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# Optimization of the Performances of a Self-mixing Velocimeter by using a Double Laser Diode Configuration

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**Abstract**—In this paper, we present a self-mixing double-head laser diode velocimeter. Several analyzes are performed to determine the optimal architecture of the double laser diode in terms of accuracy. We demonstrate that the double-head laser diode is insensitive to angle variation contrary to the single laser diode. The accuracy of the double-head laser diode sensor is verified by simulations and experiments.

**Keywords:** *Self-mixing, velocimetry, optical feedback interferometry, laser sensors.*

## I. INTRODUCTION

Velocity contactless measurements of moving targets like mechanical structures are often used in various industrial applications for nondestructive testing and quality control, like for example, when manufacturers need speed synchronization to stabilize the manufacturing of their products [1]. Moreover, velocity measurement processes may become crucial if it is one of the parameters governing the safety and performance of a system like in transportation.

Ultrasonic or microwave devices have a relatively poor spatial definition and optical sensors able to achieve this purpose are often too expensive. For example, Laser Doppler Velocimetry (LDV) is a highly accurate technique for speed measurements [2] but the use of large number of optical components (lenses, mirrors, beamsplitters, and even acousto-optic modulators) implicates an elevated price. Optical feedback interferometry [3] is an attractive emerging solution enabling us to design low-cost laser sensors presenting a good accuracy.

The purpose of this paper is to increase the robustness of a self-mixing velocimeter by using a double laser diode (LD). This approach has proved to be useful when the angle between the target and the laser can not be controlled like for an on-board velocimeter for car safety [4]. However, the configuration of this double-head sensor was not analyzed properly for optimizing its performances. After a short overview of the self-mixing velocimetry in section II, a sensitivity and uncertainty analysis performed on the self-mixing single LD velocimeter shows its limits and inconsistency in section III. We propose in section IV a self-mixing double LD velocimeter and we prove its performance in terms of accuracy and insensitivity to angle variations.

Experimental results, are given in Section V, and the last part of this paper is dedicated to concluding remarks.

## II. SELF-MIXING VELOCIMETRY

In optical feedback interferometry (OFI), commonly named self-mixing, interference occurs in the laser active cavity between the inner beam and the beam backscattered by an external target in front of the LD inducing optical output power variations due notably to the Doppler effect [3]-[5]. The relation between the target velocity  $V_T$  and the Doppler frequency (DF) shift  $f_D$  (fundamental frequency of the optical power signal) is given by (1) considering that the normal ( $N$ ) to velocity vector and the optical propagation axis realize an angle  $\gamma$  (Fig. 1).

$$V_T = \frac{\lambda f_D}{2 \sin(\gamma)} \quad (1)$$

Knowing the values of  $\lambda$ , the emitted laser wavelength, and  $\gamma$ , it is possible to determine the velocity of a target along the laser beam axis by measuring the Doppler frequency of the optical power.

## III. SINGLE LASER DIODE VELOCITY SENSOR

The self-mixing single-laser diode prototype is described in Fig. 1. It is composed of a LD, a photodiode (PD) generating an electrical signal  $v(k)$  that will be processed to estimate DF and calculate the velocity of the moving target using (1).

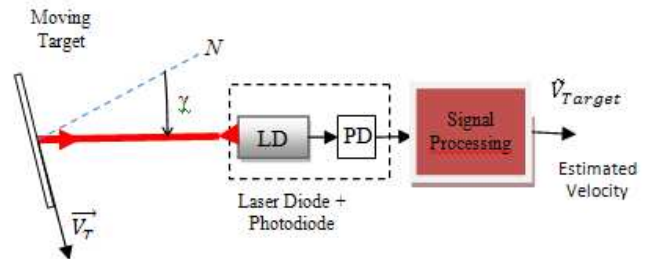


Figure 1. Self-mixing single-laser diode prototype.

Many signal processing methods have been proposed in order to estimate DF [6]-[7]. To reduce the amount of numerical calculations, two simple algorithms which give acceptable estimations accuracy were selected. The first one is based on a classical spectral analysis of  $v(k)$  and requires a Fast Fourier Transform (FFT) calculation.  $f_D$  estimation is given by the frequency corresponding to the peak value of the FFT complex modulus. However, it has been shown in [8] that estimations are not biased but have an important standard deviation when speckle effect is important. The second one is based on an autoregressive (AR) method [7]. It consists in representing the data record with a linear prediction filter. A second order prediction filter was chosen to reduce the number and complexity of numerical calculations and to ensure an estimation bias as small as possible [6]. For a second order AR model [AR(2)], the time-series governing the prediction filter is given by

$$v(k) = -a_1 v(k-1) - a_2 v(k-2) + e(k) \quad (2)$$

where  $e(k)$  represents the prediction error and  $a_1$  and  $a_2$  are the two autoregressive coefficients which have to be determined. The resonance frequency  $f_r$  of the prediction filter, corresponding to DF to be estimated, is given by

$$f_r = \frac{1}{2\pi} \arccos\left(-\frac{a_1}{2\sqrt{a_2}}\right). \quad (3)$$

The optimal set of predictive coefficients  $a_1$  and  $a_2$  are chosen to minimize the variance of the prediction error. They can be found thanks to a recursive optimization procedure as it has been proposed in [7]. Moreover, it has been shown in [7] that the AR2 method is less sensitive to the speckle effect than the FFT method.

However, with a single laser-diode, the angle  $\gamma$  must be known to calculate the velocity of the moving target, limiting drastically the potential applications. It is then necessary to quantify the influence of this angle uncertainty on the global performance of the sensor. For this purpose, we perform sensitivity analysis [9] and uncertainty propagation [9]-[10]. This analysis is done using sampling-based method as described in [9]. TABLE I summarizes, for different values of  $\gamma$  and of the velocity, the corresponding Doppler frequencies (i.e. the maximum required bandwidth) and the maximum acceptable angle variation  $\Delta\gamma$  enabling us to guarantee a maximum standard deviation of the velocity of 1%.

TABLE I. Bandwidth ( $f_D$ ) and alignment constraints ( $\Delta\gamma$ ) of the single laser diode for 1 % of standard deviation of velocity estimates.

Velocity (m/s)	$\gamma$ (°)							
	5		30		45		70	
	$f_D$	$\Delta\gamma$ (°)	$f_D$	$\Delta\gamma$ (°)	$f_D$	$\Delta\gamma$ (°)	$f_D$	$\Delta\gamma$ (°)
0.1373	30.5 kHz	$\pm 0.15$	175 kHz	$\pm 1$	247.3 kHz	$\pm 1.5$	328.7 kHz	$\pm 4.5$
1	222 kHz		1.27 MHz		1.8 MHz		2.4 MHz	
10	2.22 MHz		12.7 MHz		18 MHz		24 MHz	

Tolerance on  $\Delta\gamma$  is better for superior values of  $\gamma$  but at the usual price of a high bandwidth. For reaching the required standard deviation on the velocity,  $\Delta\gamma$  must be better than  $\pm 0.15^\circ$  for a small angle  $\gamma$  of  $5^\circ$  which is limiting strongly the potential applications. On the contrary,  $\Delta\gamma$  is of  $\pm 4.5^\circ$  when  $\gamma$  is equal to  $70^\circ$  but the bandwidth is then 11 times higher. Moreover, in some industrial applications, LD may have to be placed in front of the moving target with a small angle  $\gamma$  only, due to the production configuration. It appears clearly that a single-head OFI velocimeter is limited for applications where  $\Delta\gamma$  may vary widely. We are then proposing a double-head self-mixing laser velocimeter for increasing the potentialities of this sensing method. In the next section, we will analyze the parameters permitting to optimize the performances of this set-up.

#### IV. DOUBLE-HEAD LASER DIODE VELOCITY SENSOR

The double-head LD prototype is presented in Fig. 2 where  $\beta$  is the angle between the 2 LDs, i.e. the 2 optical propagation axes.  $B$  is the bisector of  $\beta$ ,  $N$  is the normal to the velocity vector  $V_T$ ,  $\theta = \beta/2$  is the angle between the optical propagation axes and  $B$ , and  $\alpha$  is the angle between  $B$  and  $N$ . Both LDs (named LD1 and LD2) are identical. From (1) we can write:

$$V_T = \frac{\lambda f_{D1}}{2 \sin(\alpha - \theta)} = \frac{\lambda f_{D2}}{2 \sin(\alpha + \theta)} \quad (4)$$

where  $f_{D1}$  and  $f_{D2}$  are the Doppler frequency shifts of the optical power signals emitted by LD1 and LD2 respectively. Equation (4) gives

$$\tan\alpha = \frac{f_{D2} + f_{D1}}{f_{D2} - f_{D1}} \tan\theta. \quad (5)$$

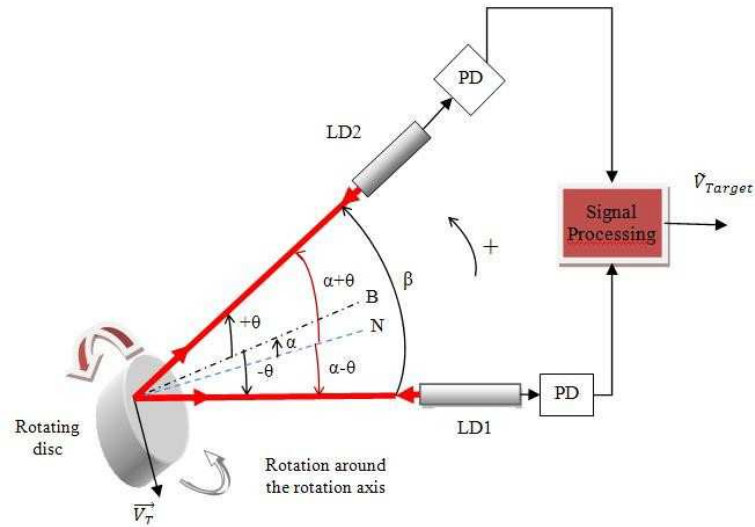


Figure 2. Double-head laser diode prototype.

Then  $\alpha$  is given by:

$$\alpha = \tan^{-1} \left( \frac{f_{D_2} + f_{D_1}}{f_{D_2} - f_{D_1}} \tan \theta \right). \quad (6)$$

With a known angle  $\beta$  between the 2 laser beams and estimating both DFs,  $\alpha$  can be estimated using (6). Finally, (4) permits to estimate the velocity.

The configuration of the double head LD-based self-mixing sensor is qualified with the above-mentioned sampling-based sensitivity / uncertainty analysis [9]–[10]. In this analysis, we consider several positions of both LDs ( $\beta = 20^\circ, 30^\circ, \dots, 90^\circ$ ) and for different velocity vector direction ( $0-90^\circ < \alpha < 90^\circ - \theta$ ), the velocity being maintained constant at  $0.1373 \text{ m/s}$ . The analysis inputs are both DFs supposed to have a normal distribution centered on the exact value calculated using (4) and a standard deviation equal to 3 kHz. Samples are generated using Latin hypercube sampling [9].

Fig. 3 presents the standard deviation and the mean squared error (MSE) of this double LD velocity sensor. It shows that better performance is obtained for  $\beta=90^\circ$ , i.e. lower standard deviation (0.85%) and lower MSE ( $1.4 \times 10^{-6} \text{ m}^2/\text{s}^2$ ). It appears that an important angle between both lasers permits to reduce the measurements errors. Moreover, it is now possible to calculate easily the value of the angle shift  $\alpha$  between the bisector  $B$  and the normal  $N$  to the target. Consequently, as  $\alpha$  can be now estimated, it has a slight influence on the accuracy of the set-up in comparison with the previously-described single-head self-mixing sensor where this parameter is unknown.

One can also notice that for all values of  $\beta$  between  $20^\circ$  and  $90^\circ$ , the standard deviation is always lower than 4% and the MSE is still lower than  $2.5 \times 10^{-5} \text{ m}^2/\text{s}^2$ . It can then be

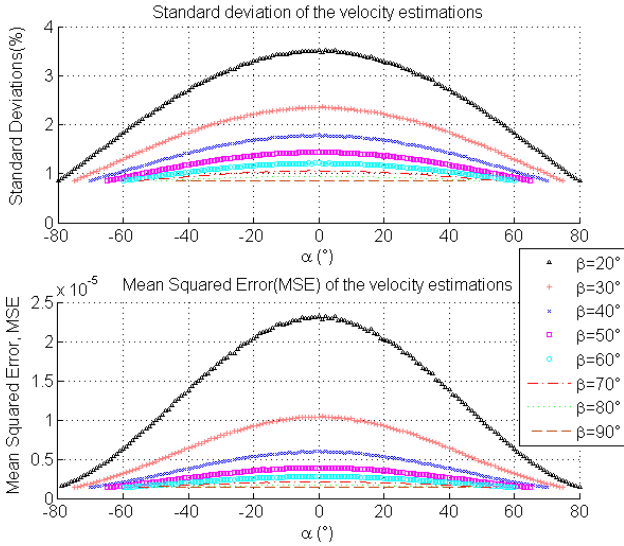


Figure 3. Mean squared error and standard deviation of the double-head laser diode velocity estimator.

concluded that the double-head LD velocity sensor is always accurate whatever is the direction of velocity vector and the position of the LDs.

In conclusion, the analysis above has demonstrated the quality of the double-head LD velocity sensor in terms of accuracy and insensitivity to angle variations of the target.

## V. EXPERIMENTAL RESULTS

The experimental set-up used for evaluating the response characteristics of the double-head self-mixing velocimeter is based on 2 LDs from Hitachi (HL7851G) emitting at a wavelength  $\lambda$  equal to 785 nm, with a maximum power of 50 mW. They are fixed on 2 orthogonal rails (i.e.  $\beta=90^\circ$  and  $\theta=45^\circ$ ). The considered target is a disc rotating at a constant velocity.

Both LDs have 2 degrees of freedom: translation in the direction of the rails and normally to the rails. The translation in the direction of the rails is used to adjust the distance (around 27 cm) between the LDs and the target. The translation normally to the rails is used to align both laser beams with the rotation axis of the target (Fig. 4), i.e. both laser beams illuminate the same point on the target that belongs to the rotation axis. The target has 3 degrees of freedom: 2 orthogonal translations in the plan of the rails used to align the target rotation axis with the 2 laser beams; and rotation around the rotation axis used to change the direction of the velocity vector  $V_T$  at the target spot (i.e.  $-30^\circ < \alpha < +30^\circ$ ). The velocity of the target at the laser spot is  $V_T = 0.1373 \text{ m/s}$ .

The acquisition of the self-mixing signal was performed with a 1 million-point memory scope at 2-MHz sampling frequency. Five acquisitions were taken for each value of  $\alpha$  between  $-30^\circ$  and  $+30^\circ$  with a step of  $5^\circ$ . DF is estimated using the FFT and AR2 algorithms. Target velocity is estimated using the method described in section IV (cf. equation (4)).

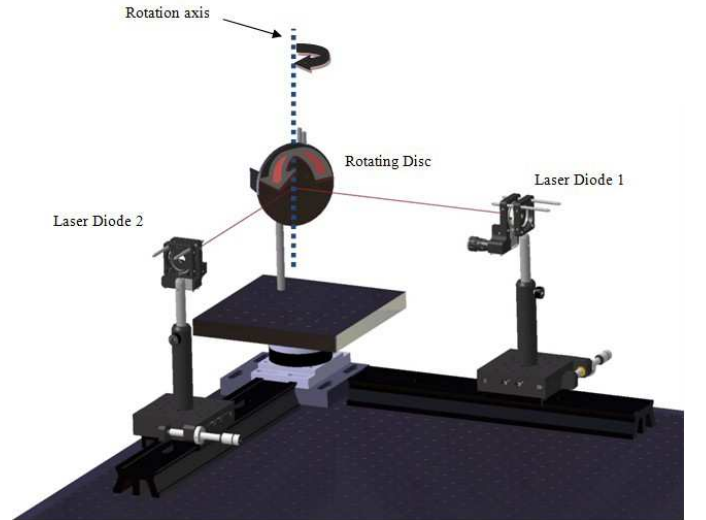


Figure 4. Experimental set-up of the double-head laser diode.

The experimental results are showed in Fig. 5, Fig. 6 and Fig. 7. Fig. 5 presents the estimated (using (6)) and reference values of  $\alpha$ . The estimation of  $\alpha$  has a maximum error of  $0.44^\circ$  regarding the reference value. Its mean percentage error (MPE) and maximum standard deviation are respectively 0.5% and 0.1% which prove the accuracy of the estimation of  $\alpha$ . Fig. 6 shows the low difference between the reference values and estimated values of velocity. The standard deviation, MSE and MPE of the estimated velocities are presented in Fig. 7. One can note the low standard deviation (lower than 0.15%), low MSE (lower than  $3 \times 10^{-7}$ ) and low MPE (lower than 0.4%). Note that these experimental results (standard deviation and MSE) are lower than those obtained in the simulations of section IV. This is due to the fact that the standard deviations of estimated DFs, using both FFT and AR2 algorithms, are about 2.2 kHz which is inferior to that chosen in the simulations (3 kHz). Note also that both FFT and AR2 methods provide similar standard deviation of the velocity estimations because of the low speckle effect in this experimentation.

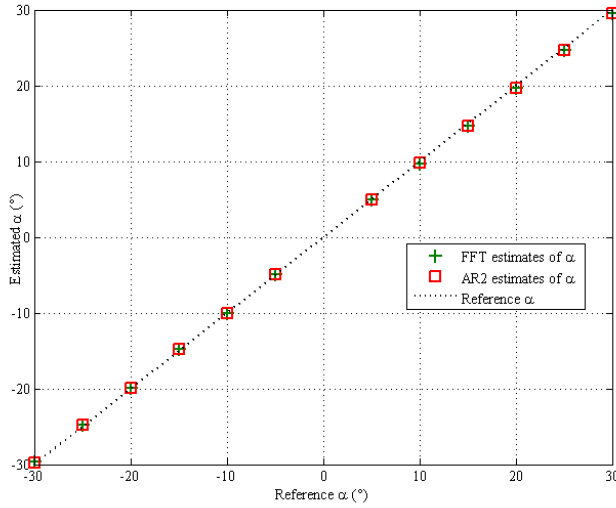


Figure 5. Estimation of the angle  $\alpha$ .

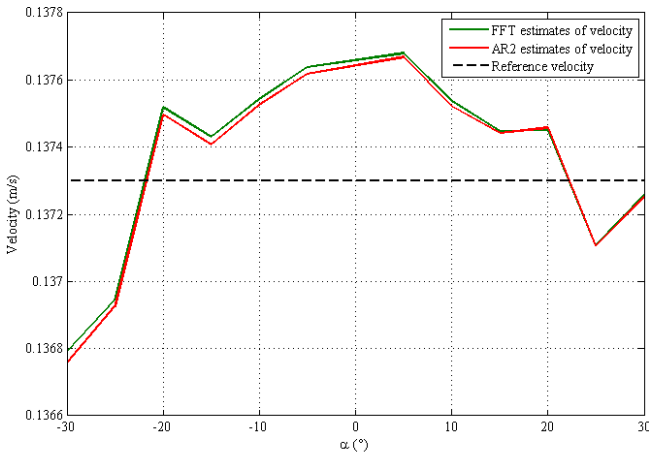


Figure 6. Representation of reference and estimated velocities.

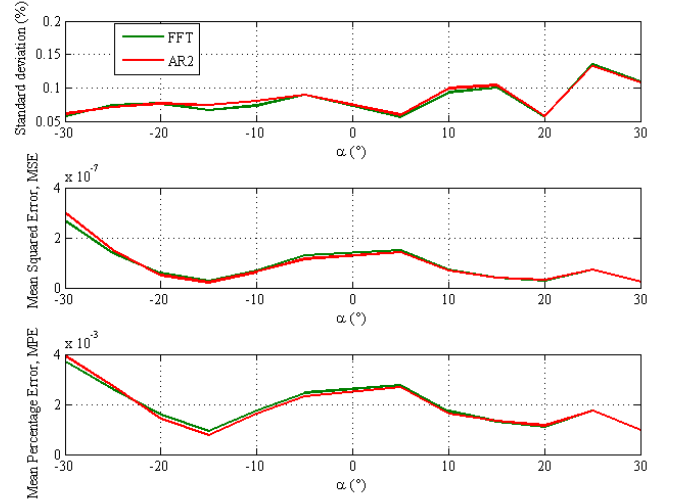


Figure 7. Experimental results of the double-head laser diode velocity sensor.

Furthermore, similar results were obtained in terms of accuracy for the double-head LD sensor by translating the second LD normally to its supporting rail, i.e. the second laser beam which remains coplanar with the first, illuminates now an alternative point noted  $C$  on the rotating disc. In this case, the orthogonal projection of the velocity vector at  $C$  onto the plane ( $P$ ) defined by the laser beams persists the same wherever is  $C$ . Then the velocity measurement is not perturbed in this case. That is, the velocity measured is the orthogonal projection of the velocity vector onto ( $P$ ).

It can then be observed from the results showed above that the double-head LD is always accurate whatever the direction of the velocity vector is.

## VI. CONCLUSION

In this paper, the configuration of a double-head LD sensor was analyzed and improved to increase the robustness of the self-mixing sensor. This double-head LD velocimeter is able to approximate the direction (by estimating  $\alpha$ ) and the value of the target velocity. The sensitivity/uncertainty analysis performed in section IV showed its performance in terms of accuracy and insensitivity to angle variations of the target. Experimental results validated the accuracy and precision (low standard deviation) of the sensor. Additional analysis and experiments should be performed to quantify the misalignment errors out of the plane and the sensitivity to misalignment for this setup.

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