Dealing With Speckle Effects in Self-Mixing Interferometry Measurements

Reza Atashkhooei, Santiago Royo, and Francisco J. Azcona, *Member, IEEE*

*Abstract***—An analysis of speckle effects and the techniques to overcome them in self-mixing interferometry signals is presented. We characterize the effect of surface roughness and laser spot size on the speckle modulation of the signal, and then propose two simple experimental approaches to overcome the amplitude fading induced by the speckle effect. Unlike the techniques proposed until now, our first approach uses an adaptive optical element in the form of a voltage-programmable liquid lens, which adaptively changes its focal length to modify the speckle pattern. Our second approach combines two laser signals which present different performance parameters. By using any of these simple methods, the introduction of inaccuracies in the measurement process due to speckle is avoided.**

*Index Terms***—Displacement measurement, interferometry self-mixing, speckle effect.**

I. INTRODUCTION

SPECKLE effect occurs when coherent light is back-reflected from a rough surface, where it is scattered forming a granular interference pattern due to the random phase superposition of the beams on the illuminated area. In the case of self-mixing interferometry (SMI) the back-reflected beams from the target re-enter the laser cavity and are mixed with the standing waves in the active laser medium. Usually diffusive surfaces are used as targets, so speckle effect appears and affects the self-mixing interference pattern. For small displacements of the target (e.g. with amplitudes from a few microns to 0.1 mm) there is no apparent speckle effect in the self-mixing signal (SMS), as the displacement is much smaller than the typical speckle size [1]. For larger displacements, going from a few millimeters to some centimeters or over, speckle effects in the SMS are easily observed as an amplitude modulation of the signal, where amplitude fading occurs frequently and where in addition a speckle phase error of random origin is introduced in the signal. The amplitude effects make extremely complex, if not impossible, to properly detect the transitions in the SMS, resulting in important inaccuracies in displacement and velocity measurements. A velocity measurement error in the range of 3% over a wide velocity range (5.2 mm/s – 479 mm/s) due to the speckle effect has been reported recently [2], while speckle-related displacement measurement errors are in the range of 10% for large displacements [1] (prior to using speckle compensation techniques).

The relationship which exists between the intensity distribution of the backscattered laser light and the target surface roughness has been extensively studied in the past decades [3]. Furthermore, speckle-modulation of the SMS due to surface profile has been investigated as well [4]. The practical problem posed is relevant as the SMI measurement principle inherently forms speckle patterns on rough targets.

Further than the roughness of the target surface, some other parameters related to the geometry of the experimental setup such as the beam spot size, the laser distance to the target, and the wavelength of the laser are known to affect the size of the speckle "grains". The presence of such speckle "grains" introduces an undesired modulation frequency superimposed to the SMS. The mean value of speckle sizes for the objective speckles which appear in the free propagation of a diffused coherent light field can be obtained from [5]

$$OS_l = \lambda \left(\frac{d}{D}\right)^2, \quad OS_t = \lambda \left(\frac{d}{D}\right) \tag{1}$$

Where OS_l and OS_t are longitudinal and transversal objective speckle sizes, respectively, D is the laser spot diameter on the target, d is the target distance from the laser and λ is the wavelength of the laser. In the case of subjective speckles, an optical element is located between the observer and the target as seen in Fig. 1. The speckles appearing on the laser diode (LD) side (the observer) are projected by the lens as virtual speckles on the target. The mean value of longitudinal and transversal sizes of these virtual speckles are given by [1]

$$SS_l = \lambda \left(\frac{2l}{D_L}\right)^2, \quad SS_t = \lambda \left(\frac{l}{D_L}\right) \tag{2}$$

Where SS_t and SS_l are transversal and longitudinal subjective speckle sizes respectively, l is the target distance from the lens and D_L is the lens diameter.

In SMI usually a collimating lens is used to focus the laser beam on the moving target to monitor the longitudinal displacement of the target. Therefore, the generated speckles are subjective speckles apparent to the LD due to imaging of the coherent superposition of reflected beams on the target. The SMS modulation frequency is related to longitudinal

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The authors are with the CD6 Research Center, Universitat Politècnica de Catalunya, Barcelona 08222, Spain (e-mail: reza.atashkhooei@cd6.upc.edu; santiago.royo@upc.edu; francisco.javier.azcona@cd6.upc.edu).

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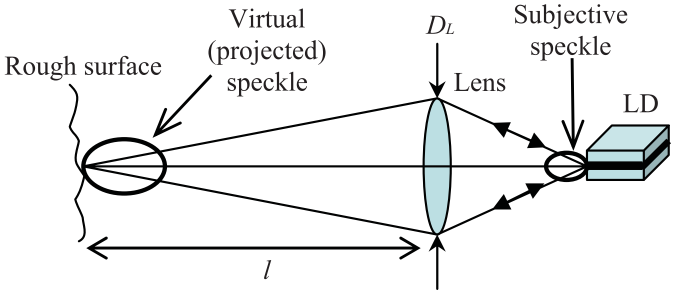

Fig. 1. Schematic diagram for subjective speckle.

speckle sizes of the virtual speckles projected on the target side (SS_l).

Larger speckle sizes lead to lower modulation frequencies in the SMS amplitude, resulting in general in less severe amplitude fading effects. Thus, the combination of target distance, lens aperture and wavelength needs be optimized to obtain speckle sizes as large as possible within given experimental conditions. However, usually there are substantial limitations on the range of variation of such parameters. Just as an example, when the target surface is diffusive and the target distance becomes very large, not enough backscattered light returns to the laser cavity, leading to poor signal to noise ratio in the SMS signal and to difficulties in the correct reconstruction of the displacement, complicated even more by the presence of speckle. Besides, the lens diameter should be large enough to focus the entire laser beam coming out of the laser cavity, which is normally divergent, and to recover enough backscattered light from the target in order to produce relevant self-mixing effect. In fact, by optimization of the mentioned parameters, the modulation frequency due to speckle may be reduced but almost never eliminated.

In addition, random speckle phase error is also introduced in the signal. Its effects are typically much less noticeable than those of the amplitude fading error, as shown in [1], where it is shown that speckle phase error corresponds to displacement inaccuracies in the order of λ for a travelling range of 50 cm.

In fact when we cross longitudinally a speckle "grain" we may assume we have a phase error of $\sigma = \lambda$ [1][6]. For a total target displacement of Z we have $N = Z/SS_l$ subjective speckles, whence introducing a phase error of

$$\sigma_Z = \lambda \frac{Z}{SS_l} = \frac{D_L^2 Z}{4l^2} \tag{3}$$

As an example, with a lens diameter of $D_L = 4$ mm, a target displacement of 10 cm at a distance of 1 m from the lens, induces a phase error of 0.4 μm.

To our knowledge, the only technique which has been implemented to overcome the problem of amplitude fading by speckle uses an in-plane piezoelectric positioning system to keep the amplitude of the signal at maximum level by scanning the target [6]. In this bright speckle tracking technique (BST), the laser is moved transversally to look for high amplitude SMS, thus avoiding signal fading.

In this paper[1], we first analyze what are the effects on SMS of having a speckled beam, including what to our knowledge is the first characterization of the SMS under speckle effect. We will analyze in detail the effect of surface roughness and of laser beam spot size on speckle modulation of the SMS. Then, we propose two new solutions to deal with amplitude fading caused by speckle effect, based on adaptive focusing and on sensor diversity [7]. We will demonstrate the performance and the viability of both solutions using experimental examples. To our knowledge, it is also the first time these solutions are applied experimentally to speckle compensation.

The rest of the paper is organized as follows: the analysis of the speckled SMS, including its characterization and the effects of roughness and spot size will be presented in section II. In section III and IV the adaptive focusing solution and the sensor diversity technique will respectively be proposed, including description of the technique, procedure, experimental examples and displacement reconstruction results. A final section will point out the main conclusions of this work.

II. SPECKLE ANALYSIS

A. Speckle Affected SMS Characterization

Our first step will be the characterization of speckle affected SMS, by calculating the coupling feedback factor C at different regions of the SMS to better understand its relationship with speckle. Coupling feedback factor is given by [8]

$$C = \frac{D}{\sqrt{A}} \frac{\varepsilon\sqrt{1+\alpha^2}}{l_{las} n_{las}} \frac{1-R_2}{\sqrt{R_2}} \tag{4}$$

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.

Fig. 2 shows the speckle affected SMS obtained for a target displacement of 20 mm. The target is a ground metallic surface with average roughness value (Ra) of 0.2 μm, which was initially placed at 17 cm from the LD and moved towards the laser until it was at 15 cm from the LD. The C values presented are calculated by using the phase unwrapping method [9], for a selected region of the signal shown in the figure. As shown in Fig. 2, very relevant changes in amplitude of output optical power (OOP) of the LD appear during the longitudinal target displacement because of speckle modulation of the signal due to coherent superposition. A very interesting feature is how consistently the value of C varies in a given pattern for these changes. The C value found in fading SMS regions can be increased up to 6.9, while in larger amplitude zones it stays in smaller values. Such a large feedback level in the blackout regions suggests that fringe loss condition may appear in these regions [10]. In addition, the SMS amplitude in a blackout zone may decrease to the noise level, thus making very complex to properly recognize the transitions. Both effects may

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[1] An earlier version of this paper was presented at the 2011 IEEE SENSORS Conference and was published in its proceedings.

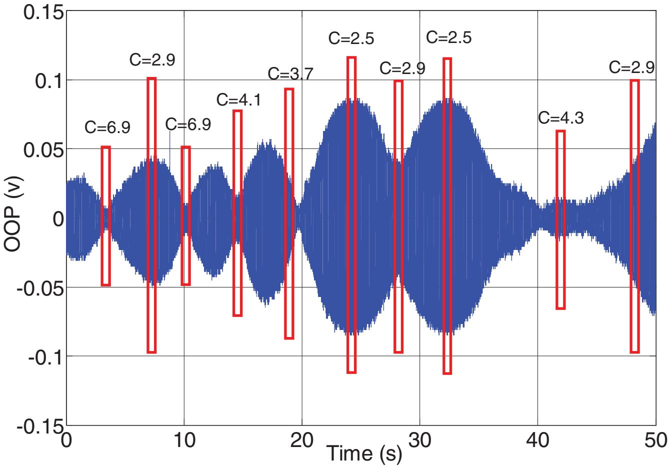

Fig. 2. Typical measurement result of speckle-modulated output optical power (OOP) for longitudinal displacement of the target. The C values shown are the values of the coupling factor calculated by phase unwrapping method for the selected area of the signal.

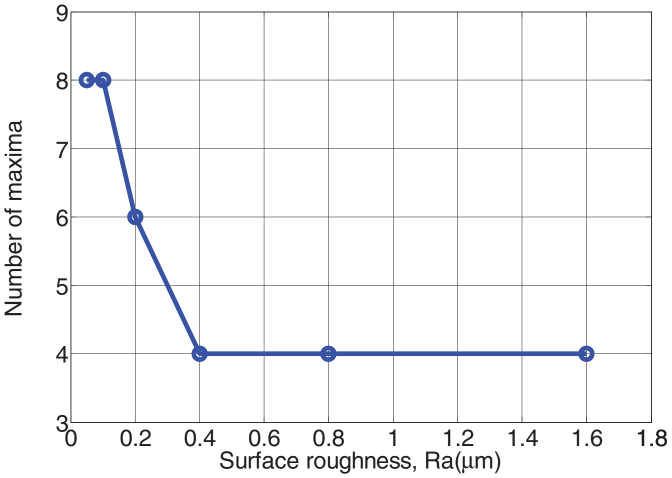

Fig. 3. Number of local maxima versus surface roughness based on experimental measurements.

bring on relevant inaccuracies in displacement reconstruction procedures.

B. Effect of Surface Roughness

In order to analyze the relationship of the frequency of the speckle modulation of the SMS with the average roughness parameter (Ra) of the target, we used standard roughness surfaces including 6 different specimens with calibrated Ra values of 0.05, 0.1, 0.2, 0.4, 0.8 and 1.6 μm, which were used as targets. For all surfaces the target moved from 17 cm to 13 cm from the LD (a 40 mm displacement), and the number of local maxima was counted.

Fig. 3 shows how the number of maxima decreases when the Ra value increases from 0.05 to 0.4 μm, which is roughly half the wavelength of the LD (784 nm). For Ra values ranging from 0.4 μm to 1.6 μm the number of maxima remains constant at a value of 4. This curve is in good agreement with equivalent ones obtained in the literature for transversal speckle patterns [11].

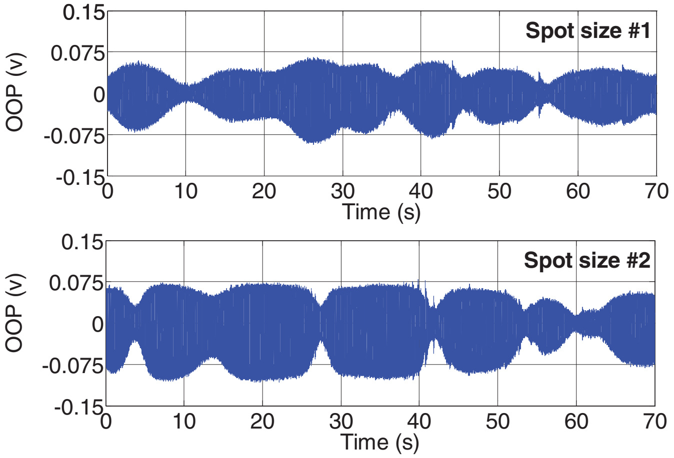

Fig. 4. Two SMSs achieved for a target displacement of 4 cm with different focus positions.

C. Effect of Spot Size

SMS amplitude modulation due to speckle appears due to the random nature of the surface roughness, so by changing spot size (through changing the position of the focusing lens) the positions of both the maxima and blackout regions may be modified. As seen in equation (2), changing the spot size should not affect the average speckle sizes if the laser wavelength, lens distance from the target and beam diameter on the lens are kept constant.

Fig. 4 shows two SMS signals obtained using the same setup with different spot sizes, using the same LD.

The target used had average roughness of 0.8 μm and was displaced along 40 mm. The average FWHM of the spot on the target in the first signal was 71 μm and in the second signal it was modified to 54 μm. To measure the FWHM of the laser spot, a CCD camera was placed at the location of the target and the spot image captured by the camera was processed to obtain the average FWHM value. It can be seen how the maxima and blackout positions may be modified by changing the spot size of the laser, that is, by modifying the position of the focal point of the lens.

III. ADAPTIVE SOLUTION

Our first proposed approach to avoid amplitude fading of the speckle affected SMS uses an adaptive optical element in the form of a voltage programmable liquid lens (LL) which changes the focal length of the system to modify the speckle pattern. The LL is embedded within an optical head unit including a collimating lens for the laser beam, the LL, and its controller. The optical head performance was optimized using optical design simulations to adjust the power, position and diameter of the collimating lens. It has been shown how changing the focal length (and, subsequently, the spot size) modifies the feedback level and the C value [12][13], allowing to keep the SMS in any given regime. Besides, in section II.C we have just shown that changing the spot size, modifies the speckle pattern and the position of the blackouts in the SMS. Thus, speckle modulation may be managed by monitoring the SMS amplitude in real time, and modifying the spot size

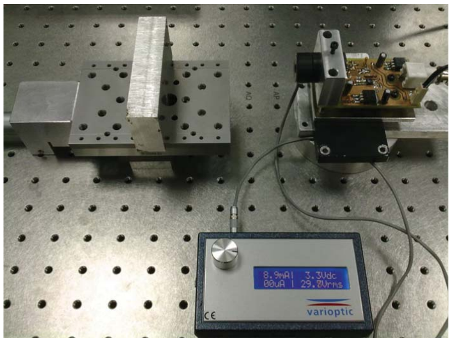

Fig. 5. Experimental setup including the adaptive optical head for speckle compensation.

using the LL when the amplitude is falling down to the fading regime.

Thus, the LL focal length needs be changed fast enough to prevent signal fading and information loss. Consequently, the method is limited by the speed at which the LL focus can change. The LL used in the proposed configuration is an ARCTIC 416SL V3 liquid lens, commercially available from Varioptic, which needs 80 ms to change its focal length. Considering signal acquisition and processing time, the total time will become further increased, so this approach becomes useful with the present specifications only in case of slow-changing displacements. It also should be considered that we may need to modify the spot size more than once in each blackout until we get a satisfactory signal level, so there is an additional velocity limitation for the target in this approach. The maximum velocity of displacement which allowed successful signal fading compensation was 0.1 mm/s, in a measurement range of 10 mm.

Fig. 5 shows the experimental setup used to demonstrate this technique. The target is mounted on a DC motorized translator stage, and the proposed optical head is mounted in the tube holding the LD, facing the target. The LD used is a Hitachi HL7851G single mode LD (SMLD) emitting at 793 nm with a maximum output power of 50 mW.

Fig. 6 shows two SMS acquired along a surface displacement of 10 mm with a velocity of 0.0208 mm/s. The first signal is a reference signal acquired using a LD with a fixed focal lens. It may be seen how two fading zones due to speckle are present. In practice, signal reconstruction becomes impossible at the first fading zone so the complete displacement profile is lost.

The second signal shows the signal obtained using the LL arrangement with the adaptive optical head, which successfully kept the signal at high enough amplitude (above 50% of the maximum amplitude) in all the displacement range.

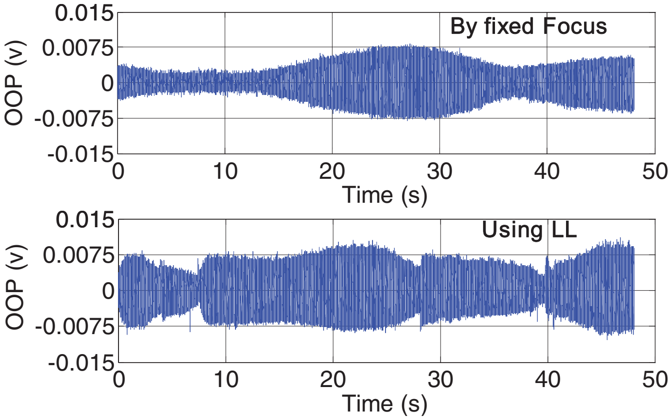

Fig. 6. Two acquired SMSs from a metallic surface displacement of 10 mm with different optical systems: one with fixed focal lens and the other by using the LL-based approach.

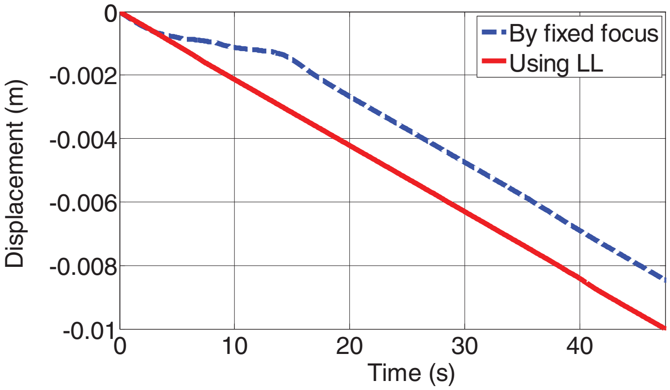

Fig. 7. Reconstruction of two acquired SMSs from a metallic surface displacement of 10 mm with different optical systems: one with fixed focal lens and the other by using the LL-based approach. Target displacement velocity was 0.0208 mm/s.

Fig. 7 shows the reconstruction of both SMS obtained using the fixed focus lens and using the adaptive optical head approach, using basic fringe-counting reconstruction algorithms [9] [14], so the target displacement was reconstructed with half-wavelength resolution. The expected speckle phase error for this experiment according to equation (3) is 1.3 μm considering the lens optical aperture of 2.3 mm and the target distance of 10 cm. Therefore, although amplitude fading was cured using the adaptive focusing approach, the speckle phase error stays within the signal. The effect of this phase error may be notably mitigated by increasing the target distance. For instance, reproducing the experiment with the target at a distance of 20 cm from the laser reduces the speckle phase error to 0.33 μm, below the basic resolution of the fringe counting technique (half-wavelength of the laser).

Signal reconstruction in the fixed focal length signal resulted in 14% error due to undetected fringes in fading zones.

IV. SENSOR DIVERSITY TECHNIQUE

In our second approach, two different LD pointing to the same target are used. Both LD are chosen so they present different speckle pattern effects, so the combination of both signals results in a lower probability of signal fading than when using one single LD.

This strategy, known as diversity, has been successfully applied in radio communication to deal with the fading effect [15]. The technique has been developed in the forms of spatial, spectral and temporal diversity. Similar to spatial and spectral diversities in radio engineering, we are proposing spatial diversity in the form of two SMLD pointing at different

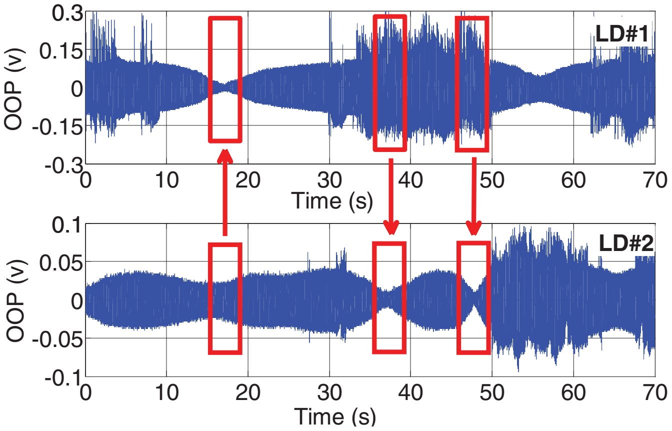

Fig. 8. Two SMSs acquired by two LDs with different focus positions (different spot sizes) pointing to the same target. Target displacement was 40 mm in this measurement.

points of the target with different spot sizes, together with spectral diversity using two SMLD with different wavelengths.

If we consider the probability of fading in the signal as the percentage of the faded signal to the whole acquired signal sequence, then the probability of fading or error probability (ep) in this strategy is below $ep_1 \times ep_2$ where ep_1 is the error probability in the signal of the first LD and ep_2 is the error probability in the signal of the second. Obviously, the error probability (ep) is always much less than the error probabilities in each individual LD signal, although not yet zero.

What is expected in both types of diversity is to avoid signal fading simultaneously for both signals. Fig. 8 shows the experimental SMS acquired using two LD pointing at two different positions of the target, for a target displacement of 40 mm from the LDs. The idea is of course using the other signal if signal fading occurs to one of them. Thus, the faded signals shown in selected windows in Fig. 8 are replaced with the data from the alternative signal for reconstruction purposes.

The algorithm proposed for this approach is shown in Fig. 9. Since the poor signal to noise ratio (SNR) in signal fading leads to unreliable reconstruction, the SNR value will be used to detect signal fading. To estimate the SNR value in the SMS, we apply the method used in SNR calculation of ECG signals [16].

Afterwards, reconstruction using fringe counting algorithm [9] is performed for each channel. Later, a decision block selects which signal reconstruction is more reliable based on the value of SNR of both signals. The reconstruction of the signal with higher SNR value is considered as the most accurate. In the offline application of this method, there is no significant limit on the target displacement velocity. As an experimental example, two laser sources with different wavelengths pointing to different positions on the target, as shown in Fig. 10, are used.

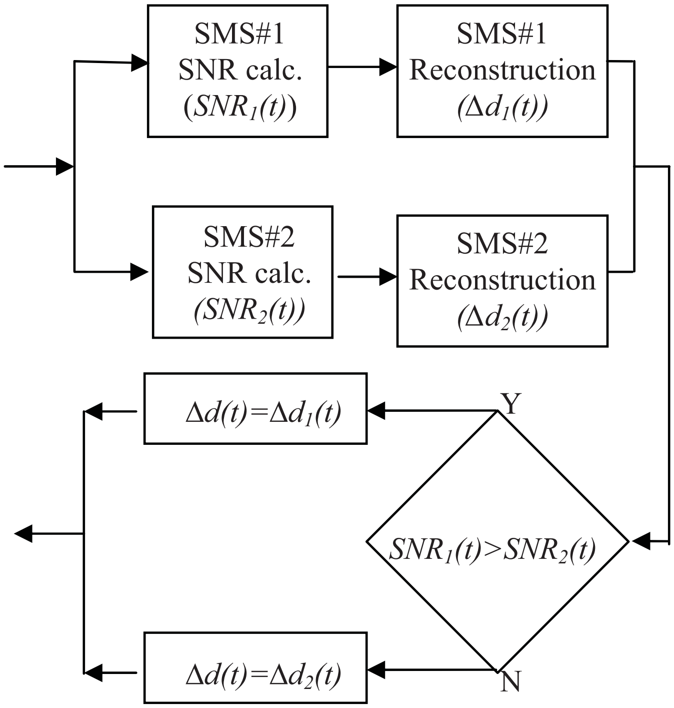

Fig. 9. Block diagram of the algorithm for sensor diversity technique.

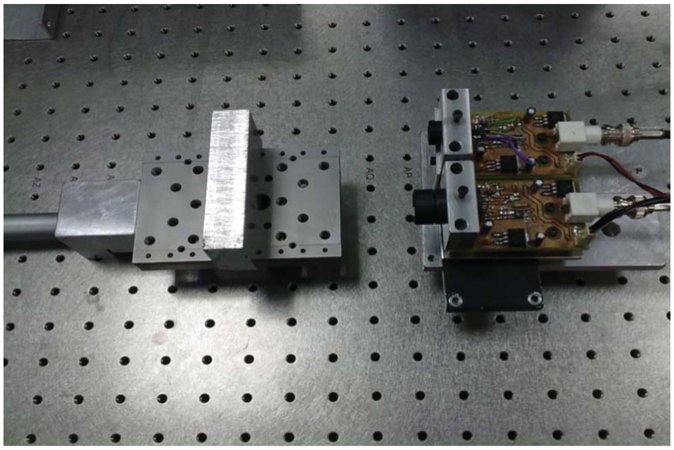

Fig. 10. Experimental setup for sensor diversity solution.

One of the lasers is a Hitachi HL7851G SMLD emitting at 793 nm and the other laser source is a VCT-F85A32-IS-V2 vertical-cavity surface-emitting laser (VCSEL) emitting at 843 nm with a maximum output power of 2 mW. The target is a metallic surface mounted on a DC motorized translator stage moved along 20 mm with a speed of 0.55 mm/s. The initial target distance from the lasers was 20 cm. The average FWHM of the SMLD spot on the target was 78 μm and the average FWHM of the VCSEL spot was 62 μm. Fig. 11 shows the experimental SMS acquired from both lasers. By applying the decision algorithm described in Fig. 9, the reconstructed displacement shown in Fig. 12 was achieved.

It may be seen how the reconstructed displacement obtained from the SMS of the SMLD had a 15.5% error, while the reconstructed displacement from the SMS of the VCSEL has 10.6% error along the complete displacement range. According to the equation (3), the expected speckle phase error for both signals was about 3.1 μm considering the lens optical aperture of 5 mm.

Using the proposed strategy, the displacement was reconstructed with no amplitude fading error in the whole

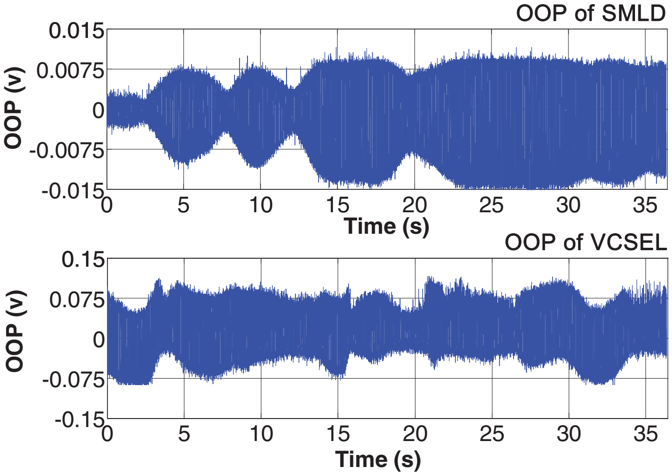

Fig. 11. SMS acquired from SMLD and VCSEL for the same target displacement of 2 cm with a speed of 0.55 mm/s.

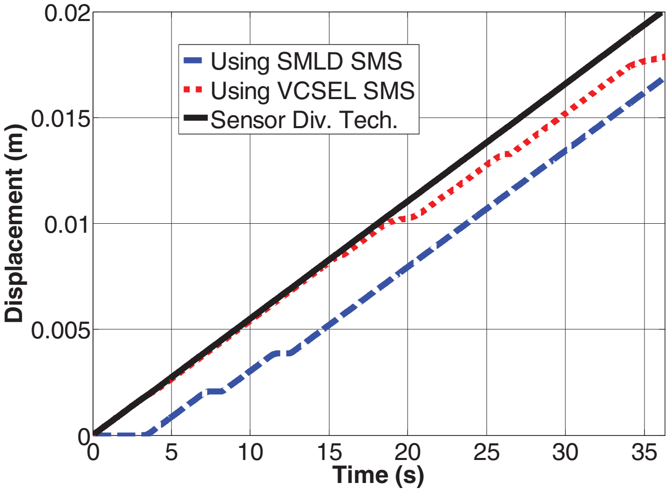

Fig. 12. SMS reconstruction for signals of SMLD and VCSEL using the sensor diversity technique.

displacement range, within the half-wavelength resolution imposed by the fringe counting algorithm used.

V. CONCLUSION

A detailed analysis of the amplitude fading effect induced by speckle in SMS signal has been presented. We have shown the coupling factor coefficient in SMS changes by speckle effect, yielding larger C values in the blackout regions, suggesting large hysteresis condition in that areas, and fringe-loss situations in the signal in addition to the complex reconstruction due to small amplitude SMS.

We have also shown how the modulation frequency of the speckle affected SMS depends on the average roughness parameter Ra, presenting how the number of local maxima present in a 40 mm displacement decreases when increasing Ra from 0.05 μm to 0.4 μm, while from 0.4 μm to 1.6 μm the number of maxima remains constant. Moreover, we have shown that changes in the spot size may modify the positions of both the maxima and the blackouts in the speckle affected SMS.

Two new methods have been proposed to improve measurements in self-mixing signals having blackout zones in a speckle affected SMS. One is using a LL as an adaptive solution to change the focal length of the lens, modifying the position of the blackout region. The proposed method cannot be used at large speeds as the LL has a slow time response. For larger speeds, we present a second approach in the shape of a sensor diversity technique which uses two lasers spatially and spectrally diverse to combine their two different SMS which present different fading zones. An SNR-based algorithm has been used to select the optimal signal of the two available ones to be used for displacement reconstruction. Experimental results in both methods show successful SMS amplitude fading management for centimeter-order displacements of a metallic target. The existent speckle phase error has not been cured with those techniques, but it introduces a displacement error of a few microns which can be significantly reduced by increasing the target distance.

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Reza Atashkhooei was born in Khoy, Iran, in 1977. He received the B.Sc. degree in applied physics from the Sharif University of Technology, Tehran, Iran, and the M.Sc. degree in photonics from the Universitat Politècnica de Catalunya, Barcelona, Spain, in 2001 and 2008, respectively. He is currently pursuing the Ph.D. degree in optical engineering at the CD6 Research Center, Centre for Sensors, Instruments and Systems Development, UPC, Terrassa, Spain.

His current research interests include vibration and velocity measurements for industrial applications, signal processing, adaptive optics, and optical metrology.

Santiago Royo received the M.Sc. degree in physics from the Universidad de Barcelona, Barcelona, Spain, and the Ph.D. degree in applied optics from the Universitat Politècnica de Catalunya (UPC), Barcelona, in 1992 and 1999, respectively.

He is currently an Associate Professor at UPC, where he is the Director of the Center for Sensors, Instruments and Systems Development (CD6), UPC, Terrassa, Spain, a research and innovation center in optical engineering with staff of 40 people, where as a Researcher, he leads projects on adaptive optics, 3-D imaging, and optical metrology, particularly wavefront sensing and self-mixing interferometry. He is a co-founder of a spin-off company of CD6, SnellOptics. His current research interests include adaptive optics, optical metrology, optical design and fabrication, and photometric testing.

Francisco J. Azcona (M'12) was born in Mexico DF in 1985. He received the B.Sc. degree in mechatronics engineering from the Universidad Panamericana, Aguascalientes, Mexico, in 2008, and the M.Sc. degree in mechatronics and micromechatronics systems from the École Nationale Supérieure de Mécanique et des Microtechniques, Besançon, France, in 2010. He is currently pursuing the Ph.D. degree in optical engineering at the Center for Sensors, Instruments and Systems Development (CD6), Universitat Politècnica de Catalunya, Barcelona, Spain.

His current research interests include robotics, computer vision, microelectromechanical systems, atomic force microscopy, and laser-based metrology systems.

Mr. Azcona was a recipient of the Research Scholarship FPI-2012 from the Generalitat de Catalunya.