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Adaptive autofocus technique for speckle control in optical feedback interferometry☆

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ABSTRACT

An adaptive autofocus technique for the control of speckle effect in optical feedback interferometry (*OFI*) is discussed. The beam spot size effect over the OFI signal is presented, justifying the proposed approach. An automated setup for the control of speckle effect using a liquid lens with electro-optical focusing is demonstrated. The spot size is modified according to the signal to noise ratio (*SNR*) bounds selected for the captured OFI signal, therefore avoiding signal fading caused by speckle effect and possible chaotic behavior because of strong feedback. The quality and shape of the acquired OFI signal when the spot size change takes place shows a transient oscillation without any additional effects over the OFI SNR and the OFI shape. Experimental examples are provided proving the effectiveness of the approach for speckle control in displacement and velocity measurements within a movement range of 20 mm.

1. Introduction

Optical feedback interferometry (*OFI*), also called self-mixing interferometry (*SMI*) has been extensively studied in the past decades [1,2]. It has been presented as a promising solution for the measurement of vibration, displacement, velocity and absolute distance in a wide variety of applications [3,4]. Optical feedback interference occurs when a portion of the laser beam is back-reflected from a target and partially reenters the laser cavity. The interference between the original and the back-reflected beams inside the laser cavity introduces modifications in the optical output power (*OOP*) of the laser, which normally may be observed using a monitor photodiode integrated inside the laser diode (*LD*) package. It follows that the typical OFI sensor includes just a LD package with a single lens for focusing the beam on the target. Compared to traditional double path and common path interferometry setups [5] the approach is simple, compact, self-aligned, and very cost-effective while still extremely sensitive as it is able to detect vibrations within the nanometer scale [1].

Whenever a laser beam is scattered from a target and interferes inside the laser cavity, an undesired random intensity variation may appear in the OOP because of speckle phenomena. Speckle is essentially a random superposition of the multiple beams scattered from a diffusive surface which interfere with each other producing a granular interference pattern. No significant speckle effect is appreciated in OFI signals for small target displacements (below 100 μm) since the spot size is typically optimized manually to yield a proper signal to noise ratio (*SNR*) and feedback level for the measurements. However, for displacements covering a range from a few millimeters to some centimeters, the amplitude of the OOP becomes randomly modulated by speckle, leading to frequent signal fading and signal loss [2]. Besides, a relatively small speckle phase error is also introduced in the signal, beyond the mentioned amplitude fading error. Because of speckle effect in OFI, the displacement measurement error has been found to be in the order of 10% [2], while the velocity measurement error lies around 3% for a wide range of velocities (from 5.2 mm/s to 479 mm/s) [6]. In the absence of speckle effect, the basic resolution in OFI is half-wavelength of the laser beam which may be improved to $\lambda/32$ (where λ is the wavelength of the laser) using the improved phase unwrapping method [7]. Thus, the considerable error caused by speckle effect hinders the behavior of OFI in long range displacement applications.

☆ This document is a collaborative effort.

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A number of solutions have been proposed to deal with the speckle noise issue. One of such approaches, known as bright speckle tracking, uses an in-plane piezoelectric positioning system [8] that moves the laser beam transversally (perpendicular to the beam axis) during the target displacement searching for a speckle spot with large OOP amplitude. An alternative method is the sensor diversity technique which employs two lasers spatially separated, but pointing at the same target [9], and which combines the OOP of the two lasers with different speckle patterns whenever any of the signals fades because of speckle. This technique reduces the probability of having errors caused by signal amplitude fading in most situations. Another approach proposes the use of an adaptive solution based on a liquid lens (LL) with electro-optical focusing [10]; in this technique, the focus point is moved along the displacement axis and, consequently, the spot size on the target is modified producing a proper level of feedback and OOP amplitude.

In this paper, we propose for the first time an automated version of the adaptive solution for speckle control, in which the OFI SNR is monitored and the LD beam spot size is modified to keep the signal within a proper range of values. The following section discusses the working principle of the proposed technique and an analysis of the spot size effect over the OFI signal. Section 3 describes the workbench used for the experiments, the effects on signal quality under focus changes and the control algorithm used in the depicted setup. Afterwards, in Section 4, a summary of the experimental results obtained by the proposed technique, which is compared with results obtained in a fixed focus approach OFI reconstruction. The final section addresses the main conclusions drawn out of this work.

2. Working principle

2.1. Concept

The intensity distribution of the light scattered from a diffusive target and its relationship to surface roughness has been characterized in the past [11]. Since the speckle amplitude modulation of the LD OOP under feedback has a random nature and is related to the surface roughness, the change of the spot size on the target is expected to modify the speckle pattern imposed over the OOP [9]. Thus, the control of the spot size may change the spatial distribution of the induced speckle pattern and, consequently, modify the OFI signal amplitude when it fades and reaches noise level.

Thereby, our proposal is to use an adaptive optical head (*AOH*) that uses a voltage programmable LL to change the focal length of the optical system, leading to spot size modification, when required. The adjustment of the feedback level and the coupling factor control using such an arrangement has already been shown in [10]. In Fig. 1 the experimental configuration of the adaptive head used in this technique is shown. As it is observed, the LD is attached to the AOH (in black) involving a fixed focal lens for collimation purposes and a LL whose focal distance can be modified by changing the voltage it has applied through its controller.

In order to use the optical head for the compensation of speckle effect, the amplitude of the OOP must be monitored in real time to introduce a change in spot size whenever the signal enters a fading region. Since the relative amplitude of the noise compared to the OFI signal amplitude may not be constant during the acquisition, specially when long displacements are involved, we propose the use of the OOP SNR instead of its amplitude as a gauge to detect signal fading. We define the OOP SNR as:

$$SNR_{OOP} = 20 \log \left(\frac{A_{SMI}}{A_{noise}} \right), \quad (1)$$

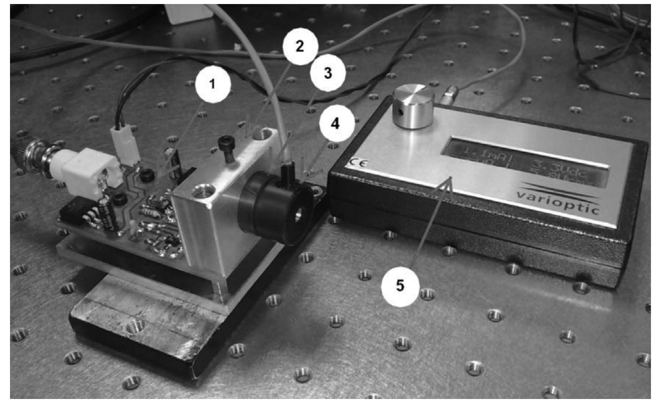

Fig. 1. Experimental configuration of the adaptive head; (1) electronic signal acquisition board, (2) metallic heat sync, (3) tube holding fixed focal length lens, (4) liquid lens, and (5) liquid lens controller.

where A_{SMI} is the peak to peak amplitude of the SMI signal and A_{noise} is the peak to peak amplitude of the electric noise measured in static target conditions.

Therefore, by controlling the OOP SNR, it may be possible to control the speckle effect on the OFI signal. Due to the similarities in shape between the LD OOP under feedback and the electrocardiogram (*ECG*) signals, it is possible to apply the SNR calculation method described in [12].

2.2. Spot size effect on signal amplitude

To test the effect of modifying the LD spot size over the speckle pattern, the OOP of a LD under feedback was measured for different spot sizes. During the experiment, a diffusive target is set into sinusoidal vibration with peak to peak amplitude of 5 μm, a frequency of 100 Hz and fixed at a distance from the optical head. When the measurements are carried out, the focus point of the system is moved from 35 cm to 7.5 cm in steps of 1 cm by changing the voltage applied to the LL. In Fig. 2, the changes in the mean amplitude

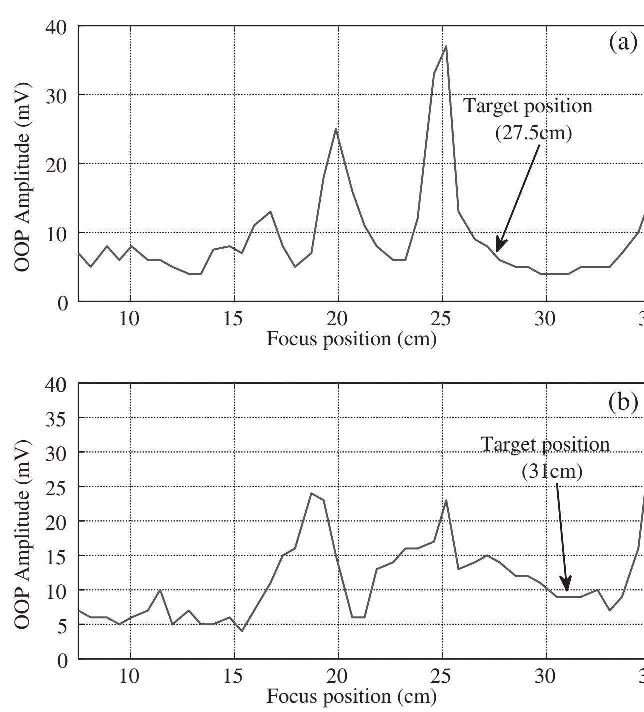

Fig. 2. OOP amplitude versus focus position for two different target distances.

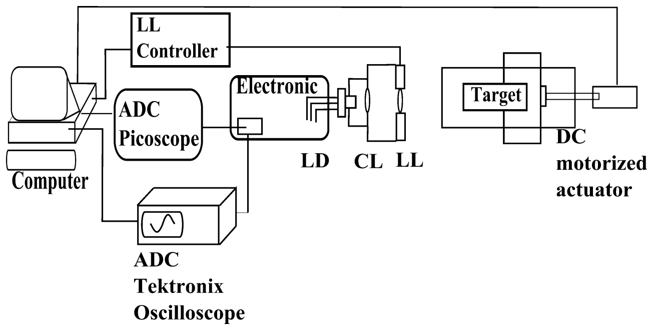

Fig. 3. Experimental configuration for adaptive speckle control.

of the LD OOP under feedback at two different distances from the target (27.5 cm and 31 cm), when the focus point is modified, are shown. Arrows indicate the points where the best focus position is coincident with the target, that is, the condition for minimum spot size.

The results show the random nature of the speckle effect. The experiment also shows the capability of modifying the amplitude of the OOP by changing the position of the spot size on the target. Signals with amplitudes below 10 mV become, in practice, faded by noise and the detection of fringe transitions in the OOP signal becomes complex. Hence, the spot size on the target should be controlled using an appropriate algorithm to keep the signal above 10 mV in order to obtain reliable measurements.

3. Experimental configuration

3.1. Measurement strategy

The experimental configuration for speckle control is shown in Fig. 3. The LD used is a Hitachi HL7851G LD emitting at 783 nm with a maximum output power of 50 mW. The target is mounted on a M-227.50 DC motorized piezo-actuator from Physik Instrumente (PI).

The collimating lens (*CL*) in the optical head is an aspheric lens with the focal length of 6.25 *mm* and the liquid lens (LL) is an ARCTIC 416SL V3 LL from Varioptic, with its controller connected to a PC by a USB2.0 connection. The control is implemented on a custom made C++ algorithm which uses the Varioptic controller as an interface to the LL.

Two different analog to digital converters (ADC) are used in the experimental setup. One of them, a Picoscope 4227 (PC oscilloscope), is used to acquire the OFI signal used as an input for the spot size control algorithm. The second ADC, a Tektronix DPO2024B oscilloscope, is used for measurement purposes. Both acquisitions must be performed on a separate ADC in order to avoid signal loss during the control stage. A time scheme of each ADC capture duration is illustrated in Fig. 4. In fact, the acquisition time (T_{acq}) and the transfer time (T_{Tran}) limit the speckle control algorithm to slow target displacements.

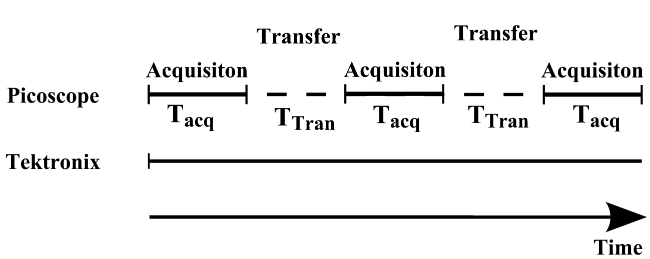

Fig. 4. Signal acquisition scheme by Picoscope and Tektronix oscilloscope.

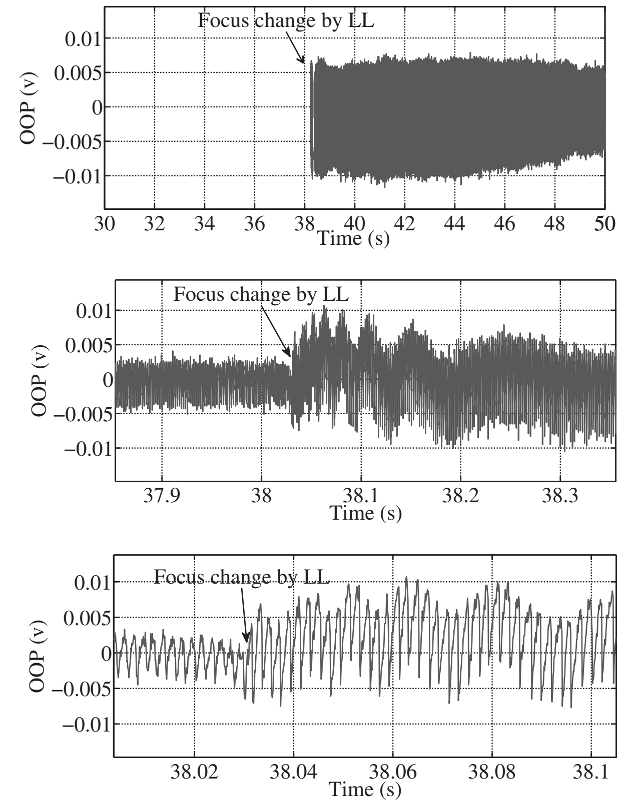

Fig. 5. Experimental OOP acquired for a target velocity of 0.2 mm/s. The signal is taken out of the speckle region by a change of the LL focus. From top to bottom: real time scale and the magnified scales. The magnified scales show a transient damped oscillation after a increase of 1 V in the LL.

With the current configuration, the maximum limit of the velocity of the target displacement is 0.2 mm/s. For the target velocities higher than this limit, we may have fading regions not detected in the control algorithm while data is being transferred.

The maximum limit of the target displacement range in this technique theoretically depends on the focusing range of the AOH (which is about a few meters), but in this work, with the current control algorithm, the measured displacement ranges in the experiments were in the order of a few centimeters.

3.2. Signal quality during the focus change

As described in Section 2, the focal point has to be changed during the target displacement to avoid getting into the signal fading regions. Also, it is necessary that no other effects (e.g. laser chaotic behavior, large stabilization transients or a change on the OFI working regime) have a significant impact over the OFI waveform. For this purpose, a test to confirm the effects of the LL focus change as well as the signal response time was performed.

According to the data provided by the manufacturer, the ARTIC 416SL V3 is capable of a response time below 500 ms [13]. The response time is defined, for this article purposes, as the time transient between two lens power steady states. The characterization of the lens showed that for a full range step response (0–60 V), the response time stayed below 80 ms.

The effect of spot size modification produced by the LL is analyzed through the changes in the acquired OOP as shown in Fig. 5. In the figure, the OOP amplitude and therefore its SNR (Fig. 6) decrease because of speckle effect. This is easily observed by comparing the relative amplitude of the SMI signal in the intervals between the seconds 30 and 32 s, and 36–38 s. After changing the input of the LL by 1 V, thus producing a variation of the spot size, the amplitude

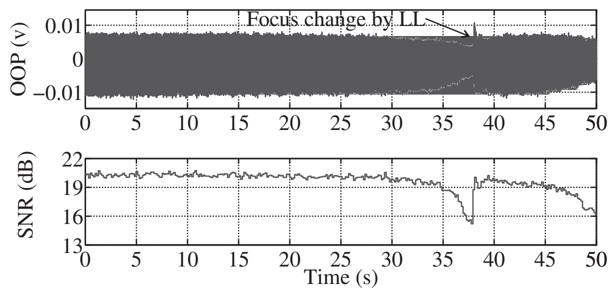

Fig. 6. Experimental OOP acquired for a target velocity of 0.2 mm/s. The OOP is sampled at 125 kS/s. SNR is calculated using a 2 kS average.

of the signal and the *SNR* are recovered. It is also observed that a damped oscillation that lasts about 200 ms is imposed over the OFI signal in the interval from 38.05 to 38.3 s. The faster fluctuations occur during the 80 ms interval (from 38.05 to 38.1 s) corresponding to the response time of the LL. Still, this oscillation provides a signal with sufficient *SNR*, therefore allowing a proper reconstruction of the target displacement. Besides the transient, no other additional effects are observed on the OOP signal.

3.3. Control algorithm

The block diagram of the proposed control algorithm is shown in Fig. 7. First, three parameters are initialized including the focal length of the LL (F_{LL}), the fail parameter (*Fail*) which is the number of times that the control algorithm has failed and N_f which is the number of focus changes by the LL. The focal point is varied whenever a SNR boundary is reached. The boundaries are defined by SNR_{thr} as the lower SNR limit, which is given by the LD OOP amplitude fading because of the speckle effect, and SNR_{up} as the SNR upper limit, which is given by the entry of the laser into chaotic regime.

After the target starts its motion, a sequence of OOP is acquired by the Picoscope and the SNR of the sequence is calculated. If the SNR lies between SNR_{thr} and SNR_{up}, then, the focal length is kept and the control loop restarts. Since there is no focus change nor a fail occurrence, the *Fail* and N_f parameters remain as zero.

If the SNR value crosses any of the thresholds, and depending on the N_f value, two possible paths may be taken. As long as N_f is less than N_m, which accounts for the maximum number of focus changes that can be performed to get back to a proper SNR within a reasonable time, the F_{LL} is increased by a small focal length difference defined as *dF*. After the focus change, the parameter N_f is increased by one unit and the control loop is re-started. Whenever N_m is reached the algorithm considers that it has failed, and it increases *Fail* value and sets F_{LL} into the initial focus condition.

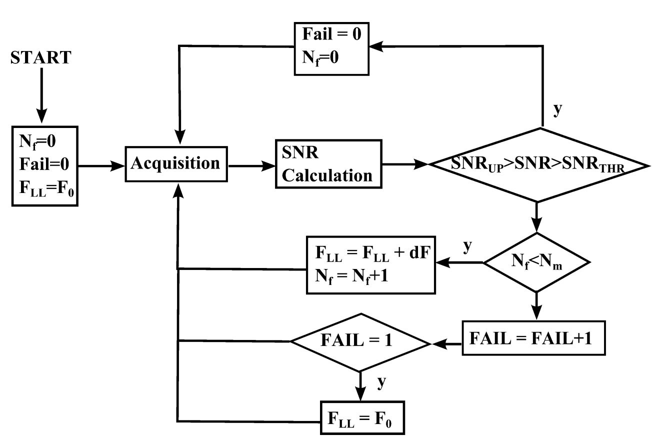

Fig. 7. Block diagram of the control algorithm.

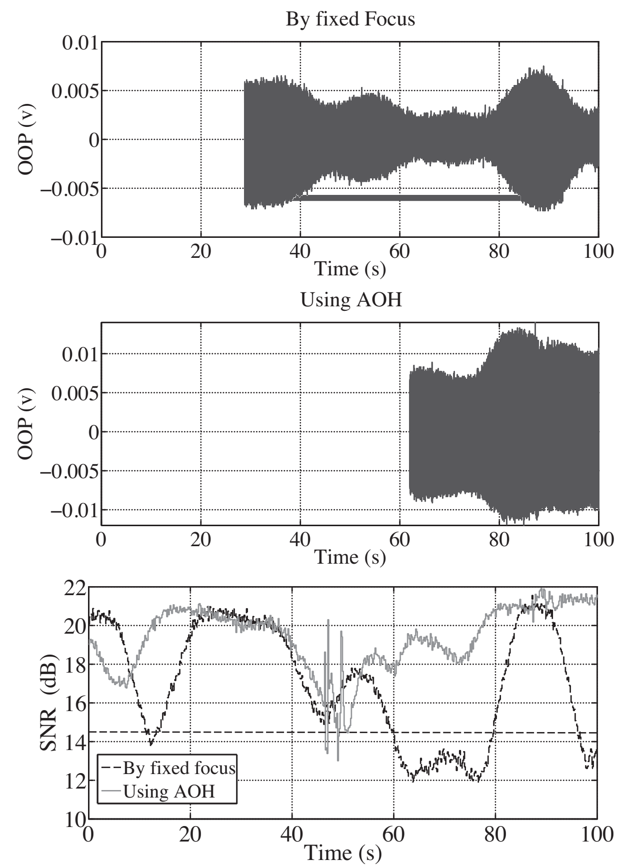

Fig. 8. Results obtained by fixed focus and by using spot locking control algorithm.

Some of the parameters in the adaptive speckle tracking algorithm require optimization prior to a proper measurement. Those parameters include SNR_{thr}, SNR_{up}, N_m, *dF* (LL focal length change) and T_{acq}, which is related to the velocity of target. In practice, we have found that using threshold values in the order of 15–25 dBs allow a simple processing of the OFI signal using the well known fringe counting method [14,15]. In most of the cases it was also observed that with this values the OFI signal was kept within the moderate feedback regime. The use of larger SNRs typically derived either in entering the strong feedback regime, in which the signal transitions are typically small compared to the maximum amplitude of the signal, or eventually result in chaotic laser behavior. Lower SNR values usually mark signals that cannot be directly processed by a fringe counting algorithm without further processing. Lower SNR can also introduce limitations in signal capturing because of quantification limits in the capturing device.

4. Experimental results

The experimental results show how the proposed adaptive autofocus technique can improve the SNR of the OOP signal when it falls into a fading region during a large target motion. For this purpose, the experimental configuration described in Section 3 was assembled and the LL was controlled using the adaptive algorithm proposed in the previous section.

In Fig. 8, two acquired OOP signals are shown; both signals correspond to a target displacement of 20 mm and a velocity of 0.2 mm/s. The top graph presents the OFI signal corresponding to the displacement described above when a fixed focus is applied. As expected, the speckle effect can be easily observed as a modulation throughout the measurement span. The middle graph is obtained using the adaptive control algorithm with the following values T_{acq} = 40 ms,

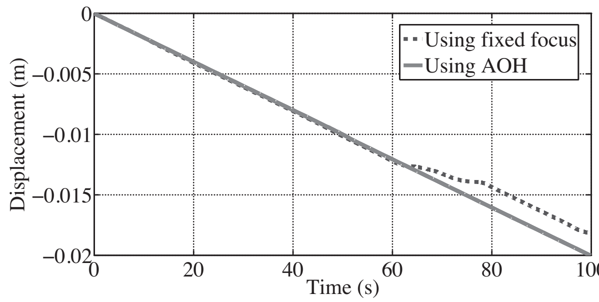

Fig. 9. Displacement reconstruction of two acquired signals for a metallic target displacement of 20 mm by two optical systems; one with fixed focus and the other using spot locking control algorithm. The difference is about 1.760 mm (8.8%) for a 20 mm displacement.

$N_m = 5$, $dF = 1$ cm, $SNR_{up} = 25$ dB and $SNR_{thr} = 14.5$ dB. As it is depicted the speckle is reduced. Finally a comparison between both SNR values during the measurement time span is shown. As seen, the SNR of the signal obtained using the AOH kept the SNR within the proposed values. As it is observed, in Fig. 8, none of the signals are close to the 25 dB upper threshold. In the case of the lower threshold represented by the dotted gray line, it is observed that the method using the AOH reacts to the signal decrease around $t = 46$ s and $t = 50$ s, after that a gradual increase of the SNR is observed. In the case of the fixed focus signal, it is observed that the lower threshold is crossed at several points of the graph ($t = 15$, the interval from $t = 60$ to $t = 80$ and $t = 90$ s), therefore causing an information loss.

The displacement reconstruction of both signals is illustrated in Fig. 9 showing a successful recovery only in the case where the control algorithm is applied. Both signals are reconstructed applying the fringe counting algorithm leading to $\lambda/2$ resolution.

As described in [9], this technique cannot eliminate the speckle phase error which is in the order of a few microns from the reconstructed displacement. However, the phase error can be significantly reduced by increasing the sensor distance to the target. The error achieved by the fixed focus signal is about 1.760 mm corresponding to 8.8% of the total target displacement. This error is in agreement with the range of the displacement measurement error caused by the speckle effect (10% in total displacement range) achieved in [2].

As an additional test to prove the effectiveness of the proposed technique, a velocity measurement was carried out. Given that the amplitude modulation caused by the speckle effect can decrease the accuracy of the target velocity measurement [6], then using the adaptive speckle control should improve the velocity measurements accuracy through out the displacement range. In Fig. 10 the measured velocity of the target during the displacement is shown. The velocity (v) is related to the Doppler frequency (fd) by:

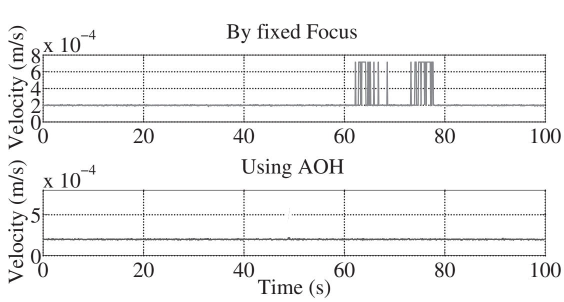

Fig. 10. Target velocity measured by fixed focus and the adaptive speckle control. The total sequence corresponds to 1.25 MS, which was divided into windows of 5 kS for FFT analysis.

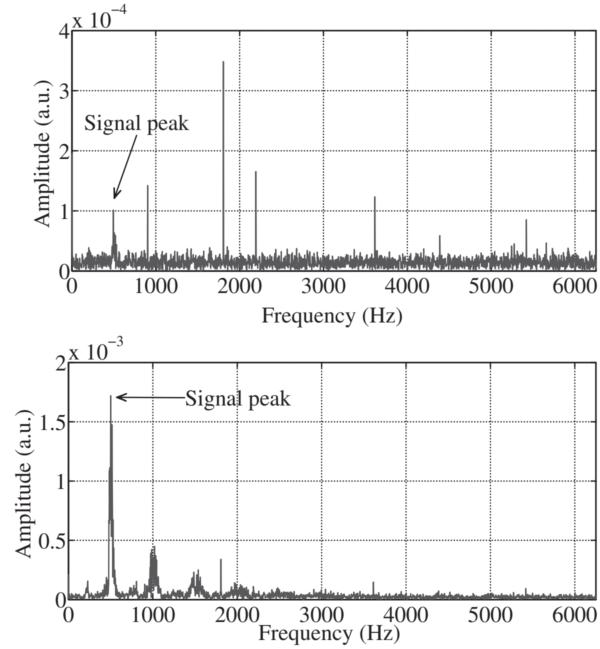

Fig. 11. Fourier spectra of OOP signals with low and high SNR. On top, the FFT of an OOP signal sequence with a low SNR. On bottom, FFT of an OOP signal sequence with a high SNR.

$$v = f_d \frac{\lambda}{2}. \tag{2}$$

The Doppler frequency is calculated by applying the FFT to the OOP and finding the frequency corresponding to the maximum magnitude [16]. A band-pass filter was also applied to both OFI signals to remove high frequency noise and low frequency effects over the OFI signal. As it can be observed in the top graph of Fig. 10, there are some error points in the velocity measurement with the fixed focus system which can be attributed to the speckle effect. In the bottom, which corresponds to the measurement performed with the adaptive control system, the errors on the velocity measurement have disappeared and corresponds to the 0.2 mm/s velocity described.

In Fig. 11 top, the FFT of the OOP OFI signal at an error point for a rectangular window of 5kS and with a SNR below SNR_{thr} is shown. As it is observed, the magnitude of a high frequency noise prevails over the frequency correspondent to the Doppler frequency. We consider that the error introduced by the noise is too high to be considered within the standard deviation reproducible with an OFI method, which for the amount of points and the sampling frequency used is close to 2 μm/s, thus at least an two orders of magnitude lower than the obtained difference. Doing the same FFT analysis on a signal with a SNR within the adaptive algorithm values described above, Fig. 11 bottom, it is possible to recover the Doppler frequency, and therefore obtain the corresponding velocity within the accuracy of the OFI method.

5. Conclusions

We have shown how the amplitude of the LD OOP under feedback can be randomly modified by changing the LD spot size for small displacements because of the speckle effect. Consequently, the speckle effect can also affect the SNR even for small displacements.

We have experimentally demonstrated the concept of an adaptive autofocusing technique enabling an optical feedback interferometer to be used for the measurement of displacement and velocity in long range motions. The effect of the LL focus change on the signal quality and the SNR value during the target displacement have been experimentally investigated and shown no additional effects on the signal.

Experimental results show the effective control of speckle effect. In the studied cases, the amplitude fading was eliminated and the SNR was kept between the thresholds for a correct signal reconstruction. Successful performance of the technique has been experimentally demonstrated for a displacement range of 20 mm with a maximum target velocity of 0.2 mm/s which is our current setup limit. The maximum limit of the target displacement range in this technique theoretically depends on the focusing range of the AOH. Thus, integrating adaptive autofocusing technique in OFI allows the sensor to be used in a long range of applications when large displacements are present keeping the resolution of the sensor with no additional inaccuracies.

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