

A Portable and Low-Cost Spirometer with Knife-Edge Optical Detection

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Summary:

We present a portable, low-cost optical spirometer that overcomes moisture-induced degradation of resistive sensors. A compliant double-leaf structure modulates transmitted light intensity under airflow, eliminating electrical elements from the airflow path. We demonstrate a linear optical response up to 160 kPa input flow pressure and distinguishable breathing patterns across multiple subjects, confirming the system's potential as a scalable disposable respiratory monitoring device.

Keywords: Spirometer, Optical sensing, Knife-edge optics, MEMS airflow sensor, Disposable sensors.

Introduction

Spirometry is a widely used diagnostic tool for assessing pulmonary function, particularly in diseases such as asthma and chronic obstructive pulmonary disease (COPD). Conventional spirometers are susceptible to contamination from saliva during repeated use and inadequate hygiene [1]. Furthermore, existing research on various sensing mechanisms indicated that many current devices are difficult to fabricate and lack disposability, further exacerbating the risk of contamination [2]-[4]. In our previous work, a disposable airflow sensor based on graphite-coated paper demonstrated low-cost fabrication and promising sensitivity. However, the electrical readout mechanism exhibited degradation due to moisture and biological contaminants, limiting long-term reliability in real-world conditions [5]. To address these limitations, here we propose an optical spirometer that eliminates electrical sensing components within the airflow path. By employing a knife-edge readout, airflow-induced mechanical deformation is transduced into an optical signal. This design leverages additive manufacturing and standard optoelectronic components, offering a robust, moisture-resistant, and cost-effective solution suitable for scalable personal healthcare applications.

System Description

Fig. 1 illustrates the proposed optical knife-edge detection system for a portable spirometer. A red LED array, mounted inside an SLA-printed tube, illuminates a flexible sensor element positioned 6 cm away from the LED source. Air pressure

impinges on the sensor, causing deflection that progressively unblocks the beam and modulates the transmitted light intensity. The diverging beam exiting the tube travels 9 cm before being collected by a convex lens, which the beam toward the photodetector positioned 3.5 cm beyond the lens. The resulting optical signal is converted to electrical domain via the photodetector and is recorded by a digital oscilloscope and transferred to a computer for post-processing.

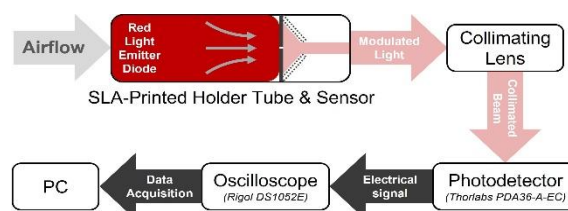


Fig. 1. Block diagram of the light-intensity-based air pressure measurement setup.

The proposed structure, shown in Fig. 2(a) and 2(b), illustrates the sensor geometry and FEM (Finite Element Method) analysis. The sensor consists of two semicircles, each with a radius (r_{dl}) of 9.5 mm and a thickness of 0.6 mm, separated by a gap (g_{dl}) of 1.4 mm in the initial (undeflected) position. The sensor is anchored inside the holder tube via cantilever beams of length (l_c) 3 mm attached to the semicircular leaves. This double-leaf structure is fabricated via SLA 3D printing (Anycubic® Photon Mono SE) using Anycubic® Tough Resin Ultra-Gray ($E = 1.35$ GPa, $\rho = 1118$ kg/m³). Simulations were performed to evaluate the mechanical response of the sensor under applied pressure.

Under a load of 11.732 kPa, the FEM analysis yielded a maximum deflection of $\delta_{max} = 7.22$ mm, confirming that the structure to support large deflections while remaining below the yield point. The geometry was optimized to ensure repeatable deflection while avoiding plastic deformation under typical spirometry pressure ranges [6].

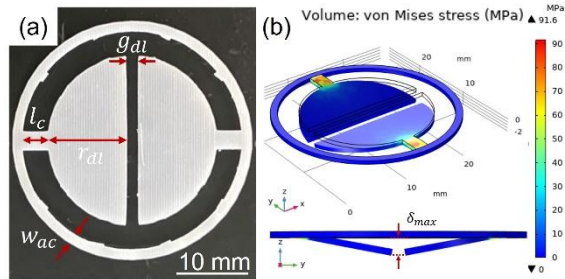


Fig. 2. (a) fabricated sensor with desing parameters, (b) FEM results of the double-leaf sensor ($\sigma_{max} = 91.6$ MPa).

Results and Conclusion

Figure 3 presents controlled airflow tests using an air compressor connected to the proximal end of the device, with pressure levels ranging from 0 to 700 kPa. Data was acquired 3 times at each pressure.

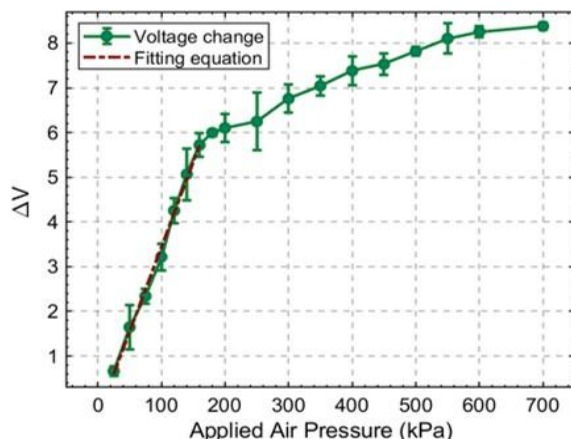


Fig. 3. Voltage response of the optical sensor versus applied pressure ($f(x) = 0.0379x - 0.3514$, $R^2 = 0.995$, $RMSE = 0.1431$). Error bars demonstrate 3 standard deviations of variability among experiments.

The sensor exhibited a linear response up to 160 kPa, with a sensitivity of 0.04 V/kPa. In this regime, mechanical deformation remains elastic and transmitted light intensity scales proportionally with the opening area of the double-leaf structure. Beyond 160 kPa, nonlinear mechanical deformation and photodetector saturation drive the sensor into nonlinearity, highlighted the importance of co-designing mechanical and optical subsystems for extended dynamic range. Second, human subject testing was conducted with four participants performing forced exhalation and inhalation maneuvers. As shown Fig. 4, distinct breathing profiles were captured across

subjects, with amplitude differences attributed to gender and smoking behavior (Subject 1 and Subject 2 are the only male smoker, and subject 4 is the only female subject). The results confirm the system's capability to extract meaningful physiological information, while the absence of electrical elements in the airflow path ensures moisture-resistant, stable operation addressing the primary failure mechanism of previously developed graphite-based sensors.

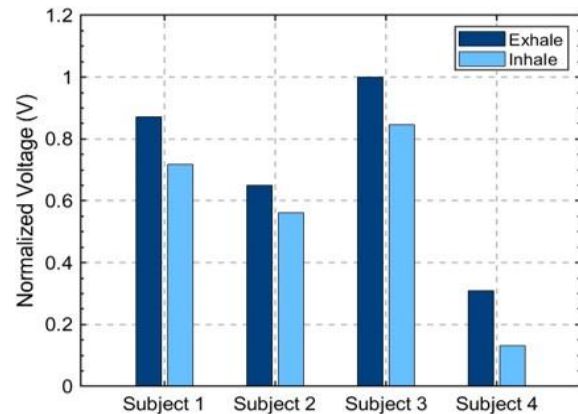


Fig. 4. Normalized exhale and inhale voltage responses recorded from four human subjects.

This work presents a low-cost optical spirometer replacing conventional electrical readout with optical modulation, demonstrating linear pressure response and successful capture of human respiratory patterns. Future work will target ray-tracing optimization, experimentation with a larger number of subjects and compact electronics integration for real-time portable healthcare applications.

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