Highly-Linearized Heterodyne Self-Mixing Vibrometer

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Abstract. Vibration meters based on self-mixing interferometry are generally made in baseband, without modulations, because it is very difficult to obtain a linear modulation of the wavelength by controlling the supply current. In this work, we propose a multi-frequency modulation scheme for a heterodyne self-mixing vibrometer, which allows us to overcome the limits of frequency estimation algorithms and can work on a diffusing target up to a few meters away.

1. Introduction

The laser self-mixing interference (SMI) harnesses the optical back-injection phenomenon within the laser cavity. It occurs when a portion of the light emitted by the laser diode is reflected back to the laser cavity from an external target and mixed with the internal lasing field. As a result, both the laser frequency and emitted power are modulated, providing information about the target's position and motion [1-4]. Due to the compact design and cost-effectiveness solution, the self-mixing effect is employed in widespread applications for high-resolution measurements. In addition to absolute distance measurement [5-8], the literature reports various SMI sensors, for measuring displacement [9-13], speed [14,15], vibrations [16-21], angles [22], liquid flow and level [23-30], biomedical applications [31,32], and also TeraHertz imaging [33,34]. A minimal SMI setup, comprises the laser diode, a photodiode positioned inside the laser cavity (referred to as the monitor photodiode, typically located within the laser case), a collimating lens, and the target (see Fig. 1). The monitor photodiode directly measures the power emitted by the laser diode, denoted as $P(\phi)$, which exhibits periodic variations with the back-injected phase, $\phi = 4\pi\, s / \lambda$, where λ represents the laser's wavelength, and s denotes the distance from the laser to the target [2].

To determine the absolute distance from a target, the conventional approach involves modulating the laser wavelength and measuring the period of fringes [5]. The first proposed signal processing relied on a simple fringe-counting method [6]. A more effective way to estimate absolute distance is by measuring the fringe period in the frequency domain [4]. Given the approximately linear relationship between beat frequency and distance, various techniques can be employed to calculate the beat frequency of fringes and subsequently estimate the distance. In terms of the tradeoff between accuracy and processing time, interpolated Fast Fourier Transform (FFT) [34] is a viable method for calculating the beat frequency of fringes and, consequently, estimating the distance [5]. However, interpolated FFT has limitations when dealing with signals that are not perfectly sinusoidal, rendering the interpolation formula invalid. These interpolation errors are systematic and cannot be reduced through averaging operations.

Several approaches have been proposed in the literature to enhance accuracy in fringe frequency estimation. One such advancement is the all-phase FFT [36], designed to reduce the influence of spectrum leakage and signal noise. However, it requires a longer processing window and consequently increases execution time. Moreover, this technique cannot compensate for errors arising from signals that do not have a perfectly constant frequency, such as real self-mixing signals. An algorithm based on Multiple Signal Classification (MUSIC) is also suggested for frequency estimation in SMI-based distance and velocity sensing systems [37]. The MUSIC method assumes that a signal vector consists of a known number of complex exponentials with unknown frequencies. By considering the covariance matrix and applying eigenvalue decomposition, dimensions containing signals exhibit larger eigenvalues, while smaller eigenvalues belong to noise dimensions. When the signal dimension is projected into the noise subspace, it results in sharp peaks at the signal frequencies, providing a frequency estimation function for MUSIC. Although MUSIC offers notable performance advantages, it demands substantial computational effort for real-time execution. Another approach, based on Genetic Algorithm (GA), is presented in [38]. A cost function is established based on the variation in emitted power from a linearly modulated laser diode. To address premature convergence and the time complexity of GA, an improved GA algorithm is proposed. Despite the high resolution in distance measurement and improvements in selection and exploration range compared to the original GA, the speckle effect is not considered: it diminishes the robustness of the GA-based SMI sensing system, as the self-mixing signal with amplitude fading strongly impacts the cost function and can lead to incorrect convergence of distance values. This paper describes the development of a laser instrument for measuring vibrations on a diffusive target placed at a few meters of distance. The proposed sensor is based on a heterodyne self-mixing interferometer (SMI), following the scheme typically used for absolute distance measurement [5-8].

2. Heterodyne Self-mixing interferometer

The measurement of absolute distance through a self-mixing interferometer requires wavelength λ modulation, easily achieved by changing the pump current I. The distance measurement s in this case is given by the evaluation of the fringe frequency f_{fringe}, during the modulation:

$$s = -\frac{\lambda^2}{2 \cdot \left(\frac{\partial \lambda}{\partial I}\right) \cdot \left(\frac{\partial I}{\partial t}\right)} f_{fringe} \tag{1}$$

The simplest modulation shape is triangular, and the distance value is obtained by averaging the frequencies of the ascendant and descendant phases of the triangular wave. Instead, the instantaneous target speed ν is given by the Doppler shift between rising and falling edges (f_{tone+} and f_{tone-}) in a sort of heterodyne detection [5]:

$$\nu = \frac{f_{tone+} - f_{tone-}}{2} \left[\frac{\lambda}{2}\right] \tag{2}$$

This approach has two main drawbacks: the non-linearity of wavelength modulation and the resolution/accuracy limit of the frequency measurement techniques. A pre-distortion of the triangular-wave modulation could partially compensate for the non-linearity of $(\partial\lambda/\partial I)$, and also its frequency dependence [39,40]. In order to extract the signal frequency, proportional to the target distance, we decided to implement the Interpolated Fast Fourier Transform (IFFT), because it gives the best trade-off between accuracy and elaboration time [5], but its performances are limited by the acquisition time, signal-to-noise ratio and signal shape, that is not perfectly sinusoidal.

To improve the performances, we propose to decorrelate IFFT systematic errors by modulating the LD current with slightly different frequencies over subsequent modulation periods. In this way the measured SMI frequency moves to different positions with respect to the FFT bins, allowing an improved resolution after averaging.

3. Realized vibrometer

The realized prototype of vibrometer consists of two parts: the analog electronics required to process the fringe signal and introduce a specific current waveform into the laser diode, along with a commercially available data acquisition card (DAQ, Analog Discovery II). The DAQ card was used to generate the modulating wave and capture the signal, with a conceptual arrangement similar to what is depicted in [7]. The schematic representation of the instrument's components is illustrated in Figure 1.

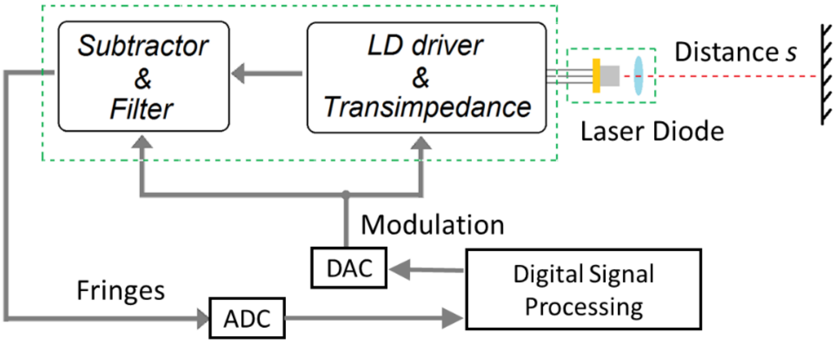

Figure 1. Block scheme of the realized interferometer.

The realized instrument, with real-time digital processing, is able to get 2000 measurements per second, working on a diffusing target up to 3 m of distance, with a simple collimating lens. In the realized prototype, the laser diode is a distributed-feedback (DFB) laser at 1550 nm (WSLD-1550-020m-1-PD).

Using the DAQ, a customized waveform is generated for modulating the laser and simultaneously capture the interferometric signal. To precisely assess the non-linearity introduced by wavelength modulation, a real-time software is developed to measure locally the frequency of the fringes. This software relies on an interpolated FFT computation performed on a sliding window of 32 samples, following the methodology outlined in [41].

At the start of any positive and negative slope of the modulation signal, it is challenging to keep constant the period of the fringes. However, for subsequent data processing, it is enough to achieve a sufficiently long flat interval. Special care should be taken into account while setting the interval size to ensure an optimal number of samples, such as 256 or 512, for efficient FFT processing and measurement speed improvement. In the realized prototype, the measured signal is acquired with a sampling rate 8 MSa/s, and IFFT is evaluated on 256 points.

Figure 2 shows an example of pre-distortion of the modulating wave, able to realize an almost constant modulation frequency, with maximum relative frequency variation limited to 10^{-3}.

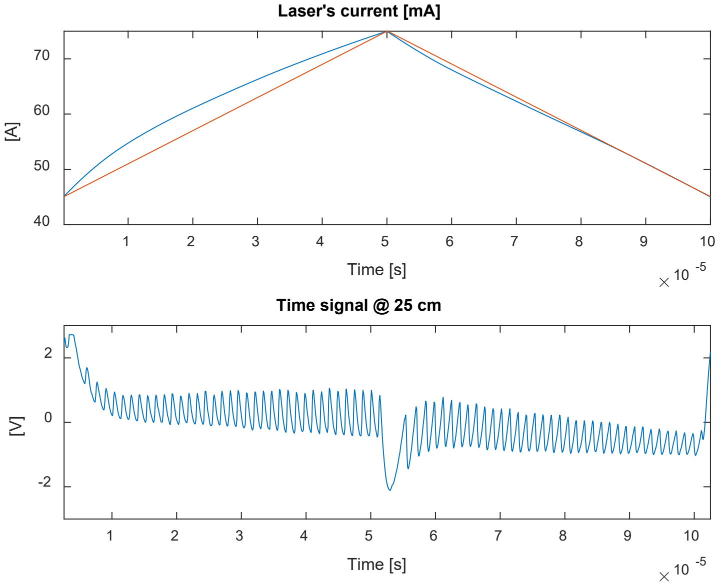

Figure 2. Upper pane: laser diode modulation, triangular and pre-distorted wave. Lower panes: corresponding self-mixing signal, with constant modulation frequency.

4. Multiple modulations

Even after effectively linearizing the wavelength modulation to better than 10^{-3}, periodic systematic errors with distance persist, contingent on the signal-to-noise ratio. These errors are deterministic in nature and cannot be mitigated through averaging. After conducting an in-depth analysis of error sources, it became evident that these errors were primarily attributed to the limitations of interpolated FFT when dealing with signals that were not perfectly sinusoidal and contained noise. To address this issue, we explored a more intricate modulation scheme comprising multiple modulating waveforms at slightly different frequencies. These modulating waves were designed to position the fringe frequencies differently with respect to the FFT bins. This implies that once a generated fringe in one period of the modulation signal is exactly on an integer bin of the spectrum, the frequency of the generated fringes during the other modulation periods is guaranteed to be on a non-integer bin position, due to the selected modulation periods. This approach introduced deterministic errors due to interpolated FFT that were distinct for each waveform and uncorrelated. Additionally, it provided the option to discard measurements from waveforms corresponding to unfavorable frequency positions, where the interpolated FFT errors were at their maximum. The worst position for this purpose was directly over a bin, as a two-bin interpolated FFT on a real signal exhibited the highest error in that position. The proposed technique effectively decorrelates individual measurements, yielding improvements through averaging procedures. However, a drawback of this approach is the time-consuming process of manually determining the correct distortion, because the individual waveforms influenced each other, and the pre-emphasis procedure needed to be applied simultaneously to the entire modulating signal. Consequently, the same shape could not be used for all modulating waves at different frequencies. To expedite this process, we implemented a recursive algorithm using LabVIEW to automatically optimize the modulation shape.

The use of several modulation periods also allows signal fading problems to be better overcome, as it is easy to select only the periods with sufficiently high amplitude in the average of the measurements. The only drawback of this technique is the reduction of the measurement frequency, by the number of realized modulations. In our realization, three modulation waves at 9 kHz, 9,5 kHz, and 10 kHz are realized, for a total measurement time of about 300 µs, allowing, in theory, 3 kSa/s of measurement frequency.

The error correction procedure of the interpolated FFT is absolutely relevant for this type of measurement, especially for low-speed movements. In vibration measurements, a minimum imbalance error between the ascent and descent phases of the modulating wave results in a constant speed offset, hence in a drift of the measured displacement. Experimentally there has been a notable improvement in the quality of the vibration measurement obtained with the proposed technique.

Fig. 3 shows an example of measurement of a target vibrating at 25 Hz with an amplitude of about 4 µm, placed half a meter from the instrument. The upper panel reports the speed calculated by the Doppler shift, the lower panel shows the target displacement given by the speed integration.

5. Conclusions

The presented work sets the stage for a low-cost vibrometer with high resolution. Thanks to the multiple modulation technique, it is able to overcome the limits of this kind of instrument, while targeting diffusive surfaces at a few meters of distance. It could therefore be the right solution for different applications, for example on human skin. The actual main limit of the realized prototype is the acquisition rate, about 2 kSa/s, suitable for not-too-fast vibration measurements.

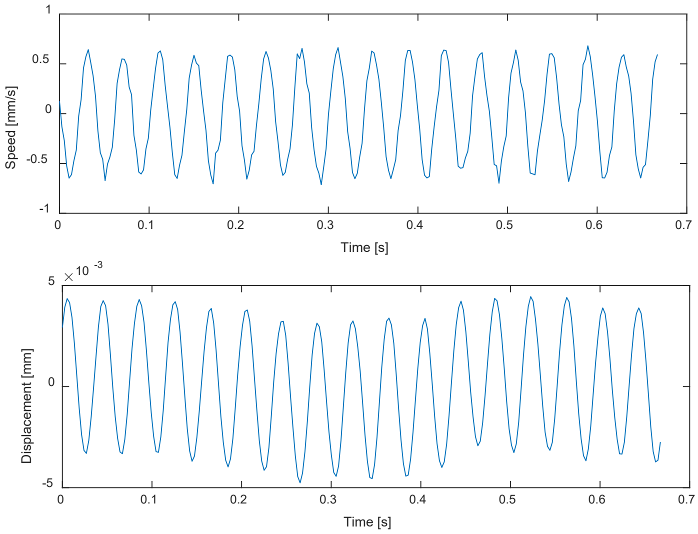

Figure 3. Measured target speed (Doppler shift) and reconstructed target vibration.

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