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A new method for the acquisition of arterial pulse wave using self-mixing interferometry ☆

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In this paper we present a technique based on self-mixing interferometry as a method for the acquisition and reconstruction of the arterial pulse wave. A modification of the classic fringe counting reconstruction algorithm is proposed to deal with some of the problems caused by biological tissue surface roughness, therefore allowing a reconstruction of the arterial displacement with a resolution of 400 nm. The traits of the arterial pulse wave have been retrieved with high detail, allowing their interpretation by a skilled practitioner. The heart beat measurements show a good agreement when compared to the readings of a commercial pulse-meter, therefore proving the versatility and the viability of the technique for the measurement of other cardiovascular signals.

1. Introduction

In recent years, different non-invasive and non-contact methods for the acquisition of biomedical signals have been developed in order to increase the quality of patient care [1–3]. Techniques based on optic sensors are an interesting solution for biomedical signal measuring because of their simple construction, resolution, bandwidth, and low cost. Optical methods, in particular, have been assessed as a suitable solution for the measurement of different cardiovascular signals such as the cardiac rhythm and the arterial pulse wave [4,5].

The development of non-invasive methods for the acquisition and interpretation of cardiovascular signals has gained importance in the last years because of the increase in cardiovascular diseases around the world. As it is described in [5], the arterial pulse wave is one of the most important signals used in clinical medicine. The analysis of this signal can lead to the diagnosis of several cardiovascular diseases such as arterial stiffness [6,7] and arteriosclerosis [8]. Different optical methods have been previously proposed for the acquisition of the arterial pulse wave, being the photoplethysmography [9–11] and the Doppler based methods [4,12,13], the most common solutions for the task.

Self-mixing interferometry (*SMI*), also known as optical feedback interferometry (*OFI*), has been previously assessed as a non-invasive technique for the pulse detection based on laser Doppler vibrometry (*LDV*) [14,15,4] . In this paper, however, we use a more direct interpretation of the SMI signal focusing on the amplitude instead of the frequency, therefore allowing a complete reconstruction of the arterial pulse shape. Thus, in this work, we consider the cardiovascular pulse as a pressure wave which induces changes in the radius of the arterial wall in a similar way as the one proposed by Hast [4]. Such changes may induce a small displacement in the order of a few microns over the skin surface which can be captured by an SMI interferometer. As it will be shown, the reconstructed waveforms show similar resolution as the one presented by photoplethysmography (*PPG*) methods.

In the following section, we introduce the elements required for the proposed method as well as a short summary of the SMI method and how it can be applied to the reconstruction of the arterial pulse wave. In Section 3, we discuss some of the main aspects regarding the processing algorithm for the SMI, as well as some precautions that should be taken to ensure an efficient readout of the pulse waveform. In Section 4, we show a summary of the results attained while using the SMI method. Finally we establish the current state of the proposed method and the intended future work.

2. Material and methods

2.1. Self-mixing interferometry

Self-mixing interferometry has been an active area of research since the early 1980s. The phenomenon was first characterized by Lang and Kobayashi [16], who analysed the effects of external optical feedback in a laser diode (LD) by means of the delayed

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differential equations of involved electric field. Later models, such as the one presented by Wang [17] (Fig. 1), use an equivalent two cavity Fabry–Perot (FP) scheme that also results in the well known phase equation [18]:

$$2\pi\tau_{ext}(\nu-\nu_0) = C\ \sin(2\pi\nu\tau_{ext} + \arctan\alpha), \tag{1}$$

where the effects of the light round trip time τ_{ext}, the emission frequency of the free-running laser ν_0, the emission frequency after feedback ν, the feedback factor C and the linewidth enhancement factor α over the SMI signal can be analysed.

In practice, the SMI can be described as the modulation of the laser optical output power (OOP) given by

$$P = P_0(1 + m\ \cos(2\pi\nu\tau_{ext})), \tag{2}$$

where P is the OOP, P_0 the initial output power and m a modulation coefficient, produced when part of the light backscattered by a target re-enters the laser cavity. Depending on the amount of feedback [19], which is accounted by C and

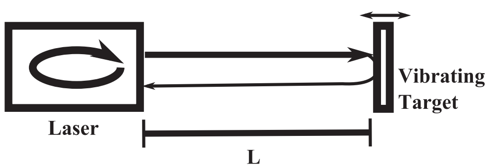

Fig. 1. A schematic of the three mirror configuration of SMI. The thin line represents the backscattered light that re-enters the laser cavity.

mathematically described in Eq. (3), where τ_l represents the round trip time inside the laser cavity, R_{ext} and R_s the reflectivity of the target and of the emitting facet respectively and ϵ the fraction of light producing the interference; the form of the modulation can change:

$$C = \epsilon\frac{\tau_{ext}}{\tau_l}\frac{\sqrt{R_{ext}}}{R_s}(1-R_s)\sqrt{1+\alpha^2} \tag{3}$$

For values of $C < 0.1$ (very weak regime) (Fig. 2B) the signal has a purely sinusoidal shape. For $0.1 < C < 1$ (weak regime) shown in Fig. 2C, the sinusoidal shape is distorted and it, progressively, acquires a saw-tooth-like shape as C increases. For $C > 1$ (moderate regime) shown in Fig. 2E the SMI signal behaves as a saw-tooth and as the C value increases, it can suffer from hysteresis and fringe loss [20]. Finally at high feedback levels (Fig. 2F), the OOP enters into chaotic regime, where it is no longer possible to extract information related to the target displacement. For most SMI applications, it is preferred to work close to the boundary between the weak and moderate regimes (Fig. 2D), which results in a good signal to noise ratio *SNR* and enables an easier detection of the transitions in the signal. In this kind of detection, each transition is equivalent to a half-wavelength ($\lambda/2$) displacement [18], and the slope preceding the transition enables to infer the direction of the displacement.

Although the SMI can be produced using different laser types, the most common SMI setups rely on the use of semiconductor lasers, typically preferring single mode lasers that include a

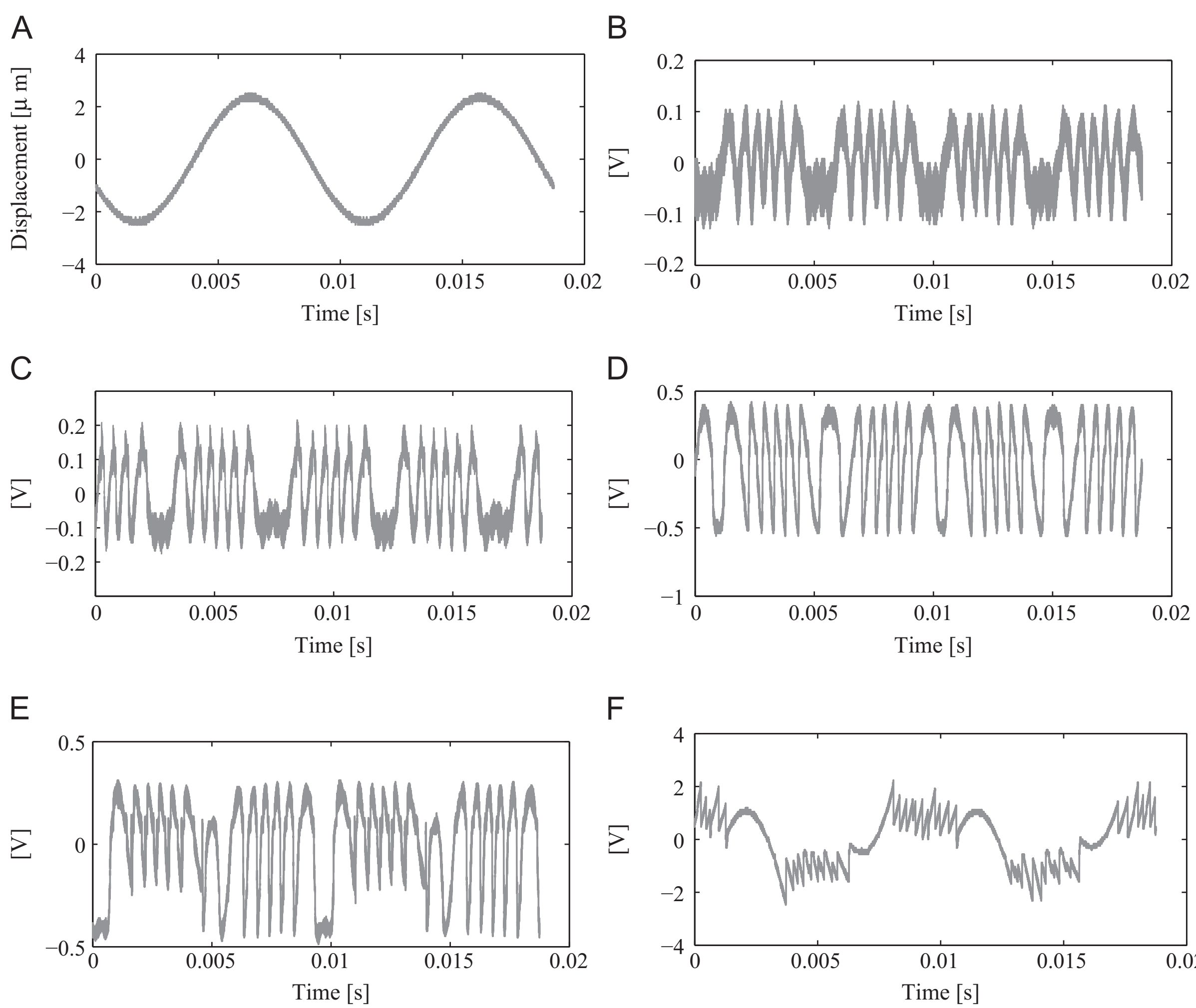

Fig. 2. Self-mixing signals for different regimes of a given sinusoidal target displacement represented in A. B very weak regime, C weak regime, D close to the boundary between weak and moderate regime ($C \approx 1$), E moderate regime and F strong regime.