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Improving Laser Feedback Interferometers Robustness Against Speckle Using Multiple Acquisition Schemes

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Abstract—This paper presents recent experimental developments in the field of interferometric sensing for displacement and/or velocity using Laser Feedback Interferometry (LFI). We demonstrate that the different acquisition schemes of LFI sensors (external photodiode and laser junction voltage) are subject to different speckle patterns and as a consequence the signal fading induced does not affect both signals simultaneously. We show that this effect largely depends on the laser to target distance. Since the speckle fading leads to incapacity to fringe detection or uncertainty in the computation of the Doppler frequency, the simultaneous acquisition of both laser voltage and in-package photodiode is a major advantage of LFI with regards to a large range of sensing applications.

Index Terms—Interferometry, laser sensor, vibrations, velocity

I. INTRODUCTION

Laser Feedback Interferometry is a not so exotic interferometric configuration where the laser light that is backscattered from a remote target is reinjected inside the laser cavity where the interference phenomenon generates a modulation of the laser emitted power as well as its frequency [1]. This modulation appears in general as periodic interferometric fringes where each fringe represents an equivalent displacement by half the laser wavelength λ . Thus, LFI sensors are most of the time implemented to monitor vibrations [2] or velocity [3] two types of applications where the detection and counting of each fringe is a condition to a proper estimation of the displacement. However, just like most of coherent light-based sensing methods, the LFI sensing scheme is subject to strong variation of the fringe amplitude due to dark speckle spot where very little light power is backscattered towards the laser cavity. In the worst cases, it results in detection losses, but in milder cases, it may as well impact the signal reconstruction when a resolution beyond the half-wavelength is expected. Although the observation of the interferometric fringes through

the laser wavelength variation exhibits interesting features in particular with regard to the signal-to-noise ratio (SNR) [4], [5], the most common acquisition method to observe these fringes is through the power variation. In general, this one is collected with an in-package photodiode (the monitoring photodiode) but it has been proposed to use directly the amplified laser junction voltage variation as an alternative [6]. The monitoring photodiode can be mounted facing the rear mirror of the laser in the case of edge-emitting lasers, but in the case of Vertical-Cavity Surface-Emitting Lasers (VCSELs) the photodiode is mounted side-by-side with the laser diode and it collects the light reflected on the protection glass of the case (see Fig. 1).

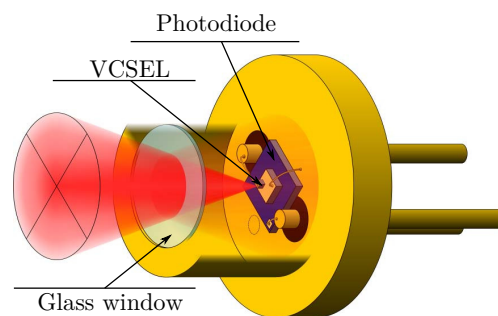


Fig. 1. Packaging a VCSEL with a monitoring photodiode. The light collected by the photodiode is the laser emission reflected on the glass window. Courtesy of [1]

We have recently observed that in this configuration, the photodetected amplified current and the amplified laser voltage are subject to different speckle patterns for reasons that are not yet completely understood. In this paper we expose our recent findings with the following approach: section II briefly presents the theoretical background and details the impact of

reflection fading induced by the speckle on the LFI signals, section III details the experimental setup and presents the experimental outcomes, while the section IV discusses the plausible origins of this phenomenon and the way it could be used to increase the robustness of LFI sensors with regards to speckle.

II. THEORETICAL BACKGROUND

The power P_F of a laser diode subject to optical feedback from a distant scatterer is modulated as

$$P_F(t) = P_0 [1 + m \cos(\phi_F(t))], \quad (1)$$

where P_0 is the laser power without feedback, m is a modulation index and $\phi_F(t)$ is a phase term which contains the phase difference between the laser inner cavity field and the back-scattered one. In the case of a vibration sensor, we can express this phase term as

$$\phi_F(t) = \omega_F \tau_{\text{ext}}(t), \quad (2)$$

where ω_F is the laser electric field angular frequency when it is subject to optical feedback, and τ_{ext} is the round-trip time of flight in the so. called external cavity between the laser and the distant scatterer. In the configuration of velocimetry for translating target, the phase term ϕ_F is linked to the Doppler frequency shift f_D so that

$$\phi_F(t) = 2\pi f_D t + \phi_D, \quad (3)$$

where ϕ_D is a constant phase term.

In the context of this study, the most interesting parameter in (1) is the modulation index that expresses the amplitude of the fringes and that can be expressed as [7]

$$m_0 = 4 \frac{\tau_p}{\tau_{\text{in}}} (1 - r_2^2) \frac{r_{\text{ext}}}{r_2}, \quad (4)$$

where τ_p and τ_{in} are the photon lifetime and the round-trip time of flight in the laser cavity respectively, r_2 is the reflectivity in field of the cavity front mirror and τ_{ext} is the ratio between the amplitudes of the field reentering the laser cavity and the one initially outgoing from it. The parameter r_{ext} takes into account numerous optical parameters: target reflectivity, absorption in the external cavity, coupling with the cavity waveguide but it is also impacted by the speckle induced by the roughness of the target. Considering the speckle introduces a modulation of the parameter $r_{\text{ext}} = s(t) \cdot r_{\text{ext},0}$ where $s(t)$ is a time varying coefficient ranging [0,1], we can express the modulation index m as

$$m(t) = s(t) \cdot m_0, \quad (5)$$

where m_0 is the modulation index in a hypothetical absence of speckle. Once introduced in (1), the speckle fading parameter $s(t)$ expresses the amplitude modulation in the interferometric signal:

$$P_F = P_0 [1 + s(t) \cdot m_0 \cos(\phi_F)]. \quad (6)$$

III. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 2. It is simply constituted from a VCSEL type laser diode (TT Electronics – OPV310) that emits light at 850 nm that is mounted in a collimation tube with a collimation lens (Thorlabs – C240) to perform focus on a rotating target located 50 mm away. The target is a 100 mm diameter metallic disc with a rough surface that causes the speckle effect. The rotation is ensured by a DC motor (Faulhaber – 2657w012) with a 43:1 reduction. The rotation axis is tilted by angle θ of $\sim 10^\circ$ from the optical axis and the laser beam hits the disk at about 45 mm from the rotation axis ensuring a Doppler shift of $f_D = 5$ kHz.

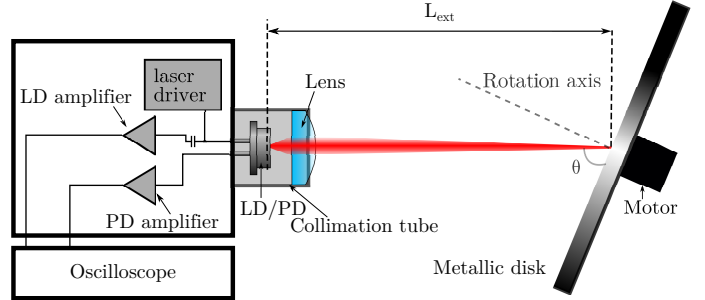


Fig. 2. Experimental setup description – Top view
The laser source (LD) and the monitoring photodiode (PD) are mounted in the same TO can. The laser focus is located on the disk 45 mm away from the rotation axis.

The VCSEL is mounted in a standard TO-can (Transistor-Outline-can) with a flat window and a monitoring photodiode. A custom-made circuit realizes the laser driver, the amplification of the laser junction voltage and the transimpedance amplification of the monitor photodiode. Both amplified signals are fed in an oscilloscope with a 62.5 MHz sampling rate to perform synchronous acquisition. The laser diode is biased at 5 mA (roughly 3 times its threshold current) that correspond to the best possible compromise for the SNR of both acquired signals [8]. After acquisition, the signals filtered with a Butterworth band-pass filter [1 – 10 kHz] in order to reject most of the electrical noise. The cut-off frequencies of this filter have been chosen so it removes as much noises as possible without affecting the fringes amplitude which frequency is very stable between 4-6 kHz. Fig. 3 presents typical signals after filtering where very visible speckle fading can be observed on both channels. To enhance the visibility of the speckle modulation, upper and lower envelopes have been plotted (in red and orange solid lines respectively). While in most of the cases, the speckle fading is consistent between LD and PD signals (at 9 or 11 ms for example) there are also fading events that cannot be observed on the two signals simultaneously. For example, in Fig. 3 between 13 and 14 ms, the laser voltage signal experiences a fading that is not observed for the photodiode signal.

In order to evaluate the occurrence of such an unbalanced phenomenon, we have computed the upper and lower envelopes of both signals. The difference of upper to lower envelope represents the peak-to-peak amplitude of our signal. For the same

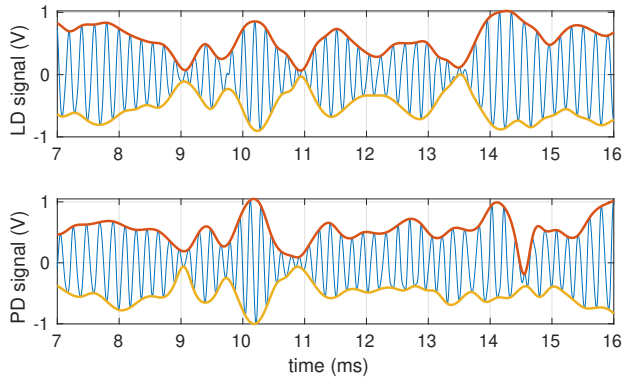


Fig. 3. Filtered laser voltage signal (top plot) and monitor diode signal (bottom plot) with upper envelop (red solid line) and lower envelop (orange solid line).

sample that were plotted in Fig. 3, Fig. 4 presents the evolution of the peak-to-peak amplitude of both signals divided by their average value. In other terms, it represents the speckle fading parameter $s(t)$ as described in (6). Again, we can observe that the fading parameter of the laser voltage signal does not evolve coherently with the one of the photodiode signal.

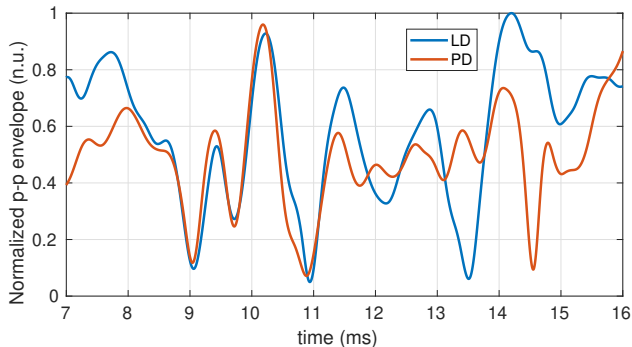


Fig. 4. Peak-to-peak envelope of the laser voltage signal (blue solid line) and the monitor diode signal (red solid line) normalized over their respective average value.

In order to estimate the incoherence of both fading speckle figures, we have set an arbitrary condition of $s(t) < 0.2$ where one can imagine the fringe detection algorithm would reveal much less efficient as compared to the case of $s(t) = 1$ that corresponds to an absence of speckle fading. We define the periods where this condition is reached as “blind zones” and thus we evaluate the ratio of time for which the sensor would be blinded due to speckle fading. In the experimental conditions described in section III, the proportion of “blind zones” for the laser voltage amplified signal (LD), the monitor photodiode signal (PD) are given in table I, both being around 15-20%. These proportions have been computed over 5 different acquisitions of 200 ms duration thus each counting for about 1000 fringes. When using both channels and considering the sensor is actually blind only when the above-mentioned condition is reached for the two channels (LD+PD) simultaneously, the rate

of “blind zones” drop to 6% thus realizing an improvement by ~ 3 times on the ability of the sensor to operate. In order, to consider other experimental conditions, we have performed the same measurement at different target velocity and thus Doppler frequency shift. Table I presents the different values computed at three different frequencies (5, 10 and 25 kHz). As can be seen and although there are dispersion in the blind zone proportion of each sensing scheme, the combination of both LD and PD acquisition provides a significant improvement in the sensor robustness to speckle fading.

TABLE I
RATIO OF “BLIND ZONES” FOR DIFFERENT DOPPLER FREQUENCY SHIFTS

Doppler frequency	LD	PD	LD+PD
5 kHz	19.47%	15.64%	6.17%
10 kHz	26.25%	24.57%	11.36%
25 kHz	30.71%	26.20%	11.76%

IV. DISCUSSIONS

The fact that the laser voltage signal and the monitoring photodiode exhibit different speckle fading is of great interest for many sensing applications that requires fringe detection and counting. For these applications, the fringe detection algorithm is very sensitive to the amplitude of the fringes with regards to the noise floor. In addition, for most of the algorithms, the coupling coefficient C shall remain in a limited range as it affects the sawtooth-like shape of the fringes [9]. It is interesting to note that the potential improvement in the ratio of “blind zones” strongly depends on the algorithm robustness to speckle fading. The results displayed in Table I have been computed while considering a condition of fringe visibility at 20%, however, this parameter is dependent on the algorithm performance and our results show that while a lower condition leads to better improvement while using laser voltage and monitoring photodiode signals. Considering the gain in visibility as the ratio between the average “blind zone” rate of LD and PD separately over the “blind zone” rate of LD+PD, Fig. 5 show the evolution of the improvement with the condition with a very significant improvement at very low condition.

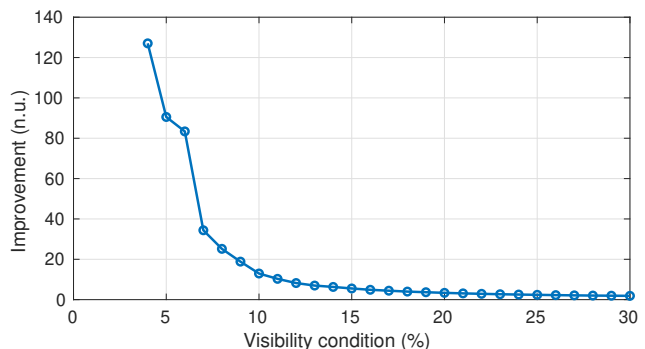


Fig. 5. Evolution of the improvement in visibility as a function of the visibility criteria (ratio between max fringe amplitude and minimum visible amplitude)

In addition, Donati *et al* [10] recently proposed to use both an internal and an external photodiodes to enhance the SNR of the sensor leading to an 8 dB improvement as compared to one single acquisition source. It would be interesting to see if in this configuration the two photodiodes are subject to similar speckle patterns. As for the origin of the phenomenon observed here, at that stage of our study, we can only propose explanations with no further validation. In the configuration described in Fig. 1, the light collected by the photodiode is mostly the laser emitted light reflected on the glass window. However, a small portion of the backscattered light from the target will be collected too. In general, the amount of light coming from the target is considered neglectable with regards to the one reflected by the window. We believe that, in case of short external cavities and with sufficiently cooperative targets, the direct contribution from the target could impact the speckle figure especially since the photodiode and the laser cavity are located at different position so they “observe” the distant target from slightly different angles leading to different speckle figures. If this hypothesis is correct, then varying the length and the reflectivity of the external cavity should impact the coherence of speckle fading for both signals. This analysis will be carried out in further studies. Others parameters of the target could also impact the improvement provided by the combination of both acquisition schemes : the target surface rugosity, the nature of the displacement (translation rather than rotation), etc... These aspects will be similarly addressed in further studies.

CONCLUSION

We have presented recent results showing that for a laser feedback interferometer, the speckle fading is not the same on the laser’s amplified junction voltage signal and from the monitoring photodiode signal when this one collects the light reflected on the glass window of the laser package. As the occurrence of conjugated severe fading on both signals is rarer than the severe fading for one single signal, we demonstrated that using both signal acquisitions can lead to a major improvement in the resilience of the laser to the speckle. However, the origins of these phenomenon are not entirely revealed and further studies will have to be carried in order to validate the hypothesis that we propose.

ACKNOWLEDGMENT

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