Real-Time Self-Mixing Interferometer for Long Distances

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I. Introduction

ONE OF THE most employed optical instruments for the movements measurement is the so-called laser doppler velocimeter. Its working principle is based on the interference observed when two coherent light beams are made to coincide [1]. The resulting intensity, measured by a photo detector, varies as a sinusoidal function of the phase difference between the two beams. Indeed, if one beam is scattered back by a moving target, it is subjected to a frequency shift, called doppler shift f_D

$$f_D = 2 \cdot \upsilon / \lambda \tag{1}$$

where υ is the target speed and λ the laser wavelength.

For the measurement of displacement, the most common solution is to realize two optical channels, to measure sine and cosine and recover the sign of the movement [1]. When measuring vibrations, the standard solution employs an acousto-optic modulator (Bragg cell), which shifts the laser frequency in the reference path [1]. This generates a modulation frequency of the fringe pattern of some megahertz also when the target is at rest. If the target moves toward the interferometer, the modulation frequency is reduced and if it moves away it increases. By this technique, it is possible to detect the target speed, proportional to the frequency shift, but also to clearly define the direction of movement.

The aim of this paper is to realize an interferometer able to measure the target speed, with sign, using only one optical channel without the addition of frequency modulation. The technique is realized with a self-mixing technique [2]–[4] and an explanation of the theory of operation has been reported in [5]. This kind of interferometry, applied to laser diodes (LDs), has been used for different applications, in addition to velocity measurements [6], [7]: from vibrations [8], [9] to distance [10]–[12], flow [13]–[16], and displacement [17], [18] contactless measurements.

The self-mixing effect is induced by the back-reflection or back-scattering of a small part of emitted light into the laser cavity. The light back-injection disturbs the laser action and induces a modulation in the emitted power and frequency [4]. The power amplitude assumes a modulation periodic with the interferometric phase $\phi = 2ks$, where $k = 2\pi/\lambda$, λ the LD wavelength and s the distance between the target and laser. The shape of the modulation mainly depends on the optical conditions, measured by the feedback parameter C [4]: for very low back-injection (until about 10^{-6} in power) the modulation assumes a sinusoidal shape. Instead, in case of moderate back-injection the modulation becomes much distorted, until reaching a sawtooth-shape, for C values higher than 1. In literature, the modulation distortion has been extensively used for discriminating the direction of movement of the target [4], [9], [15], [16], but always working in the time domain. This paper proposes a method for defining the direction of the target movement, looking at the distortion of the power modulation, but in the frequency domain, with all the advantages of this kind of elaboration in terms of strength against noise and signal fading. For example, in [17], an instrument for measuring displacement is presented, but the described elaboration consists in counting the signal fringes and it requires at least a moderate level of optical reflection ($C > 1$). This condition was partially overcome in [9], but the described time elaboration is always limited by the signal-to-noise ratio. The main novelty of the proposed signal elaboration is whole processing in the frequency domain, allowing to measure signal also with low signal-to-noise ratio.

Finally, the proposed algorithm has been implemented in a programmable device so to develop a real-time measurement prototype. The realized instrument confirms the robustness of the reconstruction, also in cases of very-low optical back-injection: it demonstrates a correct operation for target distances up to 10 m, and for good optical reflection it can reach also 20 m.

II. Signal Elaboration

The shape of a self-mixing signal in the condition of moderate back-injection, obtained typically when the LD is focused

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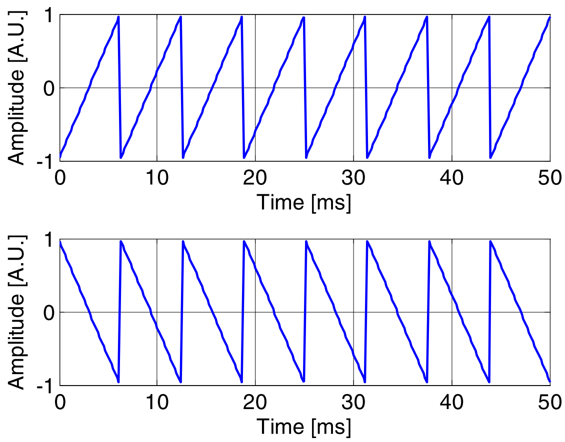

Fig. 1. Sawtooth signal and its inversion.

on the target, is close to a sawtooth. In a first approximation, when the target moves toward the laser the fringes are distorted in one way; when the movement direction is reversed the distortion is also overturned. Starting from this consideration let us consider the signals shown in Fig. 1. It is a sawtooth wave, periodic with frequency f, therefore its spectrum will show harmonics, both odd and even, multiple of f. In the particular case of Fig. 1, the signal is also odd: it is symmetric because centered in zero. It is well known that the Fourier transform of a real and odd signal is purely imaginary. Since the real part is zero, all the harmonics have a phase $\pm\pi/2$. For this particular choice of the zero-time, with the origin of the time axes coincident with the beginning of the ramp, all the harmonics have phase $+\pi/2$. In this approximation, the difference between the two directions of movement is only the sign: the lower trace of Fig. 1 is just the upper trace multiplied by -1. To discriminate the movement direction, it is possible to measure the phases of the first harmonic, which changes by π when inverting the direction [5].

In real cases, the signal is acquired at a random phase, therefore the time origin does not correspond, in general, with the beginning of the ramp. However, it is possible to bring back to the time condition of Fig. 1 (odd signal with phase $+\pi/2$ for all the harmonics) by considering a time delay ΔT. This delay changes the phases of the harmonics by a quantity proportional to their frequency; indeed it is well known that for a sinusoid the phase shift is equal to the time delay multiply by the angular frequency. For example, considering a time delay ΔT the first two harmonics exhibits a phase shift equal to

$$\Delta\phi_1 = -2\pi f \Delta T \quad (2)$$

$$\Delta\phi_2 = -4\pi f \Delta T. \quad (3)$$

Therefore, it is possible to recover the time delay ΔT as

$$\Delta T = -(\Delta\phi_2 - \Delta\phi_1)/(2\pi f) = -\Delta\phi_{2-1}/(2\pi f) \quad (4)$$

where $\Delta\phi_{2-1}$ is the difference between the phases of the first two harmonics.

We can estimate the direction of signal distortion by measuring the phase of the first harmonic ϕ_{10}, in the sampling condition of Fig. 1, when the first and the second harmonics should have both the same phase. That phase is easily obtained after the time shift

$$\begin{aligned}\phi_{10} &= \phi_1 - \Delta\phi_1 = \phi_1 + 2\pi f \Delta T \\ &= \phi_1 - (\phi_2 - \phi_1) = 2\phi_1 - \phi_2\end{aligned} \quad (5)$$

where ϕ_1 and ϕ_2 can be measured in any time instant, while ϕ_{10} should have the value $+\pi/2$ for the lower signal in Fig. 1, and $-\pi/2$ for the upper signal in Fig. 1.

In summary, the signal is sampled without time reference or trigger signal. The phases of the first two harmonics are measured by a fast Fourier transform (FFT), using as zero-time the beginning of the sampling; then ϕ_{10} is calculated by (5).

This theory also applies to triangular waves with different duty-cycles, and distorted sinusoids. The basic principle consists in finding the sign of the first harmonic in the time position where the first and the second harmonics show the same phase. For confirming the reliability of this approach, different numerical simulations have been performed. For a noiseless signal, triangular or sinusoidal with distortion, the sign of $(2\phi_1 - \phi_2)$ always indicated the direction of the distortion, as expected by the explained theory.

To work with noisy signal, and considering also the problems due to the FFT bin leakage [19], it is convenient to set the threshold for the sign evaluation to zero. Indeed, for acquired signals the term $(2\phi_1 - \phi_2)$ cannot be exactly $\pm\pi/2$, but it is always a good indicator of the signal distortion. The whole algorithm is described in the block diagram shown in Fig. 2.

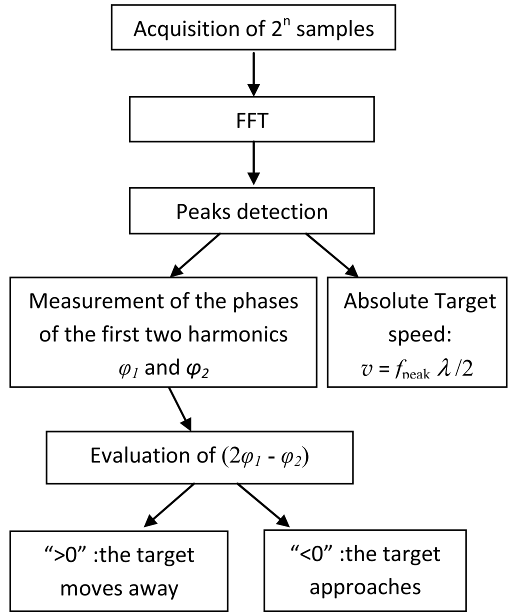

Fig. 2. Description of the algorithm for the measurement of the target speed, with sign.

The absolute value of the target speed is obtained by the measurement of the fringes frequency, using (1). The fringe frequency estimation is realized by an interpolated FFT algorithm [20] to increase the spectral resolution.

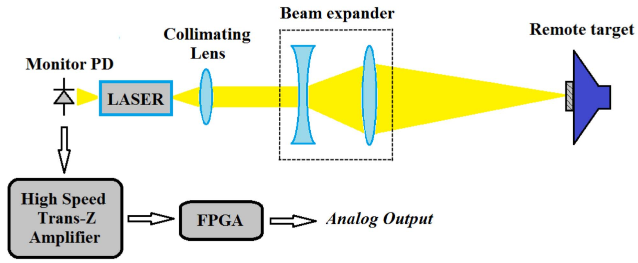

Fig. 3. Self-mixing interferometer experimental setup.

III. Hardware Setup

The system setup for the experimental demonstration of the algorithm is shown in Fig. 3. An LD (Hitachi HL7851G, 785 nm) is collimated by a first lens and then enlarged by a 6× beam expander. In this way the solid angle of reception is increased by a factor 36: more back-diffused light is collected and thus higher C levels are achieved. This kind of optical setup is realized for working at long distances, up to 20 m, limited only by the laser coherence length. For this kind of fabry-perot laser, the laser linewidth is a few megahertz [21], corresponding to a coherence length ranging from about 10 to 30 m. We found experimentally that the model HL7851G, powered at about 80 mA, exhibits a reliable self-mixing effect up to about 20 m. At 30 m, the signal is too low and it is impossible to acquire reliable measurements.

The possibility to work in extreme conditions, with low signal and long distances, is provided by the new signal elaboration. Indeed, the strength of the proposed signal elaboration is the ability of working even with very-low signal, strongly deteriorated by noise or speckle effect [22].

The self-mixing effect produces a series of interferometric fringes easily detectable with the built-in monitor photodiode. Because the presented algorithm allows working also for high-speed movements, it was designed a large bandwidth transimpedance amplifier (7.5 MHz) to read the self-mixing signal. The result is a maximum speed tracking of 3 m/s. The signal is digitally converted using an Analog to Digital Converter (Texas Instruments THS1230, 12 bit, 30 MSa/s) and acquired by an FPGA board (Field Programmable Gate Array, model Altera De0-nano). This is the kernel of the designed prototype because it executes the algorithm in Fig. 2 in real time, providing on an analog output the speed reconstruction. The analog electronics is directly interfaced to the FPGAs connectors and it presents the same dimension of the digital board: in this way, the whole prototype has reduced dimensions (8 cm × 5 cm × 4 cm, without the beam expander). The device is supplied at 5 V and consumes about 1 W (laser included).

IV. Experimental Results: Postelaboration

After the tests performed on simulated signals, the analysis algorithm has been tested on real signals, with different target speed and optical conditions. The acquired signals, obtained in correspondence to different target movements, have been elaborated, as shown in Fig. 2. As demonstrated by the theory, the target speed reconstruction operates without any problem

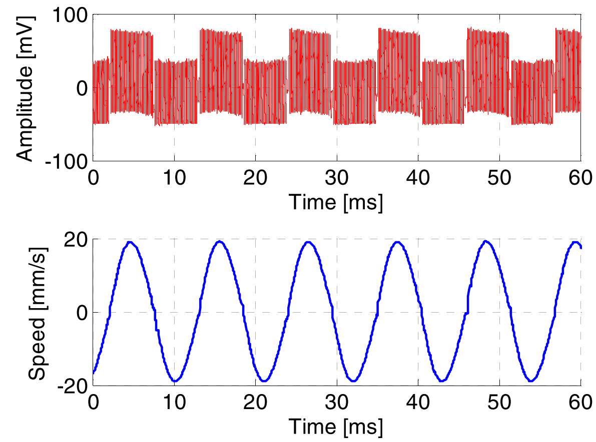

Fig. 4. Acquired signal (upper trace) and reconstructed speed (lower trace), in the case of good optical signal and absence of dark speckles.

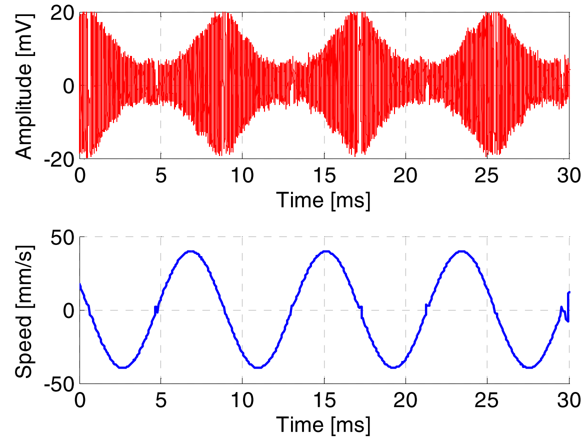

Fig. 5. Acquired signal (upper trace) and reconstructed speed (lower trace), in the case of weak optical signal and occurrence of a dark speckle.

in the case of moderate back-injection ($C > 1$). In this condition the signal is nearly sawtooth-like, and the approach of measuring the phases of the first two harmonics demonstrates an excellent performance. Fig. 4 shows an example of acquired signal (upper trace) and the correspondent speed reconstruction (lower trace), in the case of good optical signal (C value is about 2) and absence of dark speckles. The results are very encouraging: there are only small discontinuities next to the sign inversion, due to the dimension of the FFT window, and can be fixed up by a simple filtering considering the maximum acceleration physically realizable. Additional algorithms of post-processing have been implemented to achieve better results, avoiding spurious glitches and discontinuities in the speed signal.

The real strength of this algorithm, however, is the ability to work with very low signals, also in presence of dark speckles: the good working has been demonstrated for feedback coefficient C as low as 0.05. This value is 20 times lower than the required feedback for standard self-mixing elaboration [4], [18]. It means that the proposed sensor can work in much worse optical conditions. Fig. 5 shows an example of signal acquired in correspondence to very weak back injection, about 10 times lower than Fig. 4 (amplitude

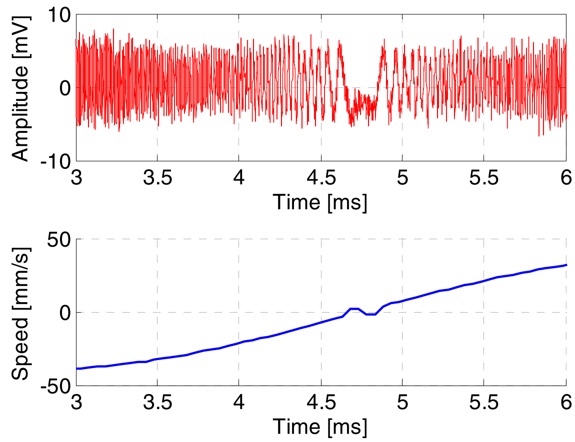

Fig. 6. Sign inversion from Fig. 5 zoomed-in view.

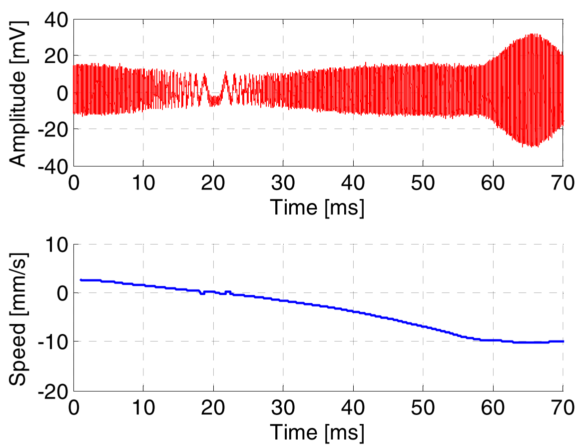

Fig. 7. Acquired signal (upper trace) and reconstructed speed (lower trace), in the case of weak optical signal and arbitrary target movement.

$<$10 mV, with respect to about 100 mV), also varying for the speckle effect.

The zoomed-in view of Fig. 6 confirms the good performances even in the region where the target changes direction. In this case also the signal-to-noise ratio is quite weak, but the spectral analysis still works with a good accuracy. There can be some sign errors only at speed inversion. As can be observed in Fig. 6, when the signal-to-noise ratio is low, a small oscillation occurs at the sign transition. The reasons of this small oscillation are the low signal-to-noise ratio, but also the very low target speed in correspondence with the speed inversion: the signal processing considers an acquisition window sliding on the signal, that begins before and finish after the point of zero speed. When the C value is low, the signal distortion could be not enough to correctly indicate the speed sign for velocity lower than 1 mm/s.

The application of the algorithm is not limited to a sinusoidal movement, but it is developed for the real-time measurement of arbitrary displacements. Fig. 7 shows an example of arbitrary target movement realized by a motorized slide, in quite bad optical conditions ($C \cong 0.1$): the laser beam is collimated on a paper target at a distance of 70 cm (the target has been placed at short distance only for laboratory convenience, the instrument can work up to 10 m).

The main advantage of the frequency domain elaboration is the robustness against noise and signal losing due to dark speckles. Therefore, it is applicable for the measurement in hard situations, when the optical back-injection cannot be controlled. For example, potentially this approach in frequency opens the possibility of realizing self-mixing interferometers for long distances, for the monitoring of structures and buildings.

V. Real-Time Implementation

The algorithm was implemented into an FPGA to achieve the real-time reconstruction. The interferometric signal, digitized by the ADC converter, is continuously stored to form a 1024-points FFT input; the spectrum output is available at the next FFT processing. Contemporary the bin position of the main tone is calculated: notice that the first harmonic may be detected within the 256 bin because, in this case, the second harmonic reaches the Nyquist limit (512 bin). Once detected the first harmonic, it is possible the accurate evaluation of the signal frequency value because of the interpolated FFT technique [20]. It exploits the bin-leakage effect to calculate the precise bin position of a particular harmonic, solving a simple algebraic equation. The information about direction, instead, is extracted through the procedure described in Section II, by using the FPGA floating point cores. As final procedure, the accurate frequency estimation is multiplied by ± 1 depending on the direction of the target movement; the resulting number is converted in metric unit and adapted to the dynamic of the output DAC converter.

Many improvements have been also implemented to upgrade the global performances. Assuming to have limited physical accelerations, when the measured speed is relatively high it is not possible to change its direction in a short-time interval. Therefore, a control is implemented for avoiding direction changes when the speed is higher than a threshold value. One problem highlighted by the experimental tests has been a spotted variation on the direction detection: sometimes, in particularly poor optical conditions, the algorithm fails the calculated direction for a single reconstruction point. This problem, due also to the digital quantization of the phases, was eliminated by inserting a nonlinear control that bypasses single changes of direction. This result is a smoother reconstruction. Another important control is based on the detection of the signal amplitude: if the target is firm, or inside a dark speckle, there is no interferometric signal and the algorithm detects only noise. To avoid a random frequency output, the amplitude of the first harmonic is compared with a threshold value and, in cases of lower signal, the reconstruction is inhibited and the speed value is kept equal to the previous elaboration.

To optimize the performances for target speeds of very different values, the acquired samples time duration should be changed. The implemented method consists in adaptively modifying the sampling frequency. More precisely, 30 MSa/s is chosen when the target speed is higher than 10 cm/s; for lower speed the FPGA sets 937 kSa/s. When sampling at the maximum rate, the highest measurable speed is equal to 2.95 m/s; in case of low sampling rate, instead, the minimal speed is given by the first spectral bin, resulting a speed

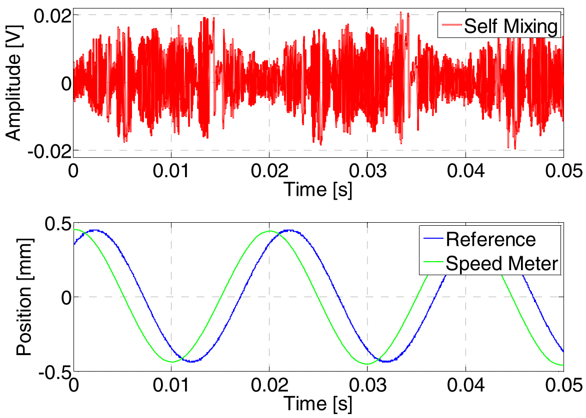

Fig. 8. Real-time comparison between our prototype and a reference instrument, in case of sinusoidal vibration.

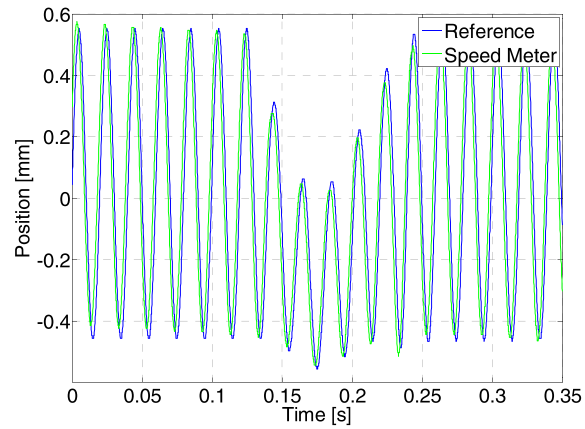

Fig. 9. Real-time reconstruction in case of disturbated sinusoidal vibration.

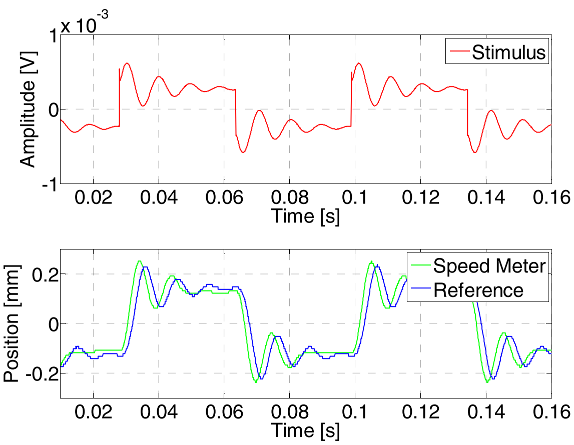

Fig. 10. Displacement reconstruction to a square stimulus.

equal to 0.4 mm/s. An auto-switching system is implemented, that changes the sampling rate as a function of the actual measured speed, with some hysteresis: when the target increases its speed, the sampling frequency is increased, and vice versa. This automatism is completely transparent to the analog reconstruction, without glitches or discontinuities.

The resolution in the speed measurement is limited by the error of the interpolated FFT algorithm, reported in [20]. With 1024 samples, depending on the number of fringes considered, the relative error is typically below 10^{-5} times the maximum measurable frequency. With a maximum speed of about 3 m/s, the expected speed resolution should be better than 30 μm/s.

VI. Experimental Results: Real Time

To validate the novel algorithm, several tests were carried out also with the real-time prototype. The aim was to demonstrate the quality of reconstruction in case of very low back-injection, when the time-domain algorithms do not allow good performances. As reference, we used a commercial triangulation sensor (Keyence, LK-G152) with micrometer resolution. Fig. 8 shows the reconstruction of a sinusoidal vibration with 0.9-mm peak-to-peak at 50 Hz. The upper trace represents the original self-mixing signal that exhibits strong amplitude variation due to the speckle-effect (the fringe frequency is very high and the figure shows only the signal envelope). The lower part of the figure compares the position measurement made by the triangulator with the displacement obtained by the integration of the speed measured by the prototype. The loudspeaker was placed at a distance of 5 m from the interferometer, while the triangulator was very close to the target (about 10 cm).

Despite the worst optical conditions, the reconstruction is equivalent to the reference one. The main difference is a delay in the output of the commercial triangulator, more than 1 ms.

Another interesting measurement is shown in Fig. 9. A sinusoidal vibration generated by a loudspeaker (equivalent to the vibration of Fig. 8), is perturbed in a way to modify its oscillating status. The developed instrument reconstructs the displacements with good agreement respect to the reference.

As the last example, Fig. 10 shows the measurement of a square stimulus for the loudspeaker. The excitation frequency is low (14 Hz), therefore the electromechanical membrane resonance oscillation is clear, also in the electric stimulus. Also in this case, the reference confirms our reconstruction. It is also evident the real-time working of the system that does not exhibit the delay of the commercial sensor.

The optical sensor is designed for working with distances up to 20 m, but experimentally the realized prototype exhibits good performances only up to 10 m. It is possible to reach also 20 m, but only with cooperative target surfaces with enough back-reflection.

VII. Conclusion

This paper proposes an instrument for the measurement of target speed, based on a novel kind of elaboration for a self-mixing interferometer, working in the frequency domain. The main novelty of the algorithm is the ability to discriminate the direction of the target movement by only measuring the phases of the first two signal harmonics. The reliability and robustness of the frequency analysis makes possible the application of the self-mixing technique for long distances measurements with very low signal-to-noise ratio. The realized prototype shows good performances up to 10 m, for speed ranging between 0.4 mm/s and about 3 m/s. The instrument measurements have been successfully compared with a very-high resolution commercial triangulator, also for nonsinusoidal target movements confirming the good performances of the realized instrument.

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