Adaptive optical head for industrial vibrometry applications

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ABSTRACT

A self-mixing laser interferometer has been combined with a compact and robust optical system including an adaptive optical element in the form of a voltage controllable liquid lens. The use of the liquid lens enables the self-mixing interferometer to adjust the optical focus position and the beam spot diameter on the target surface, and subsequently the feedback level within the laser cavity. The optical system has been designed to focus the beam at distances from a few centimetres from the front facet of the laser diode to infinity. With such a simple arrangement, it is possible to modify and control the intensity of the back reflected light from the target surface into the laser cavity, by simply changing the voltage applied to the lens to modify the focus condition on the target surface. The final effect obtained is full active control of the feedback level of the self-mixing effect taking place. This has allowed keeping the feedback level of the interferometer in the desired regime for measurements along very long distances and for different measurement situations, so extending the capabilities of a classical self-mixing interferometer. The advantage of the proposed adaptive optical head is thus its combination of precise metrology capabilities plus a great potential in automated feedback control and operator-free industrial applications. Signal reconstruction of the target vibration amplitude presents a maximum error of λ/16 as compared with a commercial capacitive sensor in the whole focusable range for displacement measurements. An improved working range of 6.5 cm to 280 cm staying in the same feedback regime has been experimentally demonstrated.

Keywords: Adaptive optical head, self-mixing, optical feedback control, laser diode interferometry.

1. INTRODUCTION

Self-mixing effect in semiconductor lasers has been widely studied during the past decades, and it has demonstrated a great potential in displacement, vibration and velocity measurements for industrial applications[1]. Self-mixing interference occurs when a part of emitted laser beam leaving a laser diode (LD) cavity is back-reflected from a moving target and partly re-enters into the active cavity of the LD. This reflected beam then interferes (becomes self-mixed) with the present standing waves inside the cavity, resulting in a variation in the spectral properties of the laser beam which yield changes in the emitted light intensity. The Output Optical Power (OOP) of the LD is monitored using a photodiode integrated in the same laser package which makes the interferometer compact, cheap, self-aligned and robust. Therefore, a self-mixing interferometry (SMI) setup becomes exceptionally attractive from the industrial application point of view when compared to the conventional two beam interferometry, specially regarding robustness, compacity and capability to operate in hostile environments, at the price of not achieving the extreme accuracies obtained in state-of-the-art two-beam interferometers.

A detailed theoretical description of the self-mixing phenomenon may be found elsewhere[1]. In the most usual approach, the effects of feedback on the spectrum of the laser, and in particular on the OOP of the LD, can be analyzed through the phase equation, whose main characteristic is the presence of a number of distinct OOP regimes for different optical feedback levels[2]. The shape of the OOP when self-mixing interference takes place has very distinct features for each feedback regime. Feedback regimes are discriminated by C, the feedback coupling factor, which is given by[1]

$$C = \frac{D}{\sqrt{A}} \frac{\varepsilon\sqrt{1+\alpha^2}}{l_{las} n_{las}} \frac{1-R_2}{\sqrt{R_2}} \quad (1)$$

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Where D is the laser-to-target distance, A (>1) is the total power attenuation in the external cavity composed by the front facet of the laser and the target, α is the linewidth enhancement factor, ε is the mismatch between the reflected and lasing modes, l_{las} is the laser cavity length, n_{las} is the refractive index of the cavity and R_2 represents the LD front facet power reflectivity.

In experimental work, using a same LD, the feedback coupling factor value can vary mainly using three parameters: the linewidth enhancement factor, the feedback level and the sensor-to-target distance. Changes in this parameter modify the OOP behavior leading to have the signals in four different regimes depending on C value; very weak ($0<C<0.1$), weak ($0.1<C<1$), moderate ($1<C<4.6$), and strong ($C>4.6$).

The weak and moderate regimes are the more adequate feedback regimes for performing accurate displacement measurements, which are performed by simply counting the number of fringes[3,4]. In fact at the very weak regime there is a directional ambiguity in displacement measurement, while at high hysteresis moderate and strong regimes some fringe(s) may be lost, decreasing the measurement accuracy below the basic resolution of half wavelength of the LD. Fringe-loss takes place when increasing the laser-target distance D and/or increasing feedback level (i.e. when the target surface is reflective). In particular, the fringe-loss condition in the moderate feedback regime appears when hysteresis becomes higher due to the appearance of multiple steady-state solutions of the phase equation, where the number of fringes N taking place for a constant target vibration amplitude can decrease depending on the value of C and of the feedback phase Φ which is given by[5]

$$\Phi = \omega_0 \tau_D + \arctan(\alpha) \tag{2}$$

where ω_0 is the angular frequency of the LD in the free running state and τ_D is the external round trip delay. Thus, to avoid fringe-loss, both C and Φ values should be kept in a proper range of values.

In a conventional SMI setup, a mechanically adjustable fixed focal lens is used to focus the beam on the target surface, and a skilled operator is required to manually adjust the lens position to bring the optical feedback level to the desired regime for measurement, that is, to the weak or low-hysteresis moderate regimes. Efficient techniques have been proposed in the past using variable attenuators to achieve the desired optical feedback strength[4]. In this method, however, it was imposed that the sensor-target distance was fixed, and known before the measurement. The situation would be enhanced using a general-purpose technique which actively changed the feedback level.

Besides, adaptive optics (AO) is a well-known technique usually used in large astronomical telescopes and retinal imaging applications for enhancements in imaging conditions using active compensation of the wavefront distortion introduced by some turbulent media. In the last decade, however, some applications of AO have been developed to improve optical sensors performance[6] using a number of active optical elements, from deformable mirrors to LLs, in fields like free-space optical communications.

Our proposal is to replace the fixed focal lens with a compact optical configuration combining a fixed focal lens with a voltage controllable liquid lens (LL), available commercially, located in front of the LD. The LL used in the setup as adaptive optical element is used to change the focal length of the whole optical setup, modifying the spot size of the beam and affecting the amount of light re-entering the LD cavity, consequently changing the feedback level and coupling coefficient.

2. EXPERIMENTAL SETUP

Figure 1 presents the experimental setup diagram of the self-mixing vibrometer with the adaptive optical head (AOH) configuration embedded. The LL used in the proposed configuration is an ARCTIC 416SL V3 liquid lens, commercially available from Varioptic. It contains two transparent non-miscible liquids with different refractive indices, one of them being insulating and non-polar, and the other being a conducting water solution[7]. The final aperture is about 2.7 mm. The radius of curvature of the liquid-liquid interface can be varied through voltage, repeatably changing the focal length of the assembly. The physical phenomena taking place has been termed as electrowetting.

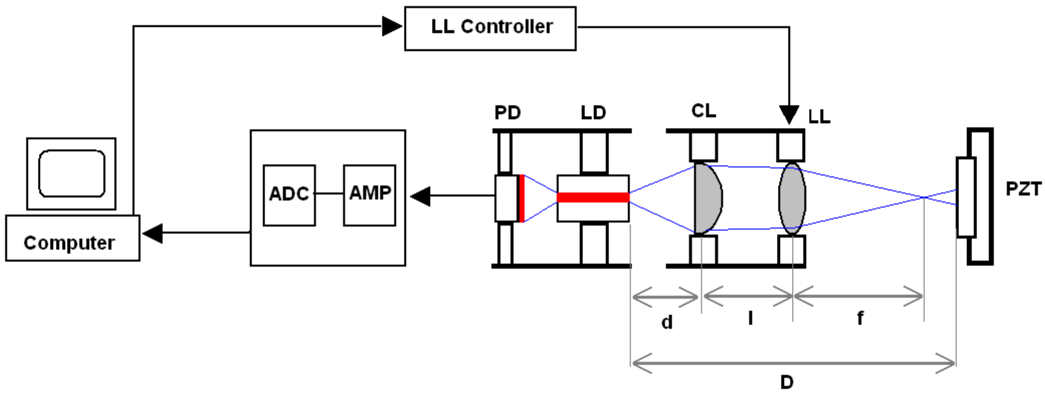

Figure 1. Schematic diagram of the experimental setup for the self-mixing vibrometer with adaptive optical head .

The LL used has an optical power variation which goes from -12D to +18.75D, corresponding to a voltage variation from 30V to 60V. The LD is emitting laterally out of a Fabry-Perot cavity, so a large lateral aperture is expected, typically around 46º for the selected diode (a Hitachi HL7851G LD with 50 mW maximum power, wavelength of 785nm). Such an aperture required a collimating lens (CL) located close enough to the front facet of the LD to collimate the beam leaving the laser, in order to prevent light losses, which was then combined with the liquid lens to yield the maximum focusing range. The CL was selected to have a focal length smaller than the LD-lens distance d to avoid the existence of divergent beams and the formation of virtual images.

The two-lens optical system presented in Figure 1 has been designed and built (Figure 2). In this prototype, the CL has a focal length of 3.1 mm, and it directs the beam leaving the laser towards the LL, placed at a distance of l = 17 mm from the CL. In all experiments, we have used as target a P-753.2 CD piezoelectric transducer (PZT) from Physik Instrumente, equipped with an integrated capacitive sensor which allows to monitor the motion of the transducer with an accuracy of 2 nm, and which has been used as reference. The OOP of the LD is monitored using an integrated PD, whose signal is amplified and converted using an AD converter. The digitized signal is then acquired by the computer (PC) through a USB connection. The LL focal length is changed using a controller which can be used in manual mode, or controlled by the PC through the USB connection, the option suitable for closed loop operation. All experiments are performed on an optical table, which limits the maximum possible distance of the target from the LD to 280 cm. The minimum possible distance of the target from the LD is about 25mm, limited by the size of the optical head assembly.

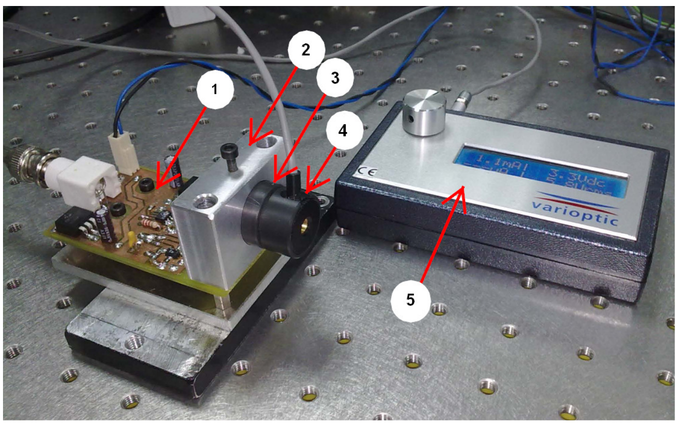

Figure 2. Experimental configuration of the AOH for a self-mixing vibrometer. (1) Electronic signal acquisition board, (2) metallic heat sink containing LD package, (3) tube holding fixed focal length lens, (4) liquid lens, (5) liquid lens controller.

3. EXPERIMENTAL RESULTS

The OOP signals of the LD (self-mixing signals) obtained at four different focus conditions for a vibrating target at a fixed distance of D = 60 cm are shown in figure 3. In this measurement, PZT excitation was a sinusoidal harmonic signal with peak to peak amplitude of ΔD = 4.25μm and a frequency of 100Hz. The target surface in all measurements was a metallic surface.

As far as the appearance of each fringe is due to a target displacement of $\lambda/2$, the expected number of fringes N (N = round($2\Delta D/\lambda$)) in each half period of the oscillation is 11 for the proposed experiment. The fringe loss condition resulting in a wrong number of fringes presented in Figure 3 is due to the large hysteresis and high feedback strength achieved, with most of the energy emitted re-entering the cavity. A well focused status of the beam on the target, results in 8 fringes in each half period (figure 3a). Then, by defocusing of the beam by changing the LL focal length, one lost fringe reappears (figure 3b), exhibiting less hysteresis for the OOP signal. Further defocusing brings on the recovery of another lost fringe (figure 3c). Finally, further defocusing of the LL achieves the desired signals in moderate regime with low hysteresis and no fringe-loss (figure 3d) which allow accurate measurements. Therefore, by using the LL focal length variation lost fringes could be recovered leading to keep the signals in moderate regime with low hysteresis enabling accurate displacement measurements. Furthermore, the feedback level was directly controlled using the change in voltage at the LL.

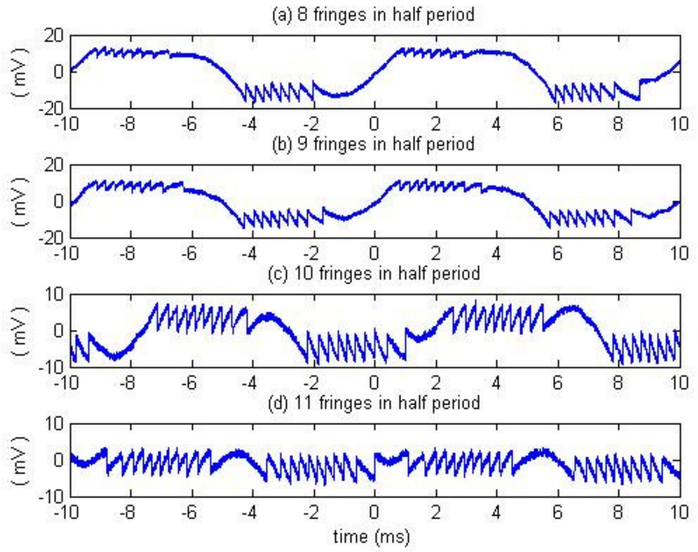

Figure 3. Experimental OOP signals for a 785 nm LD for a target distance of D = 60 cm, vibration amplitude of ΔD = 4.25 μm and vibration frequency of 100 Hz for various focus of the laser beam.

Clearly, in the described fringe counting method, losing a fringe severely increases the measurement inaccuracy in a value of half wavelength. Moreover, more accurate signal reconstruction methods like the phase unwrapping method (PUM)[8] also lose accuracy in the presence of lost fringe(s)[5]. Table 1 shows the C and Φ values estimated by PUM for each of OOP signals presented in figure 3. As it can be seen, better focusing results in more fringe-loss and a higher C value. By defocusing the beam, the feedback level is modified, changing the value of C, and the OOP signal can be kept in a regime having a proper set of (C, Φ) values, avoiding fringe-loss.

According to equation 1, modification of the laser-target distance D can change C value proportionally. However, D variation can affect other parameters relevant to C like the total attenuation A of the beam, so the total amount of back-reflected light re-entering the cavity can be modified. Usually, for a cooperative target at far distances (>1m), the moderate regime signal with large hysteresis is achieved. Decreasing D down to a few centimeters may change the moderate feedback regime to the weak regime implying directional ambiguities. Reversely, increasing D value can result in a large increase in C and in fringe-loss behavior. Thus, a direct application of our AOH is to keep the LD under moderate regime feedback with no fringe-loss conditions to keep the set of (C, Φ) in a proper range at a large amount of D values, allowing accurate measurement of the amplitude of vibration in the full distance range.

Table 1. Influence of fringe-loss on the feedback coupling factor value C and feedback phase Φ for the self-mixing signals obtained in Fig.3

No. of fringes (N)	**8**	**9**	**10**	**11**
Feedback coupling factor (C)	7.8	6.7	5.6	4.1
Feedback phase (Φ)	4.1	4.0	4.1	3.9

Figures 4(a)-4(d) show the acquired signal by using the conventional SMI optical setup, which uses a mechanically adjustable fixed focal lens (CL), with the beam focused to infinity by the CL to be able to recover a proper self-mixing signal in a large distance range of the target. Under this measurement condition, featuring the situation described in the last paragraph, D varies from 6.5 cm to 280 cm, while the target vibration amplitude is kept constant at 4.25µm. Thus, 11 fringes are expected in each half period of the interferogram. As shown in figures 4(a) and 4(b), the expected 11 fringes at half period are obtained. However, when increasing D at D=150cm two of the fringes are lost, with the subsequent unaccuracy in the measurement. When D was raised to 280 cm, it was found that just one fringe was lost, because of the significant increase in total attenuation which appeared at that distance. Figure 4(e)-4(h) show the OOP signals obtained using the AOH under the same measurement conditions previously used for the conventional optical configuration. Notice how the AOH could keep the OOP signal in low hysteresis moderate regime condition, recovering the expected 11 fringes for the complete distance range. Attenuation is observed only in the amplitude of the OOP signal.

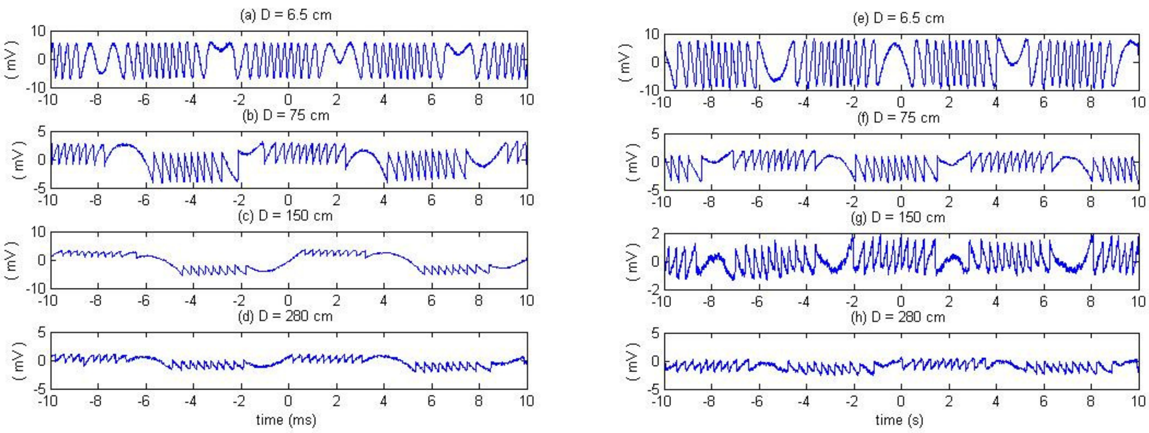

Figure 4. Experimental OOP signals for a 785 nm LD for various distance from 6.5 cm to 280 cm with vibration amplitude of ΔD = 4.25 µm and vibration frequency of 100 Hz. (a) to (d) acquired signals using a fixed focal collimating lens (conventional SMI setup) focused to the infinity; signals in c) and d) present hysteresis and fringe-loss; (e) to (h) acquired signals using AOH with feedback level adjustment so no fringe-loss appears in the whole distance range.

Table 2 presents the C, Φ and N estimated values for all measurements performed by the two optical systems described for different distances. Values of C and Φ were calculated using the phase-unwrapping method (PUM). For the signals obtained using the fixed focal optics, C value increases when the distance is increased from 6.5 cm to 150 cm, while at D=280 cm the C value decreases because of higher total power attenuation at large distances. The coupling coefficients obtained are consistent with the OOP signals obtained. At D = 6.5 cm, CL optics gets the signal in weak regime (C = 0.8) implicating possible directional ambiguity, while using the AOH we could find the moderate regime signal (C = 1.6) allowing accurate signal reconstruction. At 75 cm, both systems present OOP signals in the moderate regime. At 150 cm and 280 cm, CL optics can't keep the LD in a regime without hysteresis and fringe-loss occurs, while the AOH can control the feedback level keeping the signal in moderate regime avoiding fringe-loss. Results demonstrate how the proposed AOH can keep the C value between 1 and 4.2 at all distances, keeping the signal in the moderate feedback regime.

Table 2. Influence of distance variation on feedback coupling factor, feedback phase Φ and number of fringes detected with ΔD = 4.25 µm for both optical system: a collimating lens (focused at infinity) and AOH.

D (cm)	**Obtained by CL optics**			**Obtained by AOH optics**		
	C	Φ	N	C	Φ	N
6.5	0.8	3.7	11	1.6	4.6	11
75	4.2	4.6	11	3.8	4.0	11
150	6.1	4.2	9	3.2	4.2	11
280	5.8	4.5	10	4.2	4.4	11

As PUM is used for all vibration reconstructions, the achieved error compared with the reference capacitive sensor was less than λ/16 as expected[8]. Figure 5 presents the displacement reconstruction of the OOP signal obtained using AOH at D = 150 cm shown in figure 4(g) as compared with the reference capacitive sensor signal. As the LL can be controlled by PC through the USB connection, further usefulness of the AOH is to utilize it in closed loop applications where it can be controlled by software. This way, a set of (C, Φ) values can be considered as the input in the control algorithm, while the desired OOP feedback regime can be achieved and maintained at different distances.

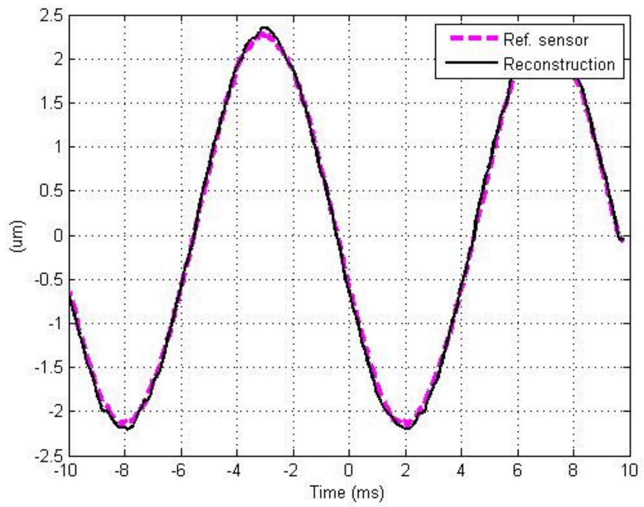

Figure 5. Displacement reconstruction of the OOP signal (shown in figure 4(g)) obtained using AOH configuration at D = 150 cm by using PUM as compared with the reference capacitive sensor signal.

4. CONCLUSION

An adaptive optical head including a combination of a fixed focal lens and a liquid lens has been proposed as a compact optical configuration in the SMI setup. The main capability of the system is its capacity for adaptively keeping the LD in moderate regime feedback under different experimental conditions. We have presented results showing how the AOH can change the weak regime to moderate, or the high hysteresis moderate to the low hysteresis moderate without fringe-loss along a very large range of distances. We have also shown that the AOH can recover lost fringes at fixed distances. Displacement measurements using PUM as the signal processing algorithm and the AOH located in SMI configuration can be performed with the maximum error of $\lambda/16$ for a large range of distances without need of optical adjustment by skilled operators. The control ability of the LL gives the possibility to use the AOH in closed loop applications where the feedback can be controlled by the PC software, using the voltage applied to the lens to control the feedback level of the laser.

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