Laser Doppler velocimeter for velocity and length measurements of moving surfaces

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An industrial laser Doppler velocimeter has been developed for accurately measuring the velocity and length of moving surfaces. The instrument's advanced optical and electronic design provides a large depth of field, high SNR, and large dynamic range making it very suitable to industrial process control applications.

I. Introduction

Laser Doppler velocimetry has become a very useful laboratory tool for the measurement of gas, liquid, and solid surface velocities.[1,2] The majority of the commercial laser Doppler velocimeters are laboratory systems which work well but require customized setups which depend upon the application. This paper presents a laser Doppler velocimeter for solid surface measurements which is robust enough to be used, without modification, in harsh industrial environments for many process control applications.

The number of possible uses for an industrial velocimeter is quite large. The primary applications thus far have been in the primary metals industries. A noncontact velocity gauge can assist in process control in many rolling mill applications. For example, in the aluminum industry large webs of sheet aluminum are cold-rolled in sizes that require more than one roller across the width of the sheet. If the rollers do not roll the material with the same tension, the resulting sheet will bow as it comes off the line. To control this type of process, a number of velocity measuring stations could be lined up across the web. By continuously adjusting the tensions to keep the measured velocities at a predetermined value, the bow in the rolled sheet will be eliminated. In the steel industry, the biggest application is for measuring the length of hot steel for cut-to-length applications and the quality assurance on bar and structural steel rolling mills. Length measurement is easily derived by integrating the measured velocity.

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The requirements of a velocimeter to be used for such applications are very stringent. For the web measuring application, the velocity must be accurate to 0.1%, and the nearly specular surface of the aluminum causes a very strong Doppler signal. The steel mill applications require that length be measured to a similar accuracy, but the steel surface is very dark and the Doppler signal is considerably weaker. Another problem with many steel mill applications is that the location of the part on the transport system is not well constrained, requiring the gauge to have both a large depth of field and large dynamic range. The cut-to-length applications require that the instrument be capable of handling both positive and negative velocities because of the manner of operation of the cutting station. The environmental problems can also be quite severe. Steam from water cooling of the transport system and scale on the hot steel must be considered. The high heat and steam can be handled by proper packaging, but the scale can cause dropouts in the return light signal which requires special processing, particularly in length measurement applications.

This paper describes a laser Doppler velocimeter which meets the above requirements. The paper is divided into five sections. Following Sec. I is a brief section on the theory of laser Doppler velocimetry. Section III is a detailed description of the optical system. Section IV describes how the signal and data processing are performed. Finally, Sec. V presents a laboratory characterization of the performance of the instrument as well as results from actual on-line tests in a steel mill environment.

II. Theory

This section presents the theory of velocimetry in a simple way with minimal mathematics. If the reader desires a more complete treatment, there are many very good references in the literature.[3,4]

A laser Doppler velocimeter works on the principle that light scattered from a moving object is frequency

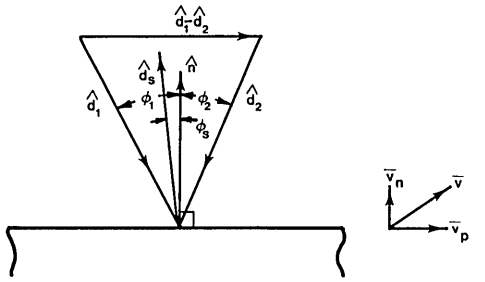


Fig. 1. Differential Doppler.

shifted with respect to the incident light. If a collimated beam of light of wavelength λ is incident on a moving surface, the frequency or Doppler shift is given by

$$\Delta\nu = (1/\lambda)(\hat{d}_1 - \hat{d}_s) \cdot \mathbf{v}, \tag{1}$$

where $\hat{d}_1$ and $\hat{d}_s$ are the unit vectors of the incident and scattered light, and $\mathbf{v}$ is the velocity vector of the moving surface (Fig. 1). For industrial applications the velocity component parallel to the surface $\mathbf{v}_p$ is of primary interest. To determine $\mathbf{v}_p$ uniquely requires that there be no motion of the surface along its normal direction $\hat{n}$ (i.e., $\mathbf{v}_n = 0$) and that the scattered light be collected over a small well-defined solid angle, necessarily resulting in a weak detected signal.

Because of these constraints, a differential Doppler method is more suitable. The method requires two incident beams $\hat{d}_1$ and $\hat{d}_2$ as illustrated in the figure. The frequency shifts are given by

$$\Delta\nu_1 = (1/\lambda)(\hat{d}_1 - \hat{d}_s) \cdot \mathbf{v}, \tag{2}$$

$$\Delta\nu_2 = (1/\lambda)(\hat{d}_2 - \hat{d}_s) \cdot \mathbf{v}. \tag{3}$$

The interference of the scattered light from each beam produces a difference frequency given by

$$\Delta\nu = \Delta\nu_2 - \Delta\nu_1 = (1/\lambda)(\hat{d}_2 - \hat{d}_1) \cdot \mathbf{v}. \tag{4}$$

Notice that all sensitivity to the viewing direction ϕ_s has dropped out. This is important in the design of the optical system because it allows a large solid angle of light to be collected without degrading the signal. In addition, if the angles of incidence are equal, $\phi_1 = \phi_2 = \psi$, Eq. (4) reduces to

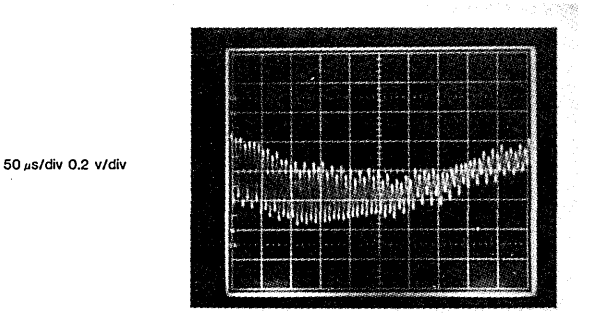
$$\nu_s = (2/\lambda)|\mathbf{v}_p| \sin\psi, \tag{5}$$

which depends only on the velocity component parallel to the surface.

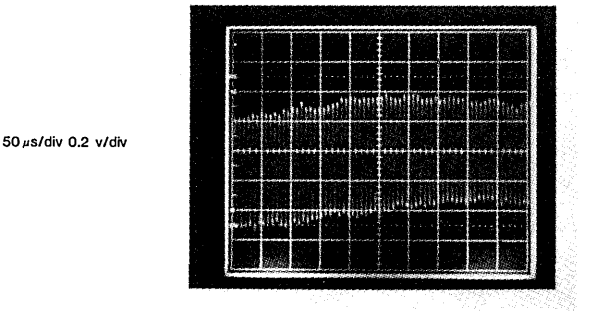
The light incident on the detector consists of many waves originating from the scattering centers on the surface. Each wave is modulated at frequency ν_s, but the phase between them is random. It can be shown that the sum of n sinusoidal waves each of amplitude A produces a resultant sinusoidal wave of the same frequency with an amplitude of $\sqrt{n}A$.[5]

In addition to sensing the modulation due to the Doppler signal, the detector also senses overall intensity variations caused by the scattering characteristics of the surface. On most surfaces this will present a problem since the scattering characteristics of the surface may vary greatly. Figure 2(a) shows a typical differential Doppler signal. Much of the surface signal component can be removed using a high pass filter as long as the surface does not have a high frequency structure that creates a modulation near the Doppler frequency. A method of eliminating the sensitivity to surface structure, as well as laser intensity fluctuations, has been suggested by Bossel *et al.*[6] This technique will be called the differencing differential Doppler technique. In this configuration, the two incident beams, $\hat{d}_1$ and $\hat{d}_2$, are orthogonally polarized, one parallel and one perpendicular to the plane of incidence. The scattered light is collected by a lens and directed through a polarizing beam splitter oriented at 45° to each polarization, causing half of the light from each polarization to be directed to separate detectors where interference occurs. The signals from each detector are 180° out of phase so that subtracting the two signals enhances the Doppler component while canceling common intensity variations due to surface structure and laser instabilities.

An example of the effectiveness of this technique is shown in Fig. 2(b). A signal of this quality is much easier to process and extract the Doppler frequency information. The use of the differencing differential Doppler method removes most of the noise in the frequency spectrum, but there will always be some low frequency components as well as noise due to the 60-Hz line frequency and external disturbances. The presence of these low frequency components makes the measurement of velocities near zero a difficult task. The



a) SINGLE DETECTOR DIFFERENTIAL DOPPLER



b) TWO DETECTOR DIFFERENCING DIFFERENTIAL DOPPLER

Fig. 2. Differential Doppler detector signals.

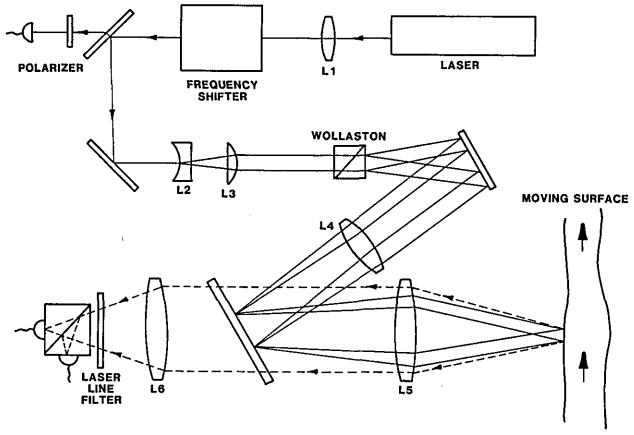


Fig. 3. Schematic diagram of the velocimeter optical system.

solution most commonly employed in laser Doppler systems is to introduce a frequency bias by frequency shifting one of the two incident beams. The frequency shifting can be done in many ways depending on the magnitude desired. For high frequency shifts >10 MHz acoustooptic modulators are used, and for low frequency shifts (<1 kHz) a rotating halfwave plate[7] can be used. For frequency shifts between these ranges, two acoustooptic modulators operating at slightly different frequencies are often used, although this is an expensive solution. The method used in this system is uniquely suited to the way data are taken, and it permits velocity measurements to be made for surfaces moving in either the forward or reverse direction. The frequency shifter is covered in the Appendix.

III. Optical System

The optical system of the velocimeter has been designed to incorporate the differencing differential Doppler technique. The design also incorporates a frequency shifter as an option. A number of other features have been incorporated to improve the SNR and to make the instrument adaptable to a large range of installations. The optical schematic of the velocimeter is shown in Fig. 3. The light source is a 5-mW polarized He–Ne laser operating in a small number of longitudinal modes and the TEM_{00} transverse mode. The output of the laser passes through lens $L1$, which controls the divergence of the laser and helps transfer the beam waist to the measuring volume. The next element in the optical train is the frequency shifter (see Appendix) which takes the input beam polarized at 45° to the plane of the paper and divides it into a vertically and a horizontally polarized beam. The vertically polarized beam is then frequency shifted by ~20 kHz, and the two beams are recombined. The polarizer and detector located directly behind the first mirror combine the two polarizations and detect the resulting beat frequency to monitor the frequency shift precisely.

The beam at this point is 0.8 mm in diameter. It is passed through beam shaping optics which create an 8- × 0.8-mm elliptical beam with its major axis in the direction of motion. The purpose of elongating the beam is twofold: the long dimension, which is in the direction of motion, narrows the frequency spectrum, and the short dimension improves the SNR.

The beam then enters the Wollaston prism which divides it into two beams of equal intensity, one horizontally polarized and one vertically polarized. The two beams emerge from the prism with a fixed angle between them. Large angles are used for measuring slow speeds and small angles for high speeds, so that the resultant Doppler shifts are comparable, maximizing the dynamic range of the measurement. Wollaston prisms typically used have angular separations of 5, 1, and 0.25°. Lenses $L4$ and $L5$ form a 1.5:1 afocal beam expander which images the beam crossing point onto the moving surface.

The light scattered by the moving surface is collected and focused onto the detectors by lenses $L5$ and $L6$. The fold mirror between lenses $L5$ and $L6$ is a long narrow strip of glass with a dielectric coating on one edge. The mirror is only 3 mm wide and, therefore, only obstructs a very small percentage of the aperture. After passing through lens $L6$, the light is spectrally filtered by a 100-nm laser line filter to remove as much of the background radiation as possible. It would be optically more correct to place the laser filter in the quasi-collimated beam between the two lenses, but these lenses have a 100-mm clear aperture requiring a large and hence expensive filter. Since the required performance of the filter is not very stringent, the position shown is a more economical choice. Following the filter is a polarizing beam splitter oriented with its polarization axis at 45° to the axis of the incident polarizations. It is drawn in the plane of the paper for clarity. This splits the light allowing an image of the moving surface to fall on each of the Doppler detectors. The optical system has also been designed with the ability to focus on surfaces varying in distance from 0.5 to 1.0 m. This was deemed a desirable feature because it allows the instrument to adapt easily to many different mounting arrangements. The focusing is accomplished by moving the Wollaston prism and lens $L6$ together in a fixed linear relationship. To move the measurement volume from 0.5 to 1.0 m, the Wollaston prism is moved to the right, and lens $L6$ is moved to the left.

This optical system fits in a box 84 cm long × 16 cm wide × 23 cm high.

IV. Signal Processing

A variety of signal processing techniques were examined for use in the velocimeter. These included tracking filters, wideband phase locked loops, correlation, and fast Fourier transform (FFT) processing. Each method has advantages for specific applications, but it was decided that the FFT approach was best suited to measuring widely varying surface types. Some characteristics of the Doppler signals which have to be handled by the signal processing are (1) frequent signal dropouts caused by sudden changes in surface finish; (2) large dynamic range to enable the instrument to handle many different surfaces and incident angles with no adjustments required by the user; (3) Doppler frequency dynamic range of >50:1; (4) discrimination be-

tween the Doppler peak and any small frequency peaks due to external sources; and (5) velocity accuracies of 0.1% and length accuracy of 0.3%. The hardware FFT system which was chosen handles these problems very nicely. Signal dropouts go virtually unnoticed in an FFT causing only a widening of the frequency peak. The large dynamic range is accomplished by using a 12-bit analog to digital converter and a 16-bit FFT. The ability to choose the correct frequency peak is handled in the software by the controlling microprocessor, and the accuracy is accomplished by using 458 frequency bins in a 1024-point FFT and averaging the resulting data.

The remainder of this section is a step-by-step description of the signal processing electronics in the velocimeter. To assist in understanding the description, a block diagram of the signal processing electronics is shown in Fig. 4.

The signals from the Doppler detectors in the measurement head are subtracted and amplified, and the resulting high level signal is transmitted to the signal processing electronics. The analog signal consisting of Doppler frequencies from 3 to 212 kHz is input to the sampling board where it is low pass filtered to eliminate the possibility of aliasing and then sampled at a rate of 468.1 kHz. The sampled signal is digitized and stored in memory. A total of 2048 samples is stored for each measurement. The first 1024 points are stored in the locations for the real part of the FFT input data, and the second 1024 points are stored in the memory locations for the imaginary part of the FFT. Since the FFT board is designed to do a 1024-point complex FFT, this allows two 1024-point real FFTs to be done simultaneously. If the two sets of real data $f_1(k)$ and $f_2(k)$ are input as a single complex data set given by

$$f(k) = f_1(k) + if_2(k) \qquad 0 \le k \le N-1, \tag{6}$$

where N is the number of data points in each set, the average magnitude of the discrete Fourier transforms of $f_1(k)$ and $f_2(k)$ is given by

$$M(j) \equiv \frac{|F_1(j)|^2 + |F_2(j)|^2}{2} = \frac{|F(j)^2 + |F(N-j)|^2}{4} \qquad 0 \le j \le N-1. \tag{7}$$

The FFT board needs 9 msec to complete these computations. The resultant spectrum is transferred to a different location in memory. The microprocessor then searches the spectrum from the seventh frequency bin to the 464th frequency bin to determine the existence and location of a valid Doppler frequency peak. The first six bins are skipped due to the inevitable noise near zero frequency. The upper bins are ignored because they are above the cutoff of the low pass filter. Once the frequency has been determined, the major part of the signal processing is finished. The remaining tasks are to subtract the frequency shift introduced by the frequency shifter and multiply the resultant frequency by a scale factor to obtain the velocity.

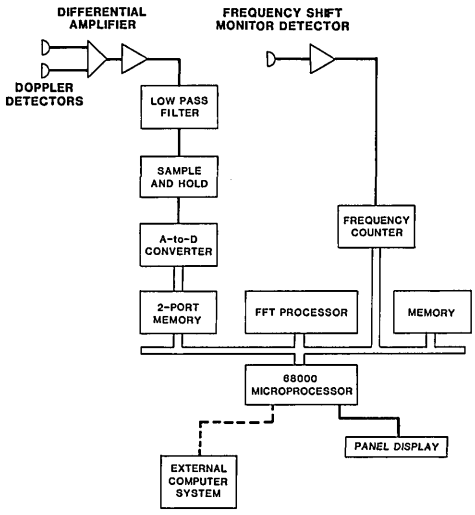


Fig. 4. Signal processing block diagram.

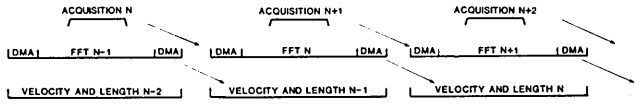


Fig. 5. Parallel data processing scheme.

The total processing time from the beginning of the data acquisition to the output of the velocity is 28 msec or ~35 measurements/sec. The update rate can be improved considerably by doing three tasks in parallel (Fig. 5). While the microprocessor is determining the location of the peak on the first set of data, the second set of data is in the Fourier transform processor, and the third set of data is being acquired. The limiting time is now the time required to do the FFT and the corresponding DMA transfers, i.e., ~16 msec. This corresponds to an update rate of ~60/sec, but it must be remembered that there is a 48-msec delay from the time that data are taken until the answer for that set of data appears at the output.

The calculation of the length of a part passing by the instrument can be determined by doing a numerical integration of the velocity. Unfortunately, the integration is not as simple as it might seem. Three major problems affect the accuracy of the integration: (1) accurate determination of the end points since the 16-msec uncertainty obtained from the Doppler data is not accurate enough; (2) the processing time for each data set is not constant introducing uncertainty into the time multiplier used to calculate the incremental lengths; and (3) the Doppler data are only a 4-msec sampling every 16 msec and, therefore, does not give a true average of the velocity over the interval. The first two problems are solved by using a combination of a separate detector to determine precisely when the part is in the field and a timer that is reset at the beginning of the part and stopped at the end. This permits accurate determination of the end points as well as a way

Table I. Sample Calibration Data

Initial velocity = 3.032 m/sec
Final velocity = 10 m/sec
Velocity increment = 1.02×
Flywheel diameter = 279 mm
Average of 100 samples
Velocimeter range setting = 10 m/sec

Actual velocity (m/sec)	Measured velocity (m/sec)	Standard deviation (m/sec)
3.032	3.047	0.0114
3.217	3.234	0.0115
3.413	3.433	0.0119
3.622	3.645	0.0135
3.844	3.867	0.0127
4.079	4.102	0.0135
4.329	4.356	0.0155
4.595	4.622	0.0166
4.875	4.902	0.0166
5.174	5.199	0.0163
5.491	5.522	0.0177
5.828	5.859	0.0185
6.184	6.219	0.0210
6.561	6.593	0.0195
6.965	7.002	0.0232
7.389	7.426	0.0230
7.842	7.883	0.0241
8.325	8.369	0.0255
8.830	8.874	0.0250
9.373	9.426	0.0273
9.946	9.999	0.0306

for the processor to time the length of each data taking interval. The third problem cannot be solved completely, but the errors it introduces can be minimized. This is done by using the trapezoidal rule to perform the integration. The combination of these factors produces accurate length calculations limited primarily by the accuracy with which the ends of the part can be detected.

V. Performance

The velocimeter has been tested extensively both in the laboratory and in steel mills on red hot steel (900°C). The laboratory tests were designed to test both velocity and length measurements. The velocity measurements were done on a custom-designed motor-driven flywheel. The flywheel is 279 mm in diameter and is rotated at speeds from 60 to 3400 rpm by a crystal controlled dc motor with <0.01% wow and flutter at 3400 rpm and 0.5% wow and flutter at 60 rpm. The velocimeter is set up to measure the edge velocity of the wheel which travels at 1–50 m/sec.

The flywheel calibrator was used for extensive characterization of the measurement of velocity. To check accuracy and repeatability, the calibrator and the velocimeter are both connected to an HP-85 computer. The computer steps the calibrator through a sequence of speeds and averages 100 velocity readings from the velocimeter at each speed. A sample of such a measurement is shown in Table I. This test is run for each velocity range more than once to test repeatability. The standard deviation that is printed with each data point is also important as it shows the number of samples that must be taken to obtain the desired repeatability. The results of the test show that the particular instrument tested was calibrated 0.025% low on the 40-m/sec range, 0.5% high on the 10-m/sec range, and 0.3% high on the 2-m/sec range. These calibrations were repeatable to within 0.1% from day to day and at different focal positions.

A graph of the log of the standard deviation of the measurements vs the log of the velocity is shown in Fig. 6. Notice on the graph that for each range is a horizontal line called the bin limit. The bin limit is the level where the standard deviation of the velocity measurement becomes $<1/\sqrt{3}$ times the frequency bin spacing in the FFT.

Below this limit the accuracy of measurement of a constant velocity object cannot be predicted by multiplying the standard deviation by the inverse of the square root of the number of data samples because the noise on the measurement is less than the bin spacing. Above this point the signal may be averaged to predictably improve repeatability. It must be pointed out that this is only for objects with very constant velocities. Notice that the entire 2-m/sec range lies below the bin limit. This can be explained by noting that to produce a 200-kHz Doppler signal from a part moving 2 m/sec there must be 100 fringes/mm on the part producing a total of 1200 fringes over a 12-mm illuminated area. This large number of fringes produces a natural frequency peak width of $1/1200$ of the frequency being measured, well below the resolution of the FFT. Therefore, the peaks produced are so narrow that they do not produce a distribution of frequencies.

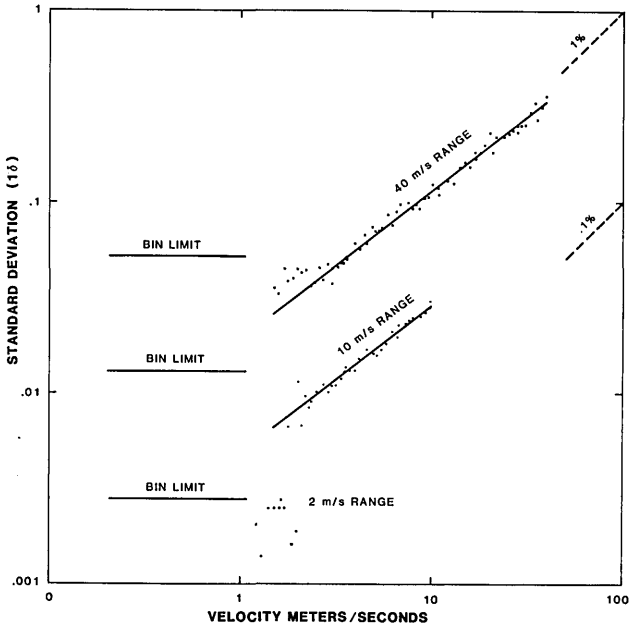


Fig. 6. Standard deviation of velocity mesurements.

Table II. Length Measurement Data

Tape length (m)
30.543
30.553
30.565
30.554
30.536
30.560
Mean = 30.552 m
Standard deviation = 0.011 m

Table III. Steel Mill Test Data

Bar	Velocimeter (m)	Tape (m)	Delta (m)	Delta (%)
26	4.812	4.801	0.011	0.21
27	4.565	4.572	0.007	−0.17
30	4.438	4.420	0.018	0.40
40	4.444	4.432	0.012	0.27
Mean error in meters = 0.009 m				
Mean error in percent = 0.18%				

The calibrator can also be used to check the instrument for drift by setting the motor to a constant speed and noting any changes in the velocity output. Such measurements show zero drift with time. This is to be expected since the only possible source of drift in the instrument is the crystal oscillator which controls the data sampling rate.

These tests were repeated with the frequency shifter in operation, and the statistical results were unchanged.

The length measurement capability is tested by manually pulling a strip of Mylar tape through a gate in front of the velocimeter. The tape is 25 mm wide and 30.398 m long. Mylar was used because it is very resistant to stretching and, therefore, makes a repeatable sample for length measurement. The results of several measurements made in the 2-m/sec range are shown in Table II. From the velocity calibration it is known that the 2-m/sec range is 0.3% high; if this is taken into account, the corrected measured mean is 30.461 m, which is within 0.2% of the actual length. This test shows that if the instrument is properly calibrated, the length measurement will be within the 0.3% required accuracy with a 3σ variation of 0.1%.

The instrument tests on line at steel mills were designed to check the accuracy and reliability of length measurements under harsh environmental conditions. To operate properly in a steel mill environment, the instrument must be able to handle high heat loads, scale on the surface of the part, steam, and lots of dirt. One steel mill test was on a continuous casting bar mill producing 5-m long × 172-mm diam bars. The bars passed by the measuring station at a temperature of 900°C.

Setting up the gauge was a very simple procedure. The gauge head was positioned alongside the roller conveyor immediately following the casting operation. The head was installed 1 m from the conveyor with an air window and a Transite shield to protect the gauge from the heat. The unit was supported on a steel table with wood cribbing and wedges to adjust the height. The electronics enclosure was located on the floor ~6 m away. The total installation time was ~30 min.

During operation of the mill, the castings were passing by the measurement head at a rate of one every 45 sec at speeds between 0.75 and 1 m/sec. The gauge was set on the 2-m/sec range, and the resulting lengths were logged on a portable printer. To verify the length measurements being made by the velocimeter, four of the bars were taken off the line immediately following the measuring station while they were still hot. These bars were then checked by tape measure with an accuracy of 12 mm. The resulting measurements are shown in Table III.

Taking into consideration the uncertainty in the tape measurements and the known 0.3% calibration error in this range, the data in Table III are consistent.

VI. Summary

This paper has presented a laser Doppler velocimeter capable of measuring length and velocity of a wide range of moving surfaces. The design of the optical head is based on the differencing differential Doppler technique which provides very good SNR and a large optical dynamic range. The data processing is done digitally using a hardware FFT processor and a microprocessor. Laboratory tests have shown that the instrument has an accuracy (3σ) which depends on the velocity range. For averages of 1 sec, the measured accuracy for the three speed ranges are: <0.1% on the 2-m/sec range; 0.1% on the 10-m/sec range; and 0.4% on the 40-m/sec range. The accuracy in length measurements is better than 0.3% on all speed ranges and is limited primarily by the uncertainty in detecting the beginning and end of the part. The instrument has been taken on numerous field tests in mills in the primary metals industry where it has performed well in harsh environments.

The authors would like to thank a number of people for assistance during the course of this work: Jim Morace for assembling and aligning the optics; Eric Ehrenfels and John Zielke for building the electronics; Adam Rubinstein for the mechanical design; and Jill Duff for the software.

Appendix: Frequency Shifter

The frequency shifter used in this instrument is of a unique design made possible because of the way data are acquired. Since the velocimeter only takes data for 4 msec every 16 msec, it is not necessary that the frequency shift be continuous, only that it be in operation during the data acquisition period. The requirements for the frequency shifter are that it be capable of producing a 20-kHz frequency shift (~10% of full scale) for a minimum of 4 msec every 16 msec and that it be capable of changing the sign of the frequency shift. The ability to change the sign of the frequency shift allows full range reversing.

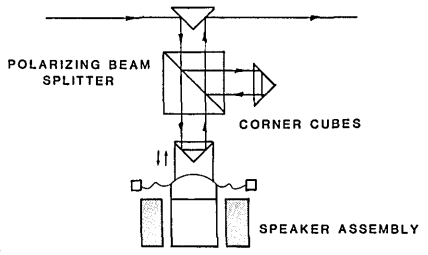


Fig. 7. Schematic of frequency shifter.

The opto-mechanical schematic of the frequency shifter is shown in Fig. 7. The optical system consists of a ½-in. polarizing beam splitter and two silvered corner-cube retroreflectors. The polarizing beam splitter divides the incoming light into two polarizations each going to a different retroreflector. By mounting the retroreflectors properly, the two return beams can be made collinear. The retroreflectors are coated with a metallic reflector to prevent polarizations from changing upon reflection. The frequency shift is produced by moving one of the two retroreflectors along its optic axis. When the retroreflector is moved away from the polarizing beam splitter, the light reflected by it is Doppler shifted down in frequency, and when it is moved toward the beam splitter the light is shifted up in frequency. Therefore, the direction of movement can be used to change the sign of the frequency shift. The amplitude of the motion required is ~25 μm in 4 msec. The retroreflectors then have 12 msec to return to its original position before the next measurement begins.

The motion of the retroreflector is provided by the driver of an audio frequency tweeter. The retroreflector is mounted on the dome of the tweeter. The tweeter is driven by a trapezoidal waveform, and a feedback loop is used to control the linearity and velocity of the retroreflector.

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Members of the Optical Society of America have chosen Jean M. Bennett of the Michelson Laboratory, Naval Weapons Center, to be their vice president next year—and thus their president in 1986—in balloting tabulated on September 12.

Three directors-at-large were also elected: James B. Breckinridge, research scientist, Jet Propulsion Laboratory; Richard K. Chang, professor of applied physics, Yale University; and William T. Rhodes, professor of electrical engineering, Georgia Institute of Technology. They will serve on the Society's nineteen member Board of Directors from January 1, 1984, to December 31, 1986.

Additional Board positions will also change in 1984: Robert W. Terhune, Ford Motor Company, previously the editor of OPTICS LETTERS, becomes the editor of the JOURNAL OF THE OPTICAL SOCIETY OF AMERICA; the new editor of OPTICS LETTERS is Paul L. Kelley, MIT Lincoln Laboratory; and Jay M. Eastman, Optel Systems, Inc., serves on the Board as chairperson of the technical council.