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Optimization of suitable wavelength for Laser Doppler Velocimetry technique based on fringe model

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***Abstract*— A lot of diseases cause impaired supply of blood to the organs. Therefore, measurement of the blood flow can provide essential information for diagnosis of various diseases i.e. peripheral artery diseases, blood clots, varicose veins and diabetes. Since the blood flow in capillaries, retina and venules is very slow in range mm/sec, a fast, reliable and non-invasive blood flow measurement technique called Laser Doppler Velocimetry (LDV) is used to give early detection and diagnosis for these diseases.**

In this paper, different wavelengths were used on the dual beam mode and their results were comprised to optimize the suitable wavelength that gives the more accurate, sensitive and higher resolution LDV setup. He-Ne laser operating at peak wavelength 635 nm shows the more sensitive one, but the Argon laser (blue) operating at peak wavelength 488nm has the best resolution result.

***Keywords*— Laser Doppler; Fringe model; blood flow; laser applications in medicine**

I. INTRODUCTION

Measurement of the fluid flow velocities without disturbing the natural flow pattern is important. LDV is interesting for biophysical and medical applications. Various diseases cause an impaired supply of blood to the organs. The measurement of the blood flow can therefore provide information for the diagnosis of diseases like Atherosclerosis[1] which can lead to a host of problems, some of which are potentially life threatening. A lot of devices can be used for evaluating the blood flow i.e. computed tomography(CT)[2],optical tomography(OCT)[3], laser speckle [4], particle image velocimetry[5], ultrasonic Doppler[6] and Laser Doppler Velocimetry[7, 8]. Blood flow velocimeters must be able to image with high resolution, specifically measure the depth, and determine the velocity of absolute blood flow. However, none of the current measuring devices satisfies all of these conditions. LDV is an accurate technique for detecting and calculating the velocity of small seeding particles suspended in a fluid .LDV is fast, accurate, high spatial resolution, non-intrusive, non-contact method and no calibration is required, but it has some drawbacks. Tracer particles and Optical access are required. The seeding particles should match with the optical properties of the fluid flow[9]. They must be small enough to follow the flow being measured, but large enough to generate a strong scattering signal. LDV technique has many medical applications i.e. Laser Doppler measurements of blood flow in capillary tubes and retinal arteries[10], Microvascular Blood Flow, Volume, and Velocity Measured by Laser Doppler Techniques[11] and study of the effect of pure oxygen breathing on retinal blood flow [12].

II. LASER DOPPLER VELOCIMETRY

A. Measurement principle

Yet and Cummins (1964) made the invention of the laser Doppler technique for flow velocity measurement, the velocity of the flow seeded with suitable tracer particles can be measured. The Laser Doppler technique is based on the heterodyne detection. Laser Doppler Velocimetery (LDV)[8] is a technique used to measure the instantaneous velocity of a flow field. It can measure all the three velocity components. The laser Doppler velocimeter sends a monochromatic laser beam toward the target and collects the reflected radiation. According to the Doppler Effect, the change in frequency of the reflected radiation is a function of the targeted object's relative velocity. Thus, the velocity of the object can be obtained by measuring the change in frequency of the reflected laser light, which is done by forming an interference fringe pattern (superimpose the original and reflected signals). As previously mentioned, according to the Doppler effect, the basic of the laser Doppler velocimetry is to illuminate a flow with a laser light, then collect the scattered signal or portion of the scattered signal and mix it with the reference beam (original) to measure the resulting beat frequency which is directly proportional with the fluid velocity. Because of the difficulty of bringing the original beam with the scattered signal in the reference beam method, a better method called dual beam method may be executed.

B. Experimental Setup

"Fig. 1," shows the block diagram of LDV which is divided to a hardware part and a software one.

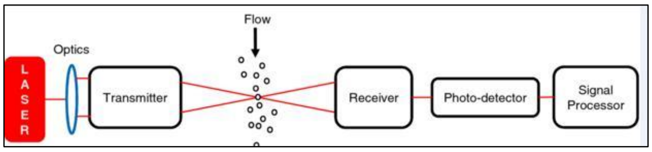

Fig. 1. *LDV system description.*

A tunable laser source is used with different wavelengths (Argon457nm, Argon488nm, and Argon514nm), and also, a 632.8nm He-Ne laser is used. The laser beam is then divided via Michelson interferometer which is 6.5cm from the laser source to obtain two equaled intensity parallel beams. These beams are then sent through the transmitting lens which is 7cm from Michelson interferometer and intersect at its focus to form the measuring volume [M.V]. The test fluid, 1um silver powder suspended in water, flows through 10cm transparent glass tube placed around the measuring volume. The flow is driven by a 7ml/min pump. Pressing screw is used to easily change the fluid velocities as shown in figure 2.when the seeding particles cross the measuring volume, they scatter light. A second lens is placed behind the objective to focus the scattered light on the photodiode. Since the laser beams intersect with an angel of ϕ = 7.125°, the lens should be placed at a suitable distance to prevent the laser beams from entering the receiving optics. In order to increase the spatial resolution, a filter with a pinhole should be placed before the photodiode. Unluckily; signal intensity is too weak to use the pinhole. To get a better signal to noise ratio, a photodiode, in a photoconductive mode, is fed into a trans-impedance amplifier followed by a band pass filter and then amplified. A digital oscilloscope is used for instant monitoring of the signal as shown in "fig. 3," A/D-card, NATIONAL INSTRUMENT NI USB-4431 with 24-Bit 102.4 KS/s, is used to digitize the signal to be affordable for digital processing using the LABVIEW software. To transfer the signal from time domain to frequency domain, FFT algorithm will be useful for looking at the spectrogram of the signal.

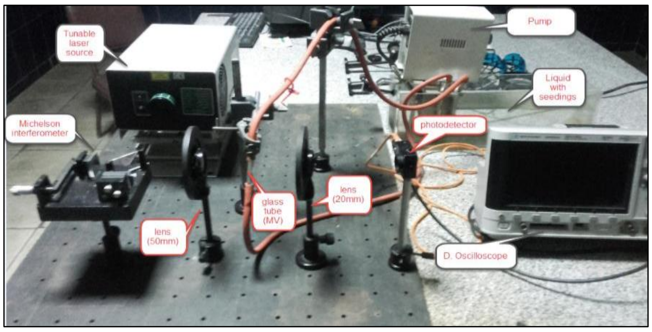

Fig. 2. *LDV Setup.*

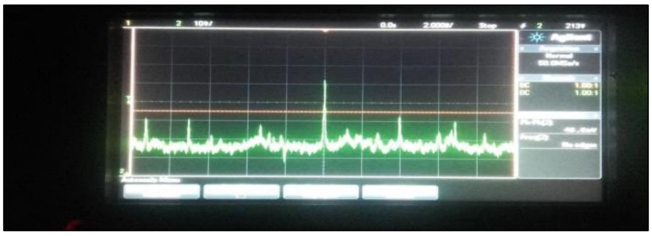

Fig. 3. *Signal in time domain.*

C. Dual beam explanation

When two coherent laser beams of equal intensity pass through a concave lens, they intersect to form a measurement volume. At the measurement volume the bold lines show where crests of waves of one beam fall on the crests of waves of the other beam. Another word, the two waves are in phase and result in a maximum light intensity (Bright). But, if the two light beams are out of phase (anti-phase), the troughs of waves fall on the crests of the other waves; they will cancel each other resulting in a minimum light intensity (Dark). When the particle traverses this fringe pattern, the scattered light fluctuates in intensity with a frequency equal to the velocity of the particle divided by the fringe spacing.

As known we can calculate the velocity (v) as follow:

$$v=s/t \qquad (1)$$

Where s is the fringe space distance and t is the time taken to pass through the fringe space

Also,

$$\Delta f=1/t \qquad (2)$$

For simplicity from the area of the overlap trigonometry, the fringe spacing s can be expressed in terms of the wavelength λ of the light and the angle ϕ between the angular bisector of the beams and each light beam from (3):

$$s = \frac{\lambda}{2\sin\phi} \qquad (3)$$

Solving for v,

$$v= \left(\frac{\lambda}{2\sin\phi}\right)*\Delta f \qquad (4)$$

Rearrange (4) for a particle moving at an angle θ with respect to the normal to the bisector of the two incident laser beams to be as follow:

$$v=\frac{\lambda}{2\sin\phi\cos\theta}*\Delta f \qquad (5)$$

D. Measuring volume

The measuring volume happens in the region of intersection of the two beams. If the two beams intersect in their beam waists, the wave fronts are approximately plane, the interference will produce parallel planes of brightness and darkness. The measuring volume is an ellipsoid due to the Gaussian intensity distribution of the beams as shown in "fig. 4,"

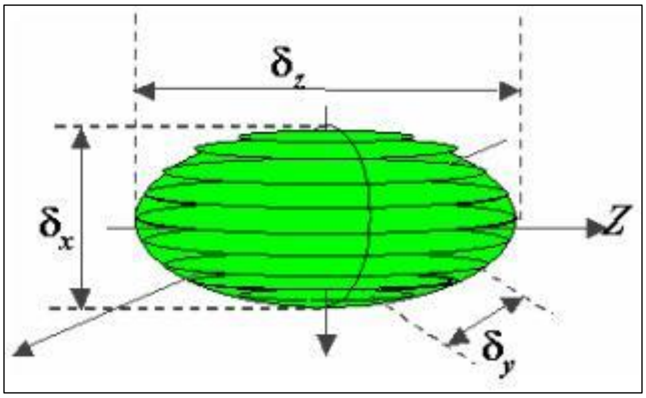

Fig. 4. *LDV measurement volume.*

Length: $\delta_z = \dfrac{4F\lambda}{\pi D' \sin(\phi)}$ (6)

Width: $\delta_y = \dfrac{4F\lambda}{\pi D'}$ (7)

Height: $\delta_x = \dfrac{4F\lambda}{\pi D' \cos(\phi)}$ (8)

Where F is the focal length of the lens (100mm) and D' is the initial beam thickness.

In the measurement volume, the fringe separation and number of fringes are given by:

Fringe separation: $\delta_f = \dfrac{\lambda}{2\sin\phi}$ (9)

Number of fringes: $N_f = \dfrac{8F\tan\phi}{\pi D'}$ (10)

To obtain a good performance from the LDV, a sufficiently high number of fringes should be in the measurement volume. When seeding particles move through a sufficient number of fringe, there will be enough periods to record signal from which the Doppler frequency can be estimated. Using FFT technology can estimate particle velocity from as little as one period. Also, high performance can be obtained by proper selection of laser source, seeding particle size and optical system parameters.

III. RESULTS

A. Fringes measurements

The next figure shows the images of the fringe pattern of different wavelengths that had been obtained experimentally in the previous setup.

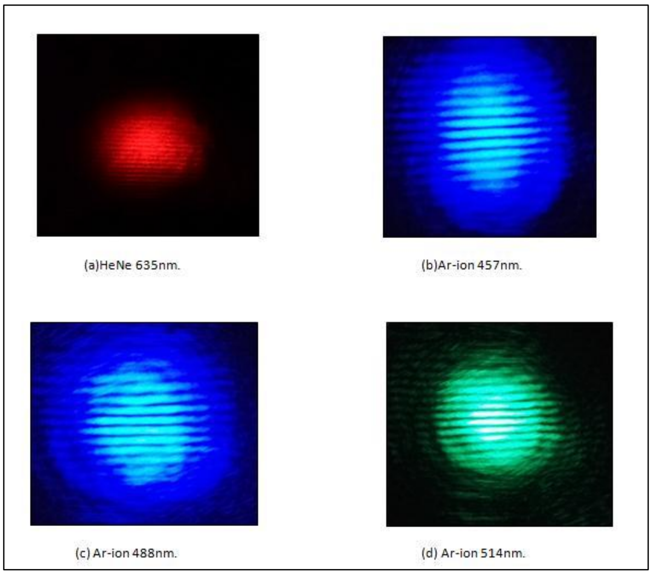

Fig.5.*Fringes pattern images*.

From section D,the equations will help us to calculate the dimensions of the ellipsoid measurement volume, fringes numbers and the fringes spacing for the different wavelengths laser sources (Argon457nm, Argon488nm, Argon514nm and He-Ne 635nm).The next table will offer the calculated results for these laser sources with half intersection angle ϕ=7.125° as follow:

Table1.Results of dimensions of M.V, fringes number and fringes spacing for used wavelength

Wavelength (nm)	**Width (mm)**	**Height (mm)**	**Length (mm)**	**Experimental fringes pacing(mm)**	**Fringes number**
635	0.1197	0.1206	0.96505	2.9	47
457	0.0781	0.0787	0.6296	2.375	42
488	0.07965	0.0802	0.642	2.2	40
514	0.0948	0.09553	0.7643	2.16	46

From the previous table, for the same half intersection angle ϕ=7.125°, changing the laser source wavelength will change the fringe spacing, dimension of M.V and the fringes number. This will affect the sensitivity and the resolution of the measurement technique. The more number of fringes crossed by the suitable seeding particles will result in sufficient periods in the recorded scattered signals to estimate the Doppler frequencies and their relative velocities.

B. Velocities calculations

When the seeding particles cross the fringe pattern, they scattered signal that can be detected by the photodetector. The photodetector converts the light to electric signal that contains frequency information relating to the velocity to be measured as shown in (5).This signal is fed to A/D-card to digitize the signal and make it available for further digital processing using LABVIEW or MATLAB software. FFT algorithm will be useful to deal with the frequency information involved in the signal. It also easily transfers the noisy signal into the frequency domain. The following figure will show different flow velocities, by the pressing screw, for the He-Ne laser source using MATLAB software.

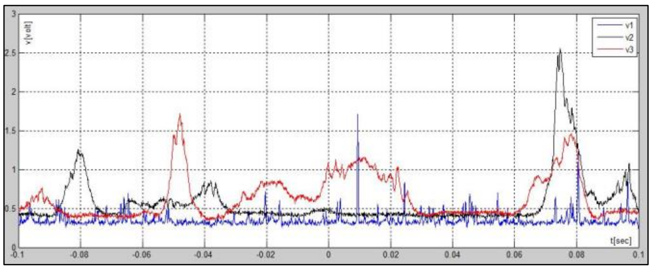

Fig.6. *Plot of different flow velocities for He-Ne laser source.*

Studying the variation of frequency with the different flow velocities was important. These signals were fed to A/D card to be available for digital processing. Scattered signals were filtered using a moving average filter and the DC voltage was removed. The major region of the original signal was extracted as it had the maximum rate of oscillations. Then, FFT algorithm was applied and power spectrum density (PSD) was got for these modified signals. The following four windows will show the original signal in the upper-left window, the modified signal after removing DC and enhancement the signal by extracting the region which contains the frequency information in the upper-right window, Doppler frequency of the modified signal by FFT algorithm in the down- left window and power spectrum density of the modified signal in the down-right window. The dominant frequency was the Doppler frequency to estimate the velocities of the flow. "Fig. 7," will show the digital processing of the scattered signal for He-Ne laser source at a certain flow velocity.

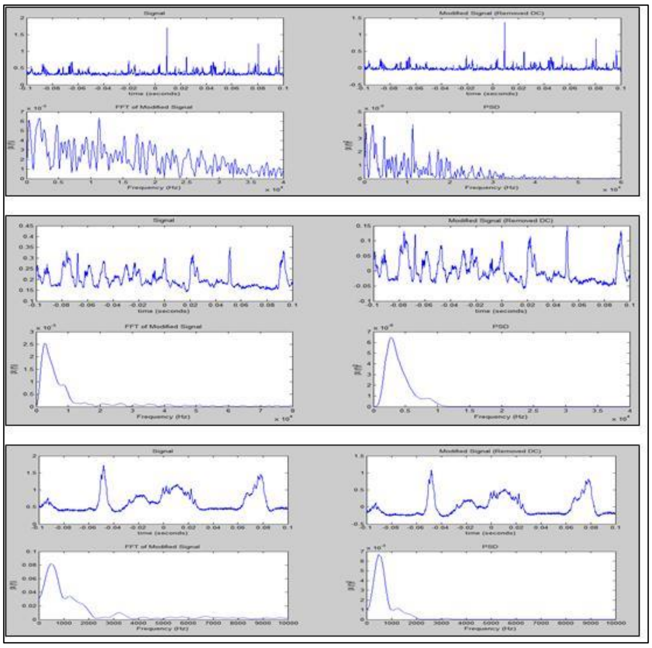

Fig.7. *Doppler frequency signal for He-Ne laser source.*

Using equation (4) and results from table (1) will help in calculations the velocities of the flow as follow:

Table 2. Velocities calculations for He-Ne laser source

Wavelength (nm)	Doppler frequency(kHz)	Flow velocity(mm/s)
	0.4909	1.311
635	4.414	10.89
	10.22	25.56

The variation of the measured Doppler frequency of the scattered signal is linearly proportional to the variation of the flow velocity as shown in "Fig. 8,"

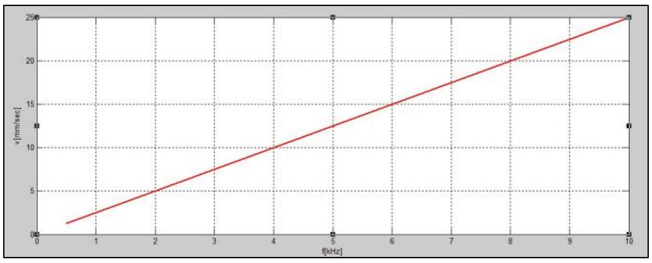

Fig.8. *The measured velocities versus the Doppler frequency for He-Ne laser.*

Similar to the He-Ne laser source with the same setup, the same velocities and only changing the laser source type, the next results were obtained for different wavelengths.

Wavelength (nm)	Doppler frequency(kHz)	Flow velocity(mm/s)
	0.6	1.08
514	1.27	2.2
	10	20.7

First, for the Argon laser source with 457nm wavelength, the following results were obtained:

Table 3.*Velocities calculations for Argon (457nm) laser source*

Wavelength (nm)	Doppler frequency(kHz)	Flow velocity(mm/s)
457	0.878	1.727
	0.9766	1.92
	1.36	2.688
	10	19.76

“Fig.9,” will show the relation between Doppler frequency and the flow velocity for Argon (457nm).

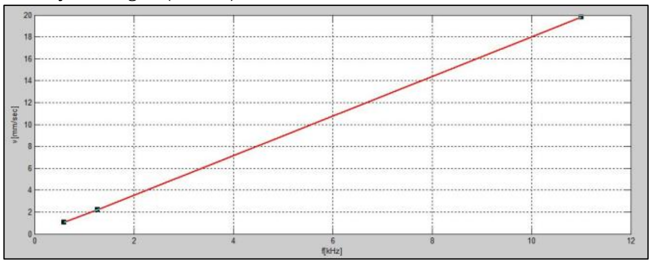

Fig.9. *The measured velocities versus the Doppler frequency for Argon (457nm) laser.*

Second, for the Argon laser source with 488nm wavelength, the following results were obtained:

Table4.*Velocities calculations for Argon (488nm) laser source*

Wavelength (nm)	Doppler frequency(kHz)	Flow velocity(mm/s)
488	0.683	1.41381
	0.8789	1.18193
	0.98	2.0286
	10	20.7

“Fig.10,” will show the relation between Doppler frequency and the flow velocity for Argon (488nm).

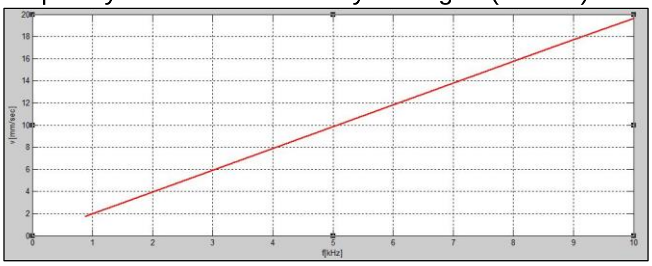

Fig.10. *The measured velocities versus the Doppler frequency for Argon (488nm) laser.*

Third, for the Argon laser source with 514nm wavelength, the following results were obtained:

Table 5.Velocities calculations for Argon (514nm) laser source

“Fig.11,” will show the relation between Doppler frequency and the flow velocity for Argon (514nm).

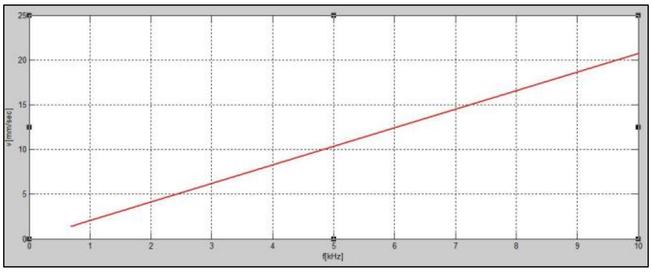

Fig.11. *The measured velocities versus the Doppler frequency for Argon (514nm) laser.*

“Fig. 12,”shows the Doppler frequency of the scattered light versus the flow velocities for different wavelengths. The slope of each curve will show the sensitivity of each setup as shown in the next figure. He-Ne laser source is the most sensitive for the previous setup.

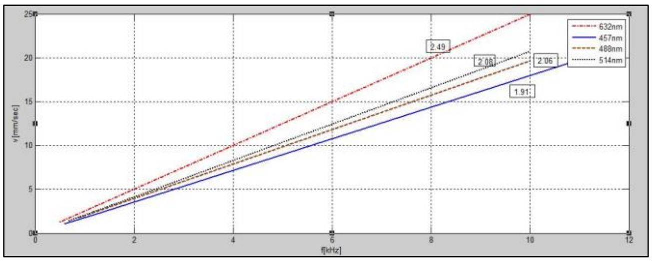

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Fig.12. *The measured velocities versus the Doppler frequency for different wavelengths.*

IV. CONCLUSION

LDV is an accurate, fast, high spatial resolution and non -intrusive technique to measure the fluid flow velocities without disturbing the natural flow pattern in several medical applications. Choosing the suitable wavelength for the fringe model technique is important. In order to increase the sensitivity of the LDV technique, He-Ne laser source is preferred as shown in the previous figure. But, the Argon (488nm) laser source is preferred to increase the resolution of LDV technique.

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