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Invited Paper

Self-mixing digital closed-loop vibrometer for high accuracy vibration measurements

Alessandro Magnani, Dario Melchionni *, Alessandro Pesatori, Michele Norgia

Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Via Ponzio 34/5, Milano, Italy

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ABSTRACT

The novelty of Self-mixing interferometry is represented by the combination of high accuracy and contactless operation with compact, very-low-cost and user-friendly setup. This paper introduces state of the art techniques to monitor vibrations focusing on a novel digital feedback vibrometer. It exploits a control loop to delete interferometric signal distortion and improve measurement accuracy. A digital implementation is proposed to enhance system performances through a real-time elaboration.

1. Introduction

Over the last few years self-mixing Interferometry has taken hold as convenient alternative to other well-established optical measurement techniques [1]. In particular, it takes advantage of the physic phenomenon of Interferometry, extensively used in many fields, but through an innovative configuration. Its characteristics such as contactless, low-cost and high-resolution, allow implementing novel kinds of systems dedicated to dimensional measurements [2,3]. This paper describes the development of different instruments exploiting the self-mixing interferometry; the first two are vibrometers operating in open-loop mode, which allows spatial resolution down to about 100 nm over an unlimited spatial range. The third instrument is another kind of vibrometer, based on close-loop technology, which guarantees spatial resolution down to few nanometers, high linearity, but operating on a dynamic range limited to about 100 µm. All the developed instruments have been studied, designed and implemented in real-time electronic devices, providing the measurement data on analog or digital output.

2. Self-mixing interferometry

Pioneered by Donati [4] and established for laser diode in 1980 by Lang and Kobayashi [5], self-mixing interferometry (SMI) represents an interferometric setup very simply with respect to the common ones. Fig. 1 shows the basic scheme of the interferometer. The light source is a laser diode that focuses the light beam on a remote target with arbitrary surface. After a round trip path equal to $2D$, the back-reflected light partially falls back into the laser cavity, inducing an optical interference with the local light.

In other words, the self-mixing effect is a sort of homodyne detection [2,3]. This phenomenon induces an amplitude and frequency modulation of the electric field inside the laser diode: the amplitude modulation is typically measured by the integrated monitor photodiode. This is the main technique to detect self-mixing signals, but it is not the only: as shown in [6,7], it is possible to read the classical fringe signal also monitoring the small voltage signal across the laser diode junction. This last technique exhibits a lower signal-to-noise ratio and therefore, when possible, the photodiode solution is preferred.

The optical setup is easy to implement, because the only requested optic is a collimating lens, and there is no need for any other external optic components, such mirrors or beam splitter.

The typical self-mixing signal consists in as a series of fringes over the optical power, as described by (1):

$$\Delta P_{opt} = P_0[1 + mF(\varphi)] \tag{1}$$

in which P_0 is the nominal output power, $F(\varphi)$ is a periodic function of $\varphi = 4\pi D/\lambda$, with spatial period half wavelength $\lambda/2$, and m is the modulation amplitude. The shape of $F(\varphi)$ depends on the optical feedback level, measured by the C parameter [3].

Fig. 2 shows some self-mixing signals corresponding to sinusoidal target displacement, for different C levels. The laser

* Corresponding author.
E-mail address: michele.norgia@polimi.it (M. Norgia).
URL: http://home.deib.polimi.it/norgia/ (M. Norgia).

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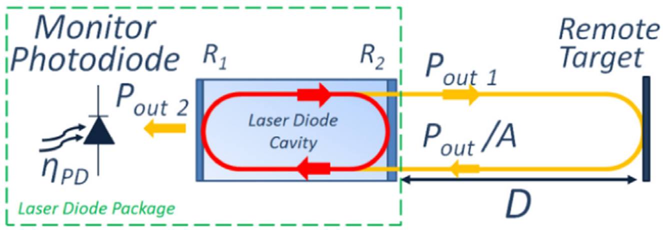

Fig. 1. Basic scheme of a self-mixing interferometer.

wavelength is about 780 nm, and the peak-to-peak vibration amplitude is about 6 μm. At low back-injection level ($C \ll 1$), the signal is nearly sinusoidal, while increasing the optical feedback it becomes sawtooth-like ($C=1$) and exhibits hysteresis ($C>1$).

For all feedback conditions, a single fringe indicates a target displacement equal to $\lambda/2$: the easiest way for measuring target displacement consists in counting the fringes [8,9].

2.1. Measurement applications

In this paper, we focus on the vibrations measurement, but SMI is suitable for very different measurement applications. Historically, the first applications were speed and displacement measurement [4,10,11]. Different techniques were developed for improving the accuracy [12,13] or fixing the problems due to the speckle effect [9,14,15]. The speed measurement technique was applied also to fluids, for flow-measurements [16–20], realized also with array of sensors [21]. Another relevant research topic is the absolute distance measurement: through a modulated SMI it is possible to implement a coherent technique for distance measurement [22–25], with potential high-accuracy and absolute insensitivity to ambient light [26]. This technique was able to measure a liquid level, directly on the water surface [27]. The self-mixing effect was employed also for measuring laser parameters [28–30]. The SMI applications range between scientific, industrial and also biomedical ones [31,32], and nowadays, the SMI technique is ready for commercial applications, as demonstrated by the mouse sensor twin-eye [33] by Philips. The subject of this paper is the measurement of vibrations through self-mixing interferometry, in the literature a deep attention was devoted to this topic [12,34–37].

3. Vibration measurements

Starting from the SMI signal, there are different techniques to reconstruct the target vibration, also operating in real-time. We can distinguish between open-loop and closed-loop techniques. The first ones are based on signal elaboration that reconstructs the vibration directly from the fringes signal, without any electronic feedback. The second ones employ a feedback to the laser pump current, in order to lock the SMI in a fringe center. In this paper, we propose for the first time a digital feedback loop, able to fix different problems of the analog version [34,35].

3.1. Open-loop techniques

The easiest way for measuring vibrations consists in counting the sharp transitions of the self-mixing signal for good optical conditions ($C>1$) [8]. In this condition we can take advantage of the fringes linearity, and realize a sort of signal unwrap, as proposed by different authors [9,12,13]. Fig. 3 reports an example of signal reconstruction, realized in real-time through a DSP (Digital Signal Processor), which recognizes the sharp transitions and assigns to each one a value $\lambda/2$. The movement between transitions is obtained by the signal itself, through a simple rescaling to $\lambda/2$.

For weak optical feedback ($C<1$), the main difficulty is estimating the movement direction. Recently, two techniques were proposed, one in the time domain [13] and one in the frequency domain [38,39].

In the time domain, it is possible to estimate the movement direction by looking at the fringes distortion, measured by their

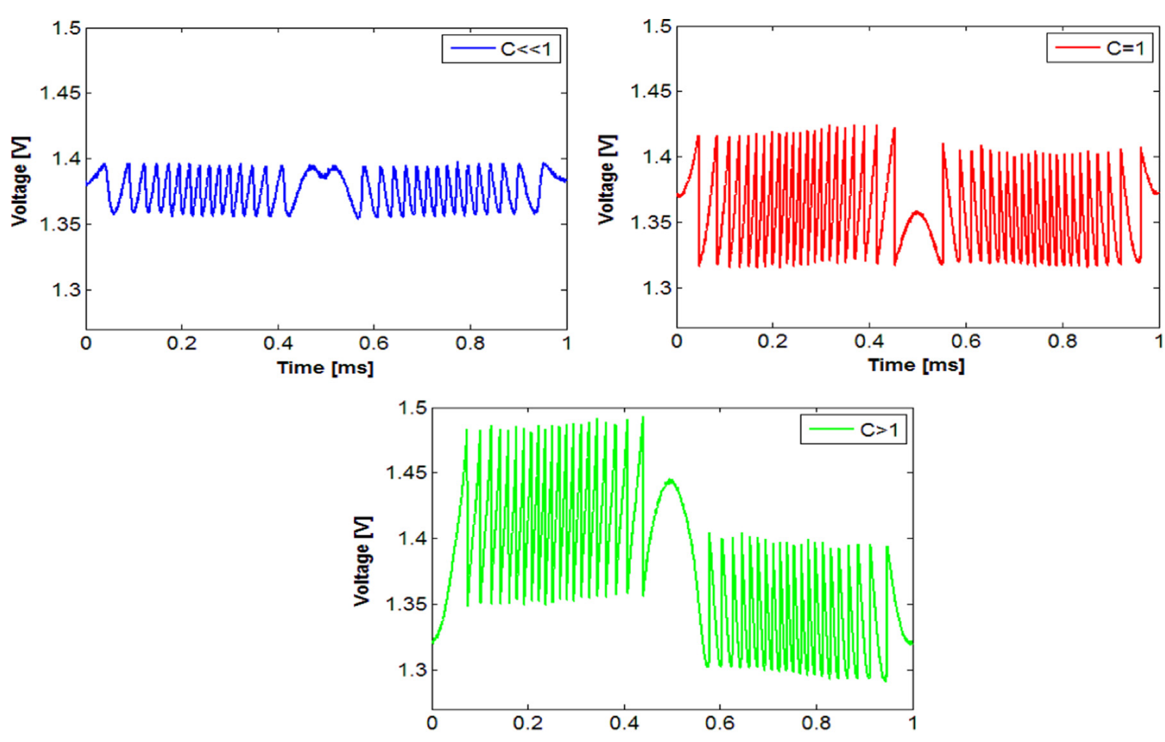

Fig. 2. Self-mixing signal in correspondence to a sinusoidal displacement, as a function of C.