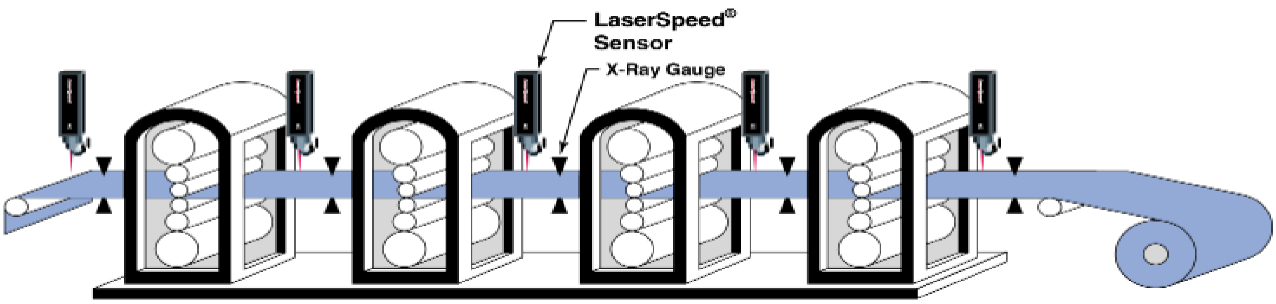

Figure 20. Typical interstand installation

For Mass Flow Automatic Gauge control, a LaserSpeed gauge is used in conjunction with a thickness gauge to perform Mass Flow Automatic Gauge control. The MFAGC is calculated by:

Mass Entry = Mass Exit

Mass = Thickness (T) X Width(W) X Density(D) X Length(L)

Length = Speed(S) X Time(T).

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Width, Density, and Time are constant.

Therefore, substituting in the Mass formula;

$$T_{Entry} \ X \ S_{Entry} = T_{Exit} \ X \ S_{Exit}$$

Or

$$T_{Entry} \ X \ (S_{Entry}/S_{Exit}) = T_{Exit}$$

In summary, you can control the thickness out of a mill stand if you know the entry side thickness and speed and the exit speed.

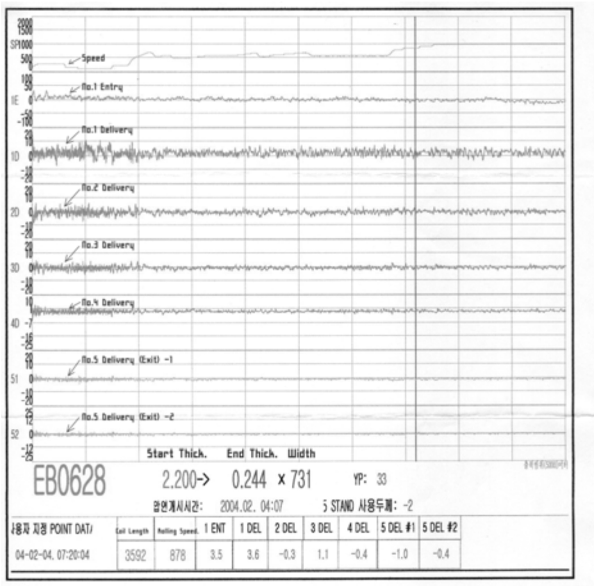

Figure 21: Thickness Gauge Graph

Figure 21 shows a graph of the thickness gauge before and after each mill stand in a 5-stand tandem cold rolling mill. LaserSpeed gauges are used in conjunction with a Thickness Gauge for MFAGC.
Additionally, the LaserSpeed gauge is small enough to fit inside the Thickness Gauge's C –Frame to form a combination gauge: thickness and speed measurements.

Figure 22. Combination LaserSpeed and Thickness Gauge

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Because of its compact rugged design, the LaserSpeed 8000 Gauge can be used as a stand-alone gauge, can be housed in an aluminum housing for harsh environmental applications, housed in a stainless steel housing for extreme environments or can be installed inside the C-Frame of the thickness gauge.

MEASUREMENT APPLICATIONS

Over 500 LaserSpeed gauges are currently installed in a wide variety of manufacturing processes for steel, aluminum, copper, brass and other non ferrous metals. LaserSpeed gauges are used to for MFAGC (mass flow automatic gauge control in the cold rolling process), crop shear optimization on hot strip mills, elongation control for temper and skin pass mills, cutting control for tube and pipe mills, reduction control of bar and rod mills, slab length measurements, slab positioning control, hot saw length control, laminar cooling speed control, position measurement on galvanizing lines, length measurements for slitter lines, coil diameter measurements, profile position measurements, aluminum extrusion control, cutter control for continuous casters, and many other applications that require accurate speed and length measurements. LaserSpeed gauges can also be used to verify the length after a cutter.

SUMMARY

Obtaining accurate speed and length measurement throughout the manufacturing process is invaluable. It directly translates to scrap reduction, improved quality, and improved productivity. New electronic and optical technologies have allowed laser-based speed and length gauge designs to become smaller, more rugged and much less expensive then previously available, while maintaining the same high level of performance. These smaller, less expensive gauges can replace tachometers, improving measurement accuracies for many processes at a cost that can be justified much more easily than could previously be done.