Sensors and Actuators A 216 (2014) 243–248

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Adaptive autofocus technique for speckle control in optical feedback interferometry☆

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ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form 2 June 2014
Accepted 3 June 2014
Available online 12 June 2014

Keywords:
Adaptive measurements
Displacement sensor
Feedback control
Self-mixing interferometry
Speckle effect
Vibration measurement

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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http://dx.doi.org/10.1016/j.sna.2014.06.003
0924-4247/

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:

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

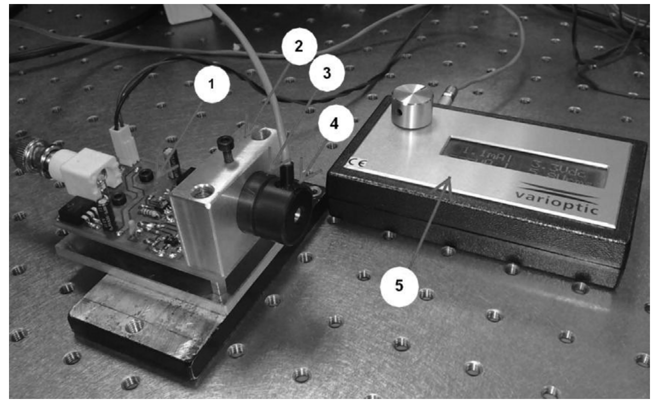

Fig. 1. Experimental configuration of the adaptive head; (1) electronic signal acquisition board, (2) metallic heat sync, (3) tube holding fixed focal length lens, (4) liquid lens, and (5) liquid lens controller.

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

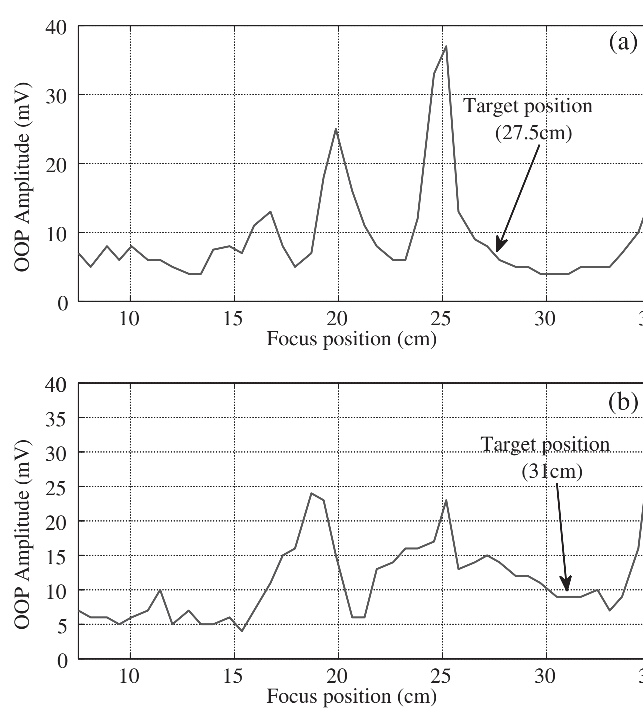

Fig. 2. OOP amplitude versus focus position for two different target distances.