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Laser Doppler Velocimetry for Flow Measurements in Pulp and Paper Research

J.Y. Zhu

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LASER DOPPLER VELOCIMETRY FOR FLOW MEASUREMENTS IN PULP AND PAPER RESEARCH

Junyong Zhu
Institute of Paper Science and Technology
500 10th Street, N.W.
Atlanta, GA 30318
(404) 894 - 5310 (404) 894 - 4778 (FAX)

ABSTRACT

Optical diagnostics have become prevalent in research and development because they provide a nonintrusive mechanism for probing active processes and physical phenomena. Many optical techniques and instrumentation have been widely used by scientists and engineers in various fields for both basic research and practical applications. While there are a few researchers in the pulp and paper community who are very familiar with and have used several optical diagnostic methods in their research, many industrial researchers are still skeptical and uncomfortable to use modern research tools. The objective of this paper is to introduce a very basic optical tool - the laser Doppler technique - to the pulp and paper scientific community.

The paper will consist of four parts: (1) the basic principle of the laser Doppler technique for velocity measurements, (2) overview of historical and recent developments in laser Doppler technology, including fiber optic, diode lasers, digital signal processing, and fast Fourier transform, (3) discussion of measurement errors, advantages, and disadvantages of certain signal processing methods used in laser Doppler technology, and (4) the challenges of applying the Doppler technique in pulp and paper research.

The intention of the paper is twofold: to make an introductory presentation on the laser Doppler technique for researchers who are new to the subject and to give an in-depth look into the fundamentals of various scientific issues associated with the laser Doppler technique for those who are familiar with the technique. It is anticipated that this paper will help readers to understand the key issues in selecting a particular commercial laser Doppler system for a particular application.

I. INTRODUCTION

Flow measurement is a common practice in pulp and paper research. Understanding the flow dynamics in pulp and paper manufacturing processes can help design better equipment and improve product quality and productivity. For example, measurements of the behavior of flow instability in coaters helped to explain the causes of coating paper quality degrading in the production of high-grade coated papers and photographic films (Higgins, 1982; Triantafillopoulos and Aidun, 1990); the study of the interaction between air jets in recovery boilers improved the understanding of the role of flow dynamics in particle carryover in recovery boiler operations (MacCallum and Blackwell, 1987a, 1987b; Jones, et al., 1989); and the investigation of the turbulent structure of fiber suspension flows can help the understanding of fiber flocculation in papermaking (Parker, 1972).

With the development of laser, photoelectronic, computing, and digital signal processing technologies, advanced flow measurement techniques and instrumentation have been developed and widely applied in many fields of scientific research, such as in fluid/thermal sciences. From improved understanding of spraying processes in food and drug processing, coating, and agricultural pesticiding, combustion aerodynamics and fuel/air mixing in engines, and blood flow behavior in the human body, to developing accurate ice-detection devises on airplanes, sensors for environmental emission monitoring, and low emission and high efficiency burners; the benefits of using advanced flow measurement techniques are invaluable. However, the pulp and paper scientific community has not taken advantage of the advanced flow measurement techniques to benefit research. The objective of this paper is to introduce a very basic optical tool - the laser

Doppler technique - to the pulp and paper scientific community.

Fibrous and particle-laden multiphase flows are common in pulp and paper research. Flow measurements in these flows is very difficult. Most of the intrusive techniques using physical probes are not suitable for measurements in these flows because they significantly perturb the flow field. Limited research have been conducted on detailed characterization of the flow dynamics of many pulp and paper unit operation processes. The designs of process equipment, such as coaters, headboxes, steamboxes, recovery boiler air ports, etc., were all based on trail and error experiences. It is believed that advanced measurement techniques, such as a laser Doppler velocimetry, can be powerful research tools to obtain improved understanding of many flow processes in pulp and paper unit operations to increase productivity and product quality. The intention of this paper is to provide an introductory presentation on the laser Doppler technique from the practical application point of view to the pulp and paper research community. It is anticipated that this paper will help readers to understand the key issues in the laser Doppler technique to ease problems in selecting a laser Doppler system for a particular application.

II. THE PRINCIPLES OF LASER DOPPLER VELOCIMETRY

A laser Doppler velocimetry (LDV) measures the velocity of a particle based on the measurement of the Doppler frequency shift of the laser light scattered from the particle. The application of a LDV for flow velocity measurements assumes that the flow velocity at a point probing is equal to the velocity of a particle passing through the same point when the particle is very small. This assumption of particle full entrainment in flows is generally valid for particles with diameters less than 1 µm in most flows.

1. The Doppler Effect

Although the Doppler frequency shift effect in wave or light radiation received from a moving body by a stationary detector has been understood and widely used in telecommunication and astronomy, the invention of the laser Doppler technique for flow velocity measurement was made until the ‘60s by Yet and Cummins (1964). During the last 20 years, the laser Doppler technique has been greatly improved with the development of computing, digital signal processing, diode laser and fiber optic technologies, and widely used for flow measurements in many scientific disciplines. However, the basic principles remain very simple.

For a stationary light source, the frequency of the light measured by a stationary observer (detector) can be expressed as,

$$f = c/\lambda \qquad (1)$$

where c and λ are the speed and the wavelength of the light, respectively.

If the light source is moving at a velocity of u, the measured frequency by the observer will be different from the frequency of the incident light. This effect is called the Doppler effect. The difference between the measured frequency and the incident light frequency is called the Doppler shift frequency f_d which is related to the velocity u and the wavelength λ,

$$f_d = u/\lambda \qquad (2)$$

2. The Laser Doppler Technique

Doppler frequency shift by particle light scattering

When a moving particle with velocity $\boldsymbol{u}$ passes through a stationary light path in the direction of $\boldsymbol{s}$(unit vector) as shown in Fig. 1, the measured frequency of the scattered light by the particle at an observation direction $\boldsymbol{r}$(unit vector) will be Doppler shifted. The Doppler shift can be related to the particle velocity $\boldsymbol{u}$, the wavelength λ, the direction of the incident light $\boldsymbol{s}$, and the observation direction $\boldsymbol{r}$ by eq. (3).

$$f_d = \boldsymbol{u} \cdot (\boldsymbol{r}-\boldsymbol{s})/\lambda \qquad (3a)$$

$$f_d = 2u \cdot \sin\phi/\lambda \qquad (3b)$$

Therefore, particle velocity can be calculated once the Doppler frequency f_d. is measured. Equation (3) is the basic principle for particle velocity measurements using the laser Doppler technique. There are three major disadvantages associated with this simple Doppler technique for particle velocity measurements: (1) a very high frequency response detection system is required as the frequency of the resultant Doppler shifted burst signal f_r ($= f + f_d$) is on the order of 10^8 MHz; (2) a high frequency resolution is required for the detection system to obtain accurate velocity measurements as the Doppler frequency shift f_d ($\approx$10-100 MHz) is very small when compared to the resultant Doppler shifted frequency measured; and (3) the technique has a poor spatial resolution as the measurement probe length is equal to the field of depth of the detection system.

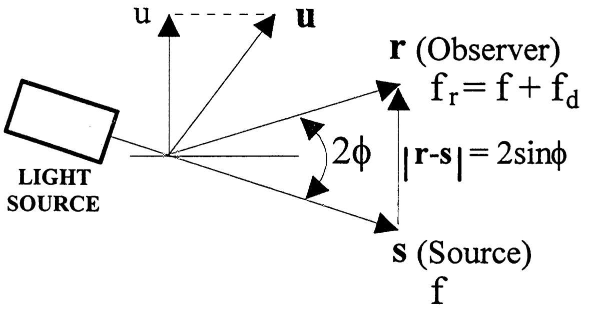

Figure 1. Schematic diagram of Doppler shift by particle light scattering

Heterodyne detection method

The laser Doppler technique based on heterodyne detection using linearly polarized laser light is developed to resolve the disadvantages of the simple laser Doppler technique discussed above. In a heterodyne detection system, a second laser beam is introduced: (1) to directly measure the frequency of the Doppler shift as a heterodyne result of light interference of the light wave of the second laser beam with the scattered light wave by the particle from the first beam; (2) to improve the frequency measurement resolution and accuracy as the signal frequency is reduced; and (3) to limit the probe volume in the cross-over region of the two laser beams to improve the measurement spatial resolution.

The initial heterodyne detection technique as shown in Fig. 2 is often called the reference beam method in which the second beam path is in the direction of the observation direction ***r***. Therefore, light scattered from the second beam is not Doppler shifted according to eq. (3a). The neutral density filter (NDF) is used to reduce the beam 2 intensity to match the intensity of the light scattered from beam 1 to obtain a high contrast heterodyne Doppler signal. The Doppler burst signal has the heterodyned frequency of $f_r = (f + f_d) - f = f_d$ as a result of the interference of two linearly polarized light waves. f_d is the Doppler shift frequency expressed by eq. (3).

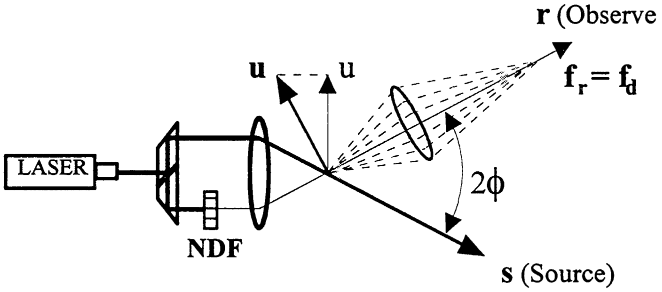

Figure 2. Schematic diagram of heterodyne detection laser Doppler technique

There are two disadvantages associated with this initial heterodyne method: the versatility of signal collection is limited to only one spatial direction and to locate the exact direction is often not trivial; the Doppler burst signal quality (the contrast of the interference pattern) is not guaranteed and varies with the intensity of the scattered light from beam 1. The dual beam method now adopted in LDV's has resolved these two problems.

Dual beam (fringe or interferometric) method

The dual beam heterodyne configuration as shown in Fig. 3 is also called the fringe or interferometric method in which the two linearly polarized incident laser beams have the same intensity and cross at the focal point to create a stationary fringe pattern by light interference as shown in Fig. 4 within the crossover region. The burst signal can be collected at any forward or backward direction. When a particle passes through the fringes, which are parallel elliptical surfaces, it scatters light to produce a burst signal with high and low intensities due to the intensity variation of the fringes as shown in Figure 4. The particle vertical component velocity u can be measured using the following equation:

$$u = d/\tau \qquad (4)$$

where τ is the transit time of the particle pass through a fringe, and d is the fringe spacing, which can be calculated using the interference principle:

$$d = \lambda/(2\sin\phi) \qquad (5)$$

The temporal frequency of the burst signal can be calculated from eqs. (4) and (5),

$$f_b = 1/\tau = 2u\cdot \sin\phi/\lambda \qquad (6)$$

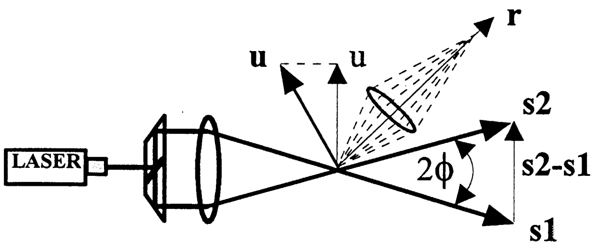

Fig. 3 Schematic diagram of the dual beam forward scattering laser Doppler technique

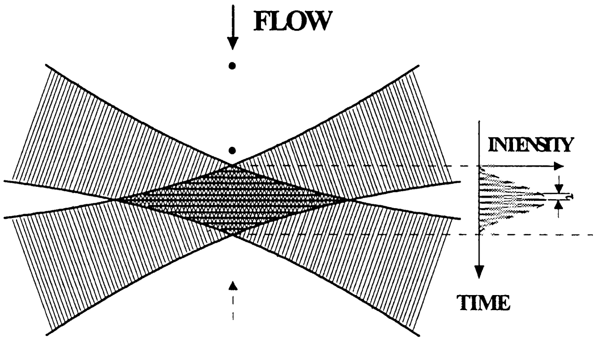

Fig. 4. Schematic diagram of the fringe model and probe volume

Fringe method and Doppler effect

The above explanation of velocity measurements using the dual beam configuration is called the fringe model. It is very easy to understand. However, it is important to remember that the fringe model is only a model and does not describe the actual physical process. Many researchers confuse this model with the physical process and thought that stationary fringes exist in the probe volume when there is no particle within the beam cross region. A few researchers even call the system laser velocimetry or laser anemometry as they thought that particle velocity measurements were no longer based on the Doppler effect.

Fringes do not exist in the actual physical process with the dual beam configuration when there is no particle in the probe volume. When a particle enters the probe volume, however, it scatters light at two different Doppler shifted frequencies f_1 and f_2 from the two laser beams, respectively. The interference of the scattered light produces a Doppler burst with a frequency f_b, which is detected by the detection system. The fringes within the probe volume is produced by the interference of Doppler frequency shifted light scattered by the particle.

The frequencies of the light scattered from beam 1 and beam 2 can be expressed using eq. (3a)

$$f_1 = f + f_{d1} = f + \mathbf{u}\cdot(\mathbf{r}-\mathbf{s1})/\lambda \qquad (7a)$$
$$f_2 = f + f_{d2} = f + \mathbf{u}\cdot(\mathbf{r}-\mathbf{s2})/\lambda \qquad (7b)$$

The frequency of the heterodyned Doppler signal can be found using the principle of interference of two linearly polarized light waves:

$$\begin{aligned} f_d &= f_1 - f_2 = \mathbf{u}\cdot(\mathbf{s2}-\mathbf{s1})/\lambda \\ &= 2u\cdot \sin\phi/\lambda = f_b \qquad (8) \end{aligned}$$

Eq. (8) clearly indicates that the dual beam fringe configuration is still based on the Doppler effect for particle velocity measurements. The fringe model is a good way to explain the laser Doppler velocimetry. Rewrite eq.(8), particle velocity can be calculated by measuring the Doppler frequency f_d (or the transit time of the particle passing through a fringe $\tau = 1/f_d$):

$$u = \frac{\lambda}{2\sin\phi}\cdot f_d = \frac{\lambda}{2\sin\phi}\cdot\frac{1}{\tau} \qquad (9)$$

Summary

- Laser Doppler velocimetry measures the particle velocity for flow measurements. It requires artificial seeding particles to be present in the flow. Each measurement is made only when there is a particle in the probe volume, and therefore, the measurement signal is not continuous.
- The LDV measurement is nonintrusive, instantaneous, and can be spatially resolved when two laser beams are crossed to form a small probe volume.
- The dual beam heterodyne detection configuration using linearly polarized light waves has been adopted as the standard for laser Doppler velocimetry. Velocity measurement using the dual (fringe or interferometric) method is based on eq. (9)
- Laser Doppler velocimetry can be easily understood using the Fringe model. However, it should be understood that the physical process is a Doppler phenomenon.

3. The LDV Sample Probe

Theoretical probe volume

A LDV sample probe is formed by the cross-over of two laser beams as discussed above. The theoretical geometry of the probe volume is ellipsoidal for circular laser beams as shown in Figure 5. The length and the diameter of the geometric probe volume can be calculated from simple geometry:

$$L_m = d_e / \sin\phi \quad \sim 0.5\ mm \tag{10a}$$

$$d_m = d_e / \cos\phi \quad \sim 0.1\ mm \tag{10b}$$

where d_e is the laser beam waist diameter defined as the diameter within which the laser intensity exceeds $1/e^2$ of its maximum amplitude and can be related to the initial laser beam diameter by the following expression

$$d_e = \frac{4\lambda f}{\pi D_e} \tag{11}$$

where D_e is the initial laser beam diameter defined as the diameter within which the laser intensity exceeds $1/e^2$ of its maximum amplitude.

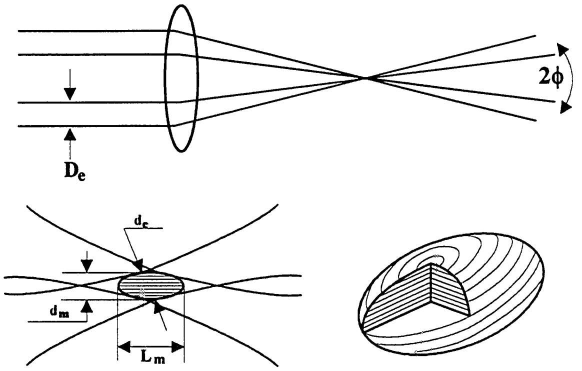

Fig. 5 Schematic diagram of a LDV probe

Actual probe volume

The actual probe diameter and probe length are defined based on the signal intensity rather than the laser beam intensity. This is because the actual probe volume is defined as a volume in which a Doppler burst produced from light scattering by a particle can be detected. Since a Doppler burst is detected through triggering by the data acquisition system. The triggering level defines the largest radial and longitudinal boundaries (or sample probe volume) within which Doppler bursts will be detected (or seen). For a given preset triggering level, however, the sample probe volume is determined by the signal intensity.

A Doppler burst signal intensity is a function of the incident light intensity and the particle size according to light scattering Mie theory (Mie, 1908; van de Hulst, 1981) as expressed by eq. (12),

$$I_d \propto I \cdot d^2 \tag{12}$$

where I_d is the Doppler burst signal intensity, d is the diameter of a given seeding particle, and I is the intensity of the incident light. Most of the commercial lasers used in laser Doppler velocimetry are TEM_{00} mode and have a Gaussian intensity distribution radially. When a laser beam is focused, the intensity has a Lorenzian distribution longitudinally within the focal region from the center of the focal point. Therefore, the signal intensity of a Doppler burst also varies with the trajectory of the particle entering the sample probe as shown in Fig. 6. It can be seen that the sample probe diameter and length vary with the size of the particle and the trajectory of the particle entering the sample probe.

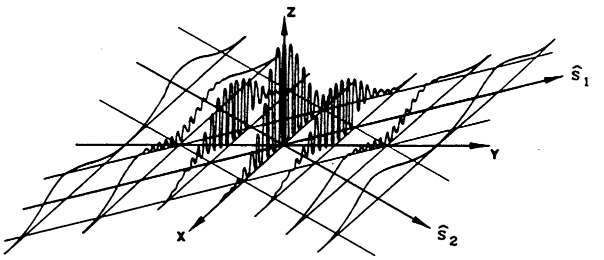

Fig. 6 Doppler signal intensity variation within a sample probe

The actual probe volume is also dependent on the geometry and orientation of the lens system of the detector. Only the part of the probe volume seen by the detection collection lens contributes to the measurements (Bachalo et al., 1988). In practical applications, the sample probe volume is defined as a cylinder whose diameter is the largest sample diameter for the largest particles and whose length is within the view of the detection lens system.

III. DEVELOPMENT IN LASER DOPPLER TECHNOLOGY

Many advances have been made in laser Doppler technology since it was invented in the '60s. Commercial LDV systems are now available using fiber optic and digital signal processing technologies. These advances can be divided into two aspects: optical configuration and signal processing.

1. Optical Configuration

A typical LDV optical system consists of a transmitter and a receiver. A transmitter directs the incident laser beams and focuses them to form a sample probe. A receiver collects the scattering light of the Doppler signals. The dual beam configuration as shown in Fig. 3 has been adopted as the standard for commercial systems.

Forward signal collection

Forward signal collection is frequently used in most commercial systems as scattering light intensity is higher in the forward direction than that in the backward direction, in particular, when transparent seeding particles are used, such as liquid droplets. In the early days, signal intensity was critical to get reliable measurements as signal processing technology was not advanced, forward scattering was often used.

Backward signal collection

In backward signal collection configuration, the optical detector is in the backward direction of the incident light. Backward light collection is used when forward light collection is limited by the physical space surrounding the test section. Figure 7 shows the most frequently used backward scattering method in which signal light and the incident light have the same optical path. This backward light collection method has the advantage of optical simplicity and is capable of eliminating any beam steering or optical light out of alignment due to a refraction index change by the flow or mechanical vibration of the test facility. This method has attracted great attention and has been frequently used recently in most commercial systems.

Frequency shift

Frequency shift of one of the incident laser beams using a rotating grating or a Bragg cell is one important development in laser Doppler technology. A Bragg cell uses a traveling acoustic wave to vary the index of refraction in glass acting as a moving diffraction grating to produce a light wave at a shifted frequency in addition to the original light wave. In standard dual beam configuration, a LDV system is not able to differentiate the traveling direction of a particle, e.g., the Doppler frequencies produced by a particle when it travels from two opposite directions as shown in Fig. 4 with the same speed. Physically, the photodetector will not measure the negative frequencies produced by eq. (8). The purpose of frequency shift is to differentiate the direction of the particle motion or the flow direction. From fringe theory, the still fringe pattern within the same probe will be in motion after one of the laser beams is frequency shifted by some mechanical-optical or electric-optical means. The fringe motion makes the difference in Doppler frequencies of a particle traveling in opposite directions across the probe volume. The frequency shift effect can be explained mathematically,

$$f_1 = f + f_{shift} + f_{d\,1} = f + \boldsymbol{u} \cdot (\boldsymbol{r} - \boldsymbol{s1})/\lambda \tag{13a}$$

$$f_2 = f + f_{d\,2} = f + \boldsymbol{u} \cdot (\boldsymbol{r} - \boldsymbol{s2})/\lambda \tag{13b}$$

eq. (13a) represents the scattered light frequency from the shifted beam and eq. (13b) is the scattered light frequency from the unshifted beam. The resultant Doppler frequency will be:

$$f'_d = f_1 - f_2 = f_{shift} + \boldsymbol{u} \cdot (\boldsymbol{s2} - \boldsymbol{s1})/\lambda \tag{14}$$

The direction of the flow can be easily identified with eq. (14). When the measured Doppler frequency is greater than the shift frequency f_{shift}, imposed on one of the laser beams, the flow velocity is often defined as the positive velocity. When flow reversal happens, the measured Doppler frequency will be less than the shift frequency f_{shift}. as $\boldsymbol{u} \cdot (\boldsymbol{s2} - \boldsymbol{s1})/\lambda$ will be negative. The maximum reversal velocity that can be measured is equal to the velocity corresponding to the shift frequency f_{shift} for a given beam crossing angle ϕ, e.g., $\lambda \cdot f_{shift} / (2 \sin\phi)$.

Fiber optics

With the development of fiber optic technology, the light transmitting efficiencies and the quality of the output laser beam profiles of single mode fibers have been greatly improved. Using fiber optics to configure a LDV optical system makes the LDV transmitter probe very compact and provides many flexibilities in measurements. Optical fiber probes can be moved to many measurement locations and can be easily mounted at any desired measurement angle and point. The polarization of the beam can be easily changed by rotating the fiber. Because of these advantageous, fiber optics have been widely used in commercial LDV systems.

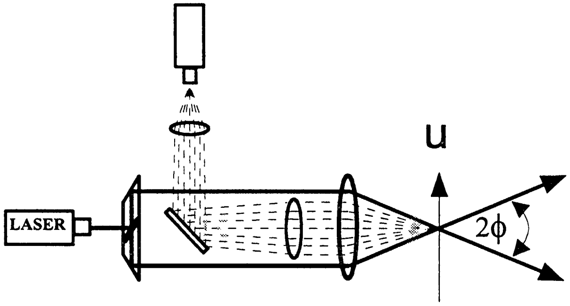

Fig. 7 Backward light scattering collection

Diode laser

Recent advances in avalanche diode laser technology significantly improved the output laser beam power stability and laser beam quality. LDV systems using diode lasers as a power source are compact and rugged, very suitable for sensors to monitor flows. The main disadvantage of diode laser is that the beam quality is relatively lower compared to commonly used TEM_{00} mode lasers, which reduced the Doppler signal S/N. Another problem with the diode laser is that a temperature controller is often required to stabilize the output laser frequency and power.

Multidimensional configuration

Simultaneous multidimensional velocity measurements are often desirable as one-dimensional flows do not exist in practical situations. For two-dimensional measurements, another set of two beams with different colors (or frequencies) are required to separate the two Doppler frequencies corresponding to the two velocity components. The plane that contains the second set of laser beams is often orthogonal to the plane containing the original set of laser beams. The four beams are focused through the same focal lens to a sample volume. The signal collected by the receiver is separated by a frequency separator or a color filter and then collected by two photodetectors. The two Doppler frequencies corresponding to the two velocity components can be easily extracted. A very compact 2-D LDV transmitter can be configured with fiber optics. An extra separate transmitter using the third color, however, is required to construct a 3-D LDV system.

2. Signal Detection and Processing

Signal detection is accomplished through a lens system to collect the scattering light and focus to a photodetector, such as a photodiode or a photomultiplier tube. The photodetector converts the optical signal to an electrical signal. The electrical signal is conditioned by a set of bandpass or filters to remove the pedestal signal and high frequency noise. The conditioned signal is amplified by a set of amplifiers. Technologies used to process the amplified signal to obtain the Doppler frequency have been developed rapidly during the last two decades. Today, a burst detector is often used to check if the amplified incoming signal is a Doppler burst. If the answer is yes, the burst will be sampled by a 1-bit A/D converter, i.e., the digitized signal is a square wave. The Doppler frequency is extracted from the digitized data by a signal processor using various techniques. A typical flow chart of modern LDV signal processing is shown in Fig. 8. Various signal processors are discussed in the following text.

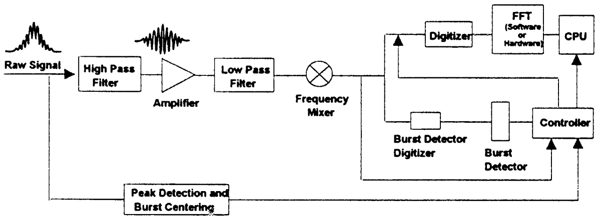

Fig. 8 Flow chart of modern LDV signal processing procedures

Counter processor

An amplified Doppler signal has many zero-cross points in terms of intensity as shown in Fig. 8. It can be interpreted that each zero-cross corresponds to one interference fringe within the probe volume. The counter type of processor was developed in the early '80s. It does not have a burst detector. Signal detection is purely dependent on signal intensity. A preset intensity level is used to trigger any incoming signals. The signal is not digitized after triggering as A/D converters were not capable of digitizing frequencies of Mega Hz range at the time. Rather a digital clock is used to measure the time period τ for the n zero-crosses (cycles) of the Doppler signal, i.e., the time for a particle to pass n fringes within a sample probe. The Doppler frequency can then be calculated,

$$f_d = \frac{n}{\sum_{i=1}^{n} \tau_i} \tag{15}$$

The electronic units on a counter processor counts time digitally and detect the signal intensity zero-crosses at the same time. The fundamental output from a counter is a digital word proportional to the time of τ_i. The number of the cycle or the fringe n_i can be fixed or varied and is also output as another digital word. A Doppler signal is detected or validated if the difference of the Doppler signal frequencies measured from two fixed cycles (8 and 5 cycles are frequently used) are within a preset limit.

The counter-type processor is often called the time-domain processor as it measures the time of the signal directly. Signal frequency is calculated from the time measurements. The main disadvantage is that the signal processing capability is limited to a signal-to-noise ratio (S/N) above 0 dB.

Autocorrelation processor

With the development of digital technology, auto correlation signal processors are developed to improve measurement accuracy. Commercial autocorrelation processors (Jenson, 1991) are produced by TSI, Inc., MN. In this type of processor, the amplified burst signal is split into two parts, the first part goes through a Burst Digitizer to roughly digitize the signal and validate the signal or detect the Doppler signal based on signal-to-noise ratio. The detected burst passes through a Burst Detector to estimate the frequency and length of the burst. The Burst Detector then sends a signal to the Sampler Digitizer or A/D converter (1-bit) to digitize the second part of the signal from the center of the burst based on the estimated burst frequency and length to a square wave. Because the signal intensity decreases exponentially from the center due to the Gaussian nature of the laser intensity distribution, sampling from the center will be advantageous in processing the signal. It will also be beneficial to sample the signal at a proper frequency based on the estimated burst frequency and length so that for a preset number of samples to be acquired and stored for each burst, the sampled data represent the entire signal rather than only a short part of the signal from the center when a very high sampling frequency is used. The digitizing frequency of the Sampler is at least two times but less than 10 times of the Doppler frequency estimated by the Burst Detector. The digitized data are stored on a personal computer.

After the signal is detected and digitized, an electronic Digital Burst Autocorrelator performs a 1-bit autocorrelation for a preset number N samples of stored data using the following equation:

$$R(j) = \frac{1}{R(0)} \sum_{j=1}^{N-1} x(i+64) \cdot x(i+j) \qquad (16)$$

where x is either 0 or 1 as a 1-bit digitizer is used and, therefore, gives $R(0) = N$. N autocorrelation coefficients $R(j)$ will be calculated from eq. (16). From the autocorrelation function, the time period τ_i of each zero-cross of the Doppler burst can be found. Doppler frequency can then be calculated using eq. (15).

In principle, the autocorrelation type of processor is based on time-domain measurements. It improves measurement accuracy due to the added burst detector, but still suffers from the disadvantages of using the time-domain methods to measure signal frequency.

FFT processor

Classical literature (Rife and Boortstyn, 1974; Popoulis, 1984; van Tree, 1968) on signal processing indicates that fast Fourier transform (FFT) provides the optimum performance for frequency estimation. With the development of digital signal processing technology, discrete FFT has been used for Doppler burst detection and frequency calculation (Ibrahim and Bachalo, 1992; Tan and Loh, 1992). FFT signal processors perform discrete fast Fourier transform of the digitized time-domain data to obtain the frequency of Doppler bursts. Therefore, frequency extraction of a Doppler burst is accomplished in the frequency domain, which gives superior performance over any time domain signal processing methods. Signals with S/N below 0 dB can be accurately processed (Ibrahim and Bachalo, 1992; Tan and Loh, 1992).

Commercial FFT Doppler signal processors are produced by several companies. These processors can be categorized by hardware-based and software-based systems, or by 1-bit FFT and multibit FFT systems. The procedures for Doppler burst detection and processing used in most of the FFT processors are very similar. However, the techniques used for burst detection or validation varies with vendors. Most of the systems have the down-mixing feature, which significantly reduces the frequency of the frequency-shifted Doppler signal to ease signal sampling and processing. Some of the systems sample the incoming signal continuously to eliminate the problem of missing bursts. Some systems have the capability of detecting the peak of the signal to sample the signal from the peak intensity outward to increase the S/N of the acquired data. The implementation of discrete FFT to extract the frequency of a burst also varies with vendors. Both hardware-based and software-based methods and single-bit and multibit digitization in data sampling have been adopted by vendors. For example, the DSA and RSA systems manufactured by Aerometrics, Inc. (Sunnyvale, CA, recently merged with TSI, Inc.) use an electronic unit (hardware) to perform single-bit FFT. The LAD/PDA processors produced by QSP Digital, Inc. (Irvine, CA) use a 8-bit digitizer to sample the signal and a computer program to perform FFT of the sampled data (8-bit FFT and software-based method).

Down-Mixer: Most of the commercial LDV systems use Bragg cell to shift the frequency of one of the laser beams by 20 or 40 MHz. The frequency-shift enables the LDV system to measure flow reversal. However, frequency-shift also increases the frequency of a Doppler signal significantly. For example, the frequency of a Doppler signal produced by a particle of velocity of 10 m/s is about 8 MHz when the beam crossing angle of a LDV system 2ϕ is 30°. If a 40 MHz Bragg cell is used, the actual signal of the Doppler signal will be 48 MHz. A 100-MHz digitizer is required in order to resolve this signal, which significantly increases the demand on the frequency resolution of the digitizers, drives up the cost of a LDV, and reduces the capability of measuring very high velocity flows. The down-mixer is an electronic unit that mixes the frequency-shifted signal to produce a signal at a reduced frequency. In the case of 48-MHz Doppler signal, the frequency of the signal can be below 1 MHz after down-mix.

Quadruple Sampling: Some processors have the quadruple sampling feature to increase the signal digitizing capability. In this type of processor, the amplified signal is split into two to generate two complex conjugate signals by two quadrature mixers and are sampled independently. The effective sampling frequency or frequency resolution is doubled.

FFT Burst Detector: As discussed in the section on autocorrelation processor, the Burst Detector detects if the incoming signal is a Doppler signal and roughly estimates the signal length and frequency after the signal is detected. Burst detection is important and necessary because accurately detecting each Doppler burst is the key to eliminating measurement bias, in particular, in low S/N environments and low particle density flows. Furthermore, the rough estimation of the signal length and frequency allows a signal to be sent to the Sampler Digitizer or A/D Converter of the processor to digitize the signal from the center of the burst using an optimum digitizing frequency. Because the signal intensity decreases exponentially from the center due to the Gaussian nature of laser intensity distribution, sampling from the center will be advantageous in improving the S/N of the acquired data as discussed previously. It will also be beneficial to sample the signal at an optimum frequency based on the estimated burst frequency and length so that for a preset number of samples to be acquired and stored for each burst, the sampled data represent the entire signal rather than only a small part of the signal from the center when the sampling frequency is too high or a mis-sampled signal when the sampling frequency is lower than the Nyquist frequency of the signal.

The FFT Burst Detector performs FFT (usually the signal is digitized by a 1-bit A/D converter) of the incoming signal while sampling. It uses the S/N of the transformed frequency spectrum to determine if a coherent Doppler signal is present to detect and validate the signal. The FFT burst detector gives a much better performance in discriminating noise from signal than that of intensity-based Burst detectors.

Single-Bit and Multi-bit FFT: In single-bit FFT processors, the incoming analog signal is digitized as either 0 or 1. The digitized signal is a square wave. The digitizer is 1-bit and its cost is low. The time required to perform a single-bit FFT will be much shorter than the time required to perform a 8-bit FFT. However, a 8-bit FFT is certainly more accurate than 1-bit FFT in calculating the signal of signals, especially when S/N is much below 0 dB.

Hardware- and Software-Based FFT Processors: There is no significant difference in performance between hardware- and software-based FFT processors in theory. The software-based processor, offers some flexibility to upgrade in the future. All the commercial hardware FFT processors use a 1-bit FFT due to hardware limitations and cost. However, it will be very easy to implement a multibit FFT on software-based systems as long as the data are digitized in multibits. With recent advances in personal computer technology, real-time Doppler burst processing and data display are becoming reality and software-based multibit FFT processors do offer some advantages, such as high accuracy and flexibility.

3. Particle Seeding

Particle seeding is a prerequisite in flow measurements using a LDV. Some flows, such as water and solid fuel combustion flows, have natural particles, seeding is not necessary. However, seeding is required for most gas flow measurements. The development in seeding technology has been very limited. Seeding for high pressure flows is still not trivial. Fortunately, most of the flows in pulp and paper mills are low pressure flows and have natural particles. Solid particles of TiO_2, Al_2O_3, SiC, and latex spheres have been used in fluidized bed to seed flows (Moss, 1980 and Ikioka, 1983). Liquid droplets of oil and water generated by blast atomizers is another way for LDV seeding. A solution of salt and sugar can also be used for seeding. Atomization of particle suspension was also adopted for LDV seeding. There are two criteria in selecting seeding technologies:

- diagnostic suitability, the seeding particles should have a uniform particle size distribution to follow the flow uniformly and the particles should be seed uniformly at an acceptable data rate and produce sufficient signal strength for processing;
- environmental suitability, the particles should be chemically inert, survive in any flow environment, be safe, and be nonfouling.

IV. ERROR SOURCES IN LASER DOPPLER TECHNIQUE

There are many sources of error associated with flow measurements using a LDV just like those associated with using any other advanced instrumentation. In general, these error sources can be divided into two categories: Instrumentation error and flow- and seeding-induced particle statistical bias. The instrumentation errors are the errors in the measurement of a Doppler signal frequency with a low S/N. Improving the S/N and data processing technology is the key to reducing these types of errors. While particle statistical errors are measurement bias associated with flow turbulence, velocity gradient of shear flows, seeding uniformity, and particle entrainment, much research has been conducted on velocity bias in LDV measurements. This section is not meant to be a detailed discussion of the subject, but rather serves as an introduction. Therefore, this section is presented in the form of suggestions and recommendations to reduce or eliminate some of the measurement errors. Readers should use the references provided for in-depth understanding.

1. Optical Alignment

Proper optical alignment can help to obtain good S/N and improve the measurement accuracy of Doppler signals.

Collimating of the incident laser beams

Collimating the two incident laser beams before entering the focus lens to form a probe volume is important. Any misalignment can cause the actual beam crossing angle to be different from that used in the instrument software for velocity calculation. Optical misalignment also distorted the fringe within the sample probe or distorted the perfect light interference between the two incident laser beams.

Adjusting the laser beam intensity

To obtain perfect interference between the light scattered from the two incident laser beams, it is necessary for the two incident laser beams to have the same intensity. A perfect interference will give a Doppler signal with a high visibility. The visibility of the signal is defined as the ratio of the Doppler amplitude and pedestal amplitude of a coherent signal (Kliafas et al., 1987) as shown in Fig. 9. Any imbalance in laser intensity between the two incident beams will contribute to the background level of the Doppler signal and reduce the signal visibility or signal-to-noise ratio (S/N).

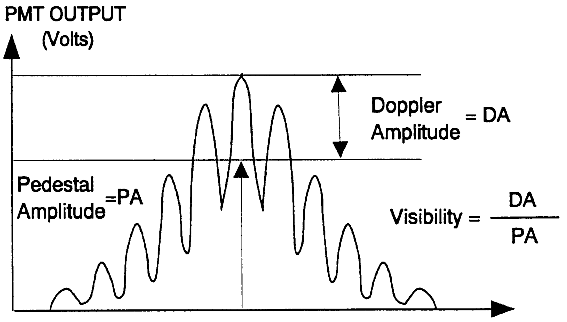

Fig. 9 Schematic of Doppler signal visibility

Fiber optics are commonly used in most of the commercial LDV systems. It should be pointed out that any small adjustment on the Fiber Driver can cause significant variation in laser intensity. Proper adjustment of laser intensity using a power meter before and during each experiment may be necessary to maximize S/N.

Checking the laser beam polarization

It is important to maintain that the two incident laser beams are linearly polarized in the same direction to obtain optimum interference of light scattered from the two incident beams. Any discrepancy in polarization direction between the two incident beams will reduce the signal visibility and S/N.

2. Particle Seeding and Statistical Errors

Laser Doppler velocimetry measures the velocity of a particle velocity in a flow. One of the fundamental assumptions of laser Doppler velocimetry for flow measurement is that the seeding particles are fully entrained by the flow and, therefore, the particle velocity is equal to the fluid velocity. It is certain that particle seeding and particle statistics can have a significant impact on the measurements. Particle seeding and statistical errors in LDV measurements are the measured velocity bias mainly due to seeding particle size distribution and particle entrainment. Much research work have been reported on velocity bias measured by LDV systems (McLaughlin and Tiederman, 1973; Stevenson and Thompson, 1982; Edwards, 1981; Edwards and Jensen, 1983; and Nejad and Davis, 1986). In this paper, the discussion will focus on the explanation of various possible velocity biases in LDV measurements and provide some recommendations.

Particle seeding

It is well-known that particle entrainment in the flow depends on the particle size (or inertia), flow turbulence (eddy size), mean flow shear rate (mean flow velocity gradient), and boundary effects. For a given flow, large particles tend to be fully entrained due to the large inertia they possess. There are two phenomena often observed that could affect LDV measurements significantly. One is particle lagging behind the flow when abrupt flow acceleration occurs, and the other is the ballistic motion of large particles. It is very difficult to predict the exact size of a particle that can be fully entrained for a set of given flow conditions. However, the general rule of thumb is that theeeding particle size should be around 1 μm. It should be mentioned that in selecting seeding particles a narrow particle size distribution is often preferred.

Particle statistical errors

In an ideal situation, the seeding particles are uniformly mixed with the fluid. When the flow velocity varies as in turbulent flows, the number of particles passing through a LDV sample volume also varies. A higher velocity means a larger than average number of particles pass through the probe volume. When the flow veloicity is lower, a smaller than average number of particles pass through the probe volume. In most LDV systems, mean velocity and other statistical flow parameters are directly calculated from the velocities of individual particles (individual realization). Therefore, the probability of measuring a velocity larger than the mean is higher than that of measuring a velocity smaller than the mean. Consequently, the velocity histogram for each individual particle is biased toward the faster end of the velocity range. This velocity bias will cause a higher mean velocity and a lower root mean square velocity. This velocity bias due to particle arrival statistics was first discovered by McLaughlin and Tiederman (1973) in their analytical studies. These two authors also proposed a one-D streamwise correction scheme to reduce the velocity bias.

Much research has been conducted in this area. Durao and Whitelaw (1975) proposed random sampling of the individual particle velocity for calculating the mean flow velocity and other statistical parameters based on their computer simulation. Johnson et al. (1976) claimed that velocity bias will not occur if the particle arrival rate is much less than the turbulence frequency of the flow. However, in this case, the turbulent frequency will not be resolved with LDV according to Nyquist frequency criteria. Hoesel and Rodi (1977) proposed that particle separation time be used for bias correction under nonuniform seeding conditions and that particle residence time or transit time through the sample probe be used for correction under uniform seeding conditions. Later, Stevenson and Thompson (1982) and Johnson et al. (1982) experimentally verified the bias and found that the bias depends on the particle concentration and vanishes at high particle number densities. Edwards (1981) analyzed the measurement statistics and found that the product of the particle number density and the sample interval is the controlling parameter for the statistical description of the measurements. Bias in a 2-D LDV system has also been reported by Nejad and Davis (1986). These authors studied the bias in turbulence shear stress due to coincidence. Although understanding the particle arrival statistical bias is limited due to the lack of a precise measurement of the velocity in the flow, many factors have been identified that contribute to the flow velocity bias in LDV measurements according to Edwards (1987):

- Velocity gradient induced particle arrival statistics.
- Flow turbulence induced particle arrival statistics.
- Seeding nonuniformity caused particle arrival statistics.
- Variation in particle entrainment due to polydispersed seeding particles.
- Signal-to-noise ratio of the signal and signal processor capability.

At the current level of understanding, velocity bias correction is not recommended for pulp and paper applications by this author.

V. SELECTION OF A LDV SYSTEM

In selecting a LDV system, the following factors should be considered:

1. Dimension

If simultaneous multicomponent velocity measurements are required, a 2-D LDV system will be ideal. A 2-D system that has only one transmitter is relatively simple and easy to operate compared to a 3-D system. The cost is also relatively lower than that for a 3-D system. If multicomponent velocity measurements are not necessary, a 1-D system will be sufficient. With some mathematical manipulation, turbulent shear stress can be obtained from two separate one-D measurements (Zhu, 1988).

2. Dynamic Range and Band Width

Velocity dynamic range is another consideration. All the commercial LDV systems specify frequency resolution, rather than the velocity range because the velocity is related to the fringe spacing, which depends on the beam crossing angle. Some vendors specify the sampling frequency of the digitizer. Some vendors specify the resolution of the Doppler frequency. The operating frequency band width is also important for high fluctuation flows. It should be mentioned that:

- The maximum Doppler frequency that can be resolved is equal to half of the digitizing frequency according to Nyquist frequency criteria.
- If a Bragg-cell is used for flow reversal measurements, the required digitizing frequency will be two times that of the Doppler frequency plus the shift frequency of the Bragg-cell. Therefore, a fast digitizer is required. For example, the maximum velocity that can be measured is 25 m/s with a 30-MHz digitizer and a Bragg-cell frequency of 20 MHz if the fringe spacing is 5 μm.

3. Fiber Optic Configuration

Fiber optics bring many conveniences to measurements. It is often preferred to use fiber optics when limited access is provided for the test section. However, fiber optics reduces the quality and intensity of laser beams. The reduced signal quality due to the use of fiber optics often can be compensated by using advanced signal processors, high power lasers, and high sensitivity detectors.

4. Signal Processor

Chosing a good signal processor is the key to obtaining accurate measurements. FFT-based frequency domain signal processors have proved to be more accurate than any time-domain processors. A side-by-side comparison of particle measurements by a time-domain processor and a

FFT processor has been made by Zhu et al. (1995). Significant signal processing improvement was demonstrated by the FFT-based processor. The FFT type of processor can easily process signals with S/N below 0 dB (Ibrahim and Bachalo, 1992). Multibit software-based FFT processors can accurately process signals with S/N ratios as low as -6 dB (Tan, 1996). If high accuracy is required, a software-based multibit processor may be required. Software-based processors also provide flexibility for upgrading and compact hardware.

5. Bragg-Cell

When reversal flow is encountered in measurements, frequency shift of one input laser beam is required. A Bragg-cell will be a good choice for frequency shift as it is very compact.

6. Laser

Laser power and beam quality are the keys in selecting a laser for LDV systems. For a one-D system, a 5 mW HeNe laser will be sufficient to construct a nonfiber optics-based LDV system. An Argon-Ion laser is often used for 2-D LDV systems. High power often gives good signal-to-noise ratio. A fiber optics LDV system often requires a high power laser as the single mode fibers have relatively low transmission efficiencies. A high power laser will also be beneficial to improve the signal-to-noise ratio for applications in hostile flow environments. Because of the relatively poor laser beam quality of diode lasers, it is usually selected only for monitoring and some special applications.

VI. APPLICATIONS IN PULP AND PAPER RESEARCH

There are several advantages to using LDV for pulp and paper research:

- The measurement is nonintrusive and instantaneous.
- The measurement can be conducted in a remote site with fiber optics.
- Seeding is not necessary as most flows encountered in pulp and paper have many natural particles.

However, limited studies have been conducted using LDV for pulp and paper research applications. There are many problems associated with using LDV for pulp and paper research, in particular, for measurements in pulp suspension flows. Ek et al. (1978) reported velocity measurements in a fiber/air suspension and later extended the measurements to a fiber/water suspension. Bercel and Shuffler (1981) obtained a quantitative relationship between fiber floc size and turbulent intensity in model headboxes. Kerekes and Garner (1982) found that the LDV signals may result from both the fibers and tracing particles, which were observed later by Hand (1982), but not by Chuang (1982). The maximum fiber consistency in all these studies was 0.5%. Steen (1989) used refractive index matching to conduct LDV measurements in a Pyrex glass fiber suspension in a mixture of Benzyl and Ethyl alcohol. The measurements of fiber velocity and fluid velocity were achieved using the signal visibility technique (Borner et al., 1986) to differentiate the two phases in a fiber suspension flow with a consistency of 1.2%.

Several issues remain to be resolved in order to apply LDV for flow measurements in wood pulp suspension flows:

- The ability to transmit light decreases significantly when the consistency of the pulp suspension increases, which creates a very difficult problem for LDV measurements. The effect of wood pulp consistency on the Doppler signal quality needs to be quantified. The consistency limit needs to be established for LDV applications.
- The difference in the refractive index of fiber and water is very large, which can affect the measurements significantly. The effect of using refractive index matching fluid for fiber suspension flow velocity measurements needs to be quantified as the shape of fibers can be easily changed in fluids. Backward scattering method may be one solution to slove the problem.
- The effectiveness of the visibility technique to differentiate signals resulted from fibers from tracing particles needs to be studied. In particular, this technique may be in question under low signal-to-noise conditions. Further

studies to interpret the measured data are required to improve understanding of fluid mechanics behavior of pulp suspension flows.

VII. SUMMARY

- This review paper discussed the basic principles of laser Doppler velocimetry (LDV), recent developments in laser Doppler technology, and issues associated with applications for pulp and paper research.
- The author made a clear comparison of various Doppler signal processing techniques so that readers can understand their advantages and disadvantages.
- The paper described various techniques used in commercial LDV systems and their functions in data handling, acquisition, and signal conditioning.
- The paper provided guidelines for selecting a commercial LDV system.
- The paper also briefly explained the sources of error and bias in flow velocity measurement using laser Doppler velocimetry.
- Lastly, the paper outlined the advantages and difficulties in using LDV for pulp and paper flow research.

It is anticipated that this paper will help readers gain a fundamental and introductory understanding of laser Doppler velocimetry in selecting a particular commercial laser Doppler system for a particular application.

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