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Experimental investigation on dynamical performances of a novel fiber-optic pressure sensor for pulmonary ventilation

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***Abstract* – A new optical fiber differential pressure sensor has been proposed for neonatal pulmonary ventilation and an experimental investigation on its dynamical metrological performances is here reported. The proposed measurement system has been preliminarily tested by monitoring the mouth pressure during simple respiratory tests in healthy patients and during mechanical ventilation performed by means of a infant ventilator typically used in the neonatal intensive care units; results show that the output of the transducer is consistent with that measured by means of a reference sensor.**

***Keywords* – optical fiber sensor, mechanical measurement, biomedical instrumentation, pulmonary ventilation**

I. INTRODUCTION

Pressure measurements in neonatal mechanical ventilation and spirometry are carried out for the assessment of respiratory functions [1], both for physiology investigations, the evaluation of effects of respiratory diseases, as well monitoring of airway pressure in the therapeutic action performed by means of lung ventilators [2-3] and for testing and the evaluation of lung ventilators efficiency [4-6], in order to verify at least the fulfilment of minimal performance criteria, and to prevent lung injuries caused by mechanical ventilation [7-8].

Measurement of respiratory pressure in mechanically ventilated infants is typically performed by means of capsule-type and diaphragm-type pressure sensors [1]. In order to convert into an electrical signal the mechanical movement, due to pressure, of the above quoted elastic elements, different sensing techniques are currently employed [9]: capsules are typically connected to translational displacement transducers (e.g. a Linear Variable Displacement Transducer (LVDT)) and capacitive, piezoelectric and piezoresistive methods are usually used for the detection of the motion of diaphragm (e.g. elastic membranes instrumented with electrical strain gauges).

As the traditional above mentioned measurement system are based on electromagnetic or electrical working principles, they are subject to electromagnetic interferences and, consequently, exposed to errors; in order to reduce the considered drawback, several fiber-optic sensing techniques have been proposed for medical application [10–12], because of their electrical insulation and immunity to electromagnetic interferences [13], providing an improvement in electrical safety conditions and the reduction of measurement errors, e.g. during electrosurgery operations and during magnetic resonance imaging examinations. With the aim of reducing these shortcomings, in the last few years several optical fiber pressure sensors have been proposed: most of these transducers are based on interferometric techniques, on fibre Bragg gratings (FBG) and on light intensity modulation.

The proposed optical fiber interferometers, mainly developed as Michelson [14] and Fabry-Perot interferometer (FPI) [15–16], are based on phase detection and allow metrological performances better than the other measurement techniques and independence by external light fluctuations; nevertheless require a relatively complex and expensive techniques and set-up (i.e. stabilized coherent light sources and fringe counters) which do not allow the development of a portable device.

FBGs have been employed in the development of several devices for detecting pressure [13–16]; in some cases, FBGs have been configured as optical strain gauge applied on an diaphragm and on a Bourdon tube, in place of electrical strain gauges: they aren't affect by apparent pressure variations (e.g. due to optical power fluctuations) but require FBGs interrogators or optical spectrum analyzers that are expensive and their wavelength scanning speed is not always suitably fast [13].

Finally, several techniques based on light intensity modulation, such as diaphragm reflectance methods [17–

18], photoelastic effect [19], microbending [20–21] and macrobending [22] have been proposed: as example, considering the reflectance principle, a multimode optical fiber is used in order to measure the light intensity reflected by an illuminated diaphragm; the movement of the diaphragm, due to pressure, varies the amount of light energy coupled to the fiber, and as a consequence, the variation of light intensity is a function of the differential pressure applied on the diaphragm.

Light intensity modulation techniques are characterized by a simple set-up (e.g. a photodiode or a receiving fiber), they don't require a stabilized coherent light source and are low-cost. Nevertheless, they are affected by light source fluctuations independent on pressure, such as light intensity variations due to the instability of light source, as well to the drift time characteristics of the optical component of the measurement system and to the losses from the optical fiber bending. Therefore these optical power fluctuations could be confused with a misleading differential pressure variation.

In order to reduce the above shortcomings, a novel fiber-optic sensing technique is here proposed based on a transducer device that is independent on light intensity variations not related to the measurand (i.e. differential pressure and air flow rate) [23–28]. This technique has been used for monitoring respiratory pressure in mechanically ventilated infants [28]: the differential pressure applied to a capsule causes the deflection, measured by means of a photodiode linear array, of an emitting optical fiber cantilever. However, up to now the sensor has been only statically calibrated, but it is intended for neonatal ventilation and, as a consequence, a dynamical investigation of metrological characteristics of the proposed optical fiber sensor (OFS) is needed. In this work, we report an experimental study on the dynamical performances of the sensor during simple respiratory trials in healthy patients and during mechanical ventilation performed by means of an infant ventilator typically used in neonatal intensive care units.

II. PRINCIPLE OF OPERATION

The sensor is based on a drive stinger AT with the lower extremity placed in the middle of a capsule C and the upper extremity is connected to an emitting optical fiber OF supplied by a LED (Fig. 1): the linear movement of the capsule, due to pressure, is amplified by means of an optical fiber cantilever and causes the vertical translation of drive stinger and, therefore, of the emitting optical fiber; a photodiode linear array A (TSL1401R-LF, 400 dots per inch, 128 pixel), placed in front of the emitting face of the optical fiber, detects the illumination pattern of fiber and consequently performs a measurement of the fiber tip displacement. In fact, the intensity distribution profile detected by the photodiode array is characterized by a maximum light intensity value shifting according to variation of the pressure applied to the capsule: the value of the differential pressure applied on the capsule can be found from the position of the most lighted photodiode on the array.

As the sensorial signal is directly encoded into an intensity distribution profile and into the position of the most illuminated photodiode, which is independent by external optical power fluctuations (as long as the measured light intensity is significantly over the noise level), the proposed measurement system isn't affected by environmental light intensity fluctuation.

The relationship between the displacement δ_L of capsule, which is theoretically equal to the ones of emitting fiber tip, and the differential pressure ΔP applied on the capsule is:

$$\Delta P = P - P_{atm} = \frac{A}{k \cdot C} \cdot \delta_L = \frac{1}{S} \cdot \delta_L \qquad (1)$$

where P and P_{atm} are respectively the pressure inside and outside the capsule (P_{atm} is typically the atmospheric pressure), A is the cross sectional area of the capsule, k is stiffness of the capsule, S is the sensitivity of the differential pressure sensor and C is an amplification factor due to the cantilever:

$$C = \frac{3L - a}{2a} \qquad (2)$$

where L is the length of the optical fiber cantilever and a is the distance on the optical fiber between the wedge and the drive stinger AT as shown in Fig. 1.

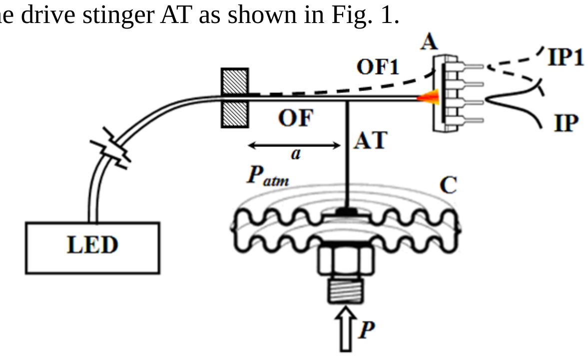

Fig. 1. Scheme of the fiber-optic pressure sensor. C: capsule; AT: drive stinger; A: photodiode array; OF: configuration of optical fiber if a pressure P is applied inside C; IP: light intensity profile measured by A if a pressure P is applied inside C; OF1: configuration of the optical fiber if a pressure P_1>P is applied inside C; IP1: light intensity profile measured by A if a pressure P_1>P is applied inside C.

As reported in previous work [28], the static calibration of the OFS show that the sensitivity of the OFS is 173±7 μm/cmH_2O (i.e. 27±1 pixel/dmH_2O) and its measurement range is from –15 cmH_2O to 15 cmH_2O (i.e. the usual range of airway pressures encountered during tidal breathing of infants [29]). In order to verify the performances of the OFS for the measurement of typical dynamical waveforms of differential pressure occurring in the field of neonatal pulmonary ventilation, the proposed measurement system has been preliminarily tested during simple respiratory tests in healthy patients breathing into a spirometer and during mechanical ventilation performed by means of a commercial ventilator. As reported in the following, the output of the proposed OFS has been compared with results provided by a reference pressure sensor RP (Freescale MPXV7002, measurement range from –2.00 kPa to 2.00 kPa, measurement uncertainty of ±0.05 kPa, sensitivity of 1 V/kPa).

III. EXPERIMENTAL SET-UP AND RESULTS

In the spirometric trial, the optical fiber pressure sensor has been placed in order to measure the mouth-pressure. Fig. 2 shows consecutive light intensity distribution profiles measured by means of the photodiode array during the displacement of the optical fiber tip due to respiratory pressure applied by the healthy patient during the respiratory trial. The correspondent measured mouth pressure is showed in Fig. 3 and it is compared with the differential pressure measured by the reference sensor: differential pressures measured with the optical fiber sensor (OFS) are consistent with that ones measured by the reference sensor (REF) and a maximum percentage error of about 7 percent is found.

The proposed measurement system has been preliminarily tested during mechanical ventilation performed by the positive-pressure ventilator Bird VIP (Fig. 4), which as been set as follow:

- type of ventilation mode: Intermittent Mandatory Ventilation (IMV) / Continuous Positive Airway Pressure (CPAP), Time cycled;
- high pressure limit: 6 cmH_2O;
- positive end-expiratory pressure (PEEP): 2 cmH_2O.

The infant ventilator V has been connected, by means of a pneumatic circuit ending with a wye-shaped element, to a simulated load TL (Infant Test Lung supplied by Innotech Medical). Reference pressure sensor and fiber-optic pressure sensor have been placed on a platform P and arranged in order to measure respiratory pressure at the wye. The comparison between the output of the two sensors (Fig. 5) shows differential pressures measured with the optical fiber sensor (OFS) are consistent with that ones measured by the reference sensor (REF) and a maximum percentage error of about 7 percent is found.

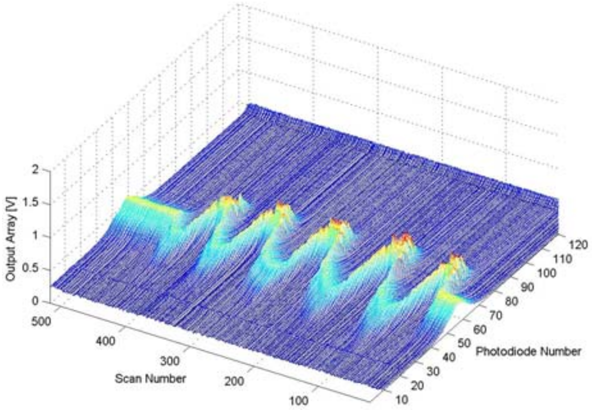

Fig. 2. Consecutive scans performed by the photodiode array during a respiratory trials (sampling frequency 20 scans/s; photodiode array responsivity 35 V/(μJ/cm2); single scan duration: 206.4 μs).

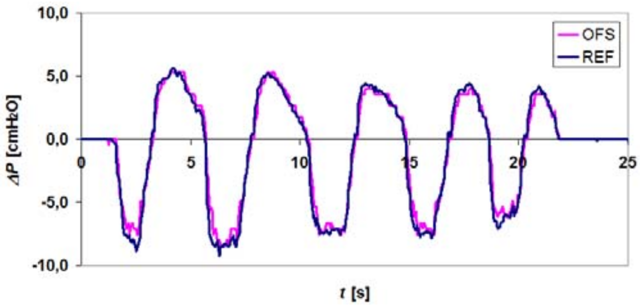

Fig. 3. Temporal variation of mount pressure during a respiratory tests performed by an healthy patient. OFS: differential pressure measured by optical fiber sensor (violet curve); REF: differential pressure measured by reference pressure sensor (blue curve).

Fig. 4. Experimental set-up. P: platform with reference pressure sensor (RP) and fiber-optic pressure sensor (OFS); TL: infant test lung; V: infant ventilator; DAQ: data acquisition card connected to OFS and RP.

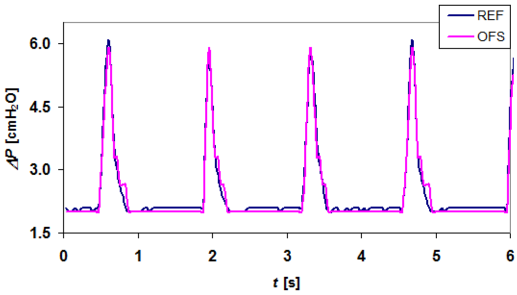

Fig. 5. Temporal variation of respiratory at the wye of pneumatic circuit. OFS: differential pressure measured by optical fiber sensor (violet curve); REF: differential pressure measured by reference pressure sensor (blue curve).

IV. CONCLUSIONS

A new optical fiber differential pressure sensor has been proposed for neonatal pulmonary ventilation and an experimental investigation on its dynamical metrological performances is here reported. The measurement system is based on a fiber-optic sensing technique, allowing the improvement of electrical safety conditions and the reduction of errors due to electromagnetic interferences.

The sensor principle is based on measuring the displacement of an optical fiber due to the differential pressure applied on a capsule by means of a photodiode linear array placed in front of the emitting face of the optical fiber. As the sensorial signal is encoded into an illumination pattern and into the position of the most lighted photodiode, that is independent by external optical power fluctuations, the proposed sensor isn't affected by environmental light intensity fluctuation.

The proposed measurement system has been preliminarily tested by monitoring the mouth pressure during simple respiratory tests in healthy patients and during mechanical ventilation performed by means of an infant ventilator typically used in neonatal intensive care units; results show that the output of the proposed optical fiber sensor is consistent with the one measured by means of a reference sensor. Other configurations are currently developed to improve sensor performances and applications.

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