A PIEZOELECTRIC ACTUATED AIRWAVE OSCILLOMETRY DEVICE

Lucas Posada[1], Hamed Hanafi[1], Guy Drapeau[2], Geoffrey N. Maksym[1]

1. School of Biomedical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3H 3J5
2. Thorasys Medical Systems, Halifax, Nova Scotia, Canada B3K2S2

ABSTRACT

Oscillometry (OS), also known as the forced oscillation technique (FOT) is used to measure lung mechanics and can be used to assess airflow obstruction in diseases such as asthma and chronic obstructive pulmonary disease in adults and children that, over the last decade, has gained a place as an alternative to conventional spirometry used in research studies and clinical practice. OS applies low amplitude pressure oscillations during normal breathing and, unlike spirometry, it doesn't require challenging respiratory maneuvers enabling its use in over a wider range of ages, patient physical conditions and treatment settings.

The present article describes the design and construction of an OS device. Current technology for measuring impedance using oscillatory pressure and flow is bulky using a loudspeaker and devices are substantially more expensive than spirometers, which significantly slows the adoption of this technology despite its clinical advantages. The device we develop here is innovative in that it uses an inexpensive lightweight beam bending piezoelectric based actuator system potentially greatly reducing cost, and simplifying the mechanical requirements. The device applies oscillatory pressure at 6 Hz or 19 Hz by moving a mesh disk of known resistance within a chamber through which the patient also breathes. The signal to noise ratios of the pressure and flow signals were satisfactory, achieving greater than 30dB even when employed on test loads up to a resistance of 15 cmH2O/l/s. This device can be implemented as a clinical diagnostic device or for home use in monitoring applications or included within the breathing circuit during mechanical ventilation.

INTRODUCTION

The OS principle is to apply forced oscillations at the airway opening at frequencies greater than the respiration frequency and its harmonics, thus the pressure and flow registered by the OS device are, for the most part, independent of the underlying respiratory pattern. For most clinical applications the preferred frequency rage starts as low as 4 Hz, and more commonly 5 or 6 Hz up to 32 Hz [1]. Lung mechanical parameters, for diagnosing and monitoring lung disease, are then estimated from the impedance of the respiratory system (*Zrs*) to the resulting flow oscillations *Zrs* is a complex quantity and consists of a real and an imaginary part. The real part describes the resistance of the respiratory system (*Rrs*) which is governed by the diameters of the airways while the imaginary part describes the reactance of the respiratory system (*Xrs*) and this governed largely by the elasticity of the lung tissues at low frequencies and inertia of the oscillating air at the upper frequency range.

Depending on its design, each type of OS device must generate an oscillatory pressure or flow signal to the airways. These external forcing signals may be mono-frequency or multi-frequency. Mono-frequency OS can be used for monitoring rapid changes in *Zrs,* monitor airway patency, or changes in the bronchomotor tone [2]. In most FOT devices, the pressure oscillations are either selected sine waves, random noise, or even impulse trains covering a broad frequency range. The signals are usually generated by a loudspeaker-in-box assembly and therefore are large and heavy.

In order to generate the oscillations, piezoelectric actuators bring many advantages compared to other methods of motion generation, like the most used electromagnetic (EM) type. They are more suitable to miniaturization since the stored energy density is larger than the EM type. There is no electromagnetic noise generation and therefore, there is no need for heavy shielding. They achieve higher efficiency since the energy density is insensitive to the size. And furthermore, piezoelectric actuators are safer under overload forcing [3].

METHODS

The general criteria from Oostveen et al.'s recommendations for FOT clinical practice provide recommended operating parameters for FOT devices [2]. Thus these provided the key design requirements for our design. In order to meet these requirements, fluid dynamics, vibration engineering theory and piezoelectric multilayered beam bending actuator practical concepts were used as described in the flowing sections. The prototype of the device was modeled in SOLIDWORKS®. For its construction, the custom parts were machined using computer numerical control (CNC) machining and off-the-shelf components where used to keep the cost of the prototype low.

Design

This device embodies a moving mesh to impose pressure oscillations of 6 Hz and 19 Hz on top of the breathing of the patients breathing. Equation 1 and 2 were used to calculate the displacement (amplitude) at which the mesh disk with area *A* must move to achieve the chosen pressure and resistance magnitudes at any particular frequency.

$$\delta = \frac{P}{R \cdot \omega \cdot A} \quad (1)$$

$$A = (\pi \cdot or^2) - (\pi \cdot ir^2 \cdot \gamma) \quad (2)$$

where δ is amplitude at the center of the mesh screen, *P* is pressure, *R* is resistance to air flow, *or* is the outer radius of the mesh, *ir* is the inner radius and γ is the percentage of open area of the wire cloth (mesh). Figure 1 shows the required amplitude of oscillation for different mesh-disk surface areas for an oscillating pressure amplitude of 0.5 cmH2O and mesh resistance of 0.5 cmH2O/l/s.

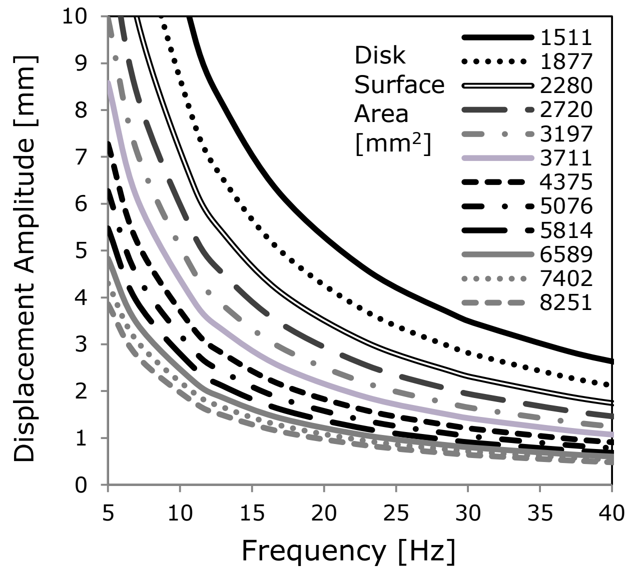

Figure 1

To deliver the motion of the mesh disk (Figure 5), the configuration of the piezoelectric was chosen to be a cantilever bender bimorph type of piezoelectric actuator due to the high displacement capability. To minimize costs, we chose an off-the-shelf bimorph with the longest available active length of 60mm, width 20mm and 0.70mm thickness, which could achieve a maximum deflection without mass at the tip of 2.6 mm at 150 DC Volts and a blocking force of 0.5 N. These actuators have a parallel electrical configuration that ensures high sensitivity to input drive and helps prolong the life of the actuator by eliminating the potential for depolarizing the ceramic layers as it uses a bias voltage circuitry [4].

In order to get larger displacements, the actuator had to be driven at resonance frequency. Since the oscillation frequency is a key aspect of the OS, the system was tuned so the desired frequency for FOT matched the damped resonance frequency (ω_d) of the actuator including the mesh-disk affixed on the end of the actuator tip. After some testing of the performance of the actuator by static and quasi-static tests [5], it was evident that the system was underdamped and the damping ratio was found by the log decrement method and half power method to be ζ=0.07. It was also found that the stiffness *k* became nonlinear after applying loads greater than 0.3 Newton. Equation 2 was used to calculate a theoretical estimate of ω_d as follows,

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \quad (2)$$

$$\omega_n = \sqrt{(k/m)} \quad (3)$$

where ω_n is the natural resonance frequency, k is stiffness, m is mass and ζ is the experimentally determined damping ratio.

Figure 2 shows the comparison of experimental data to the theoretical estimation given an average k of 340 N/m. Based on the experimental curve, we could choose the mass at the tip of the piezoelectric actuator for ω_d equal to 6 Hz and 19 Hz. Consecutively, two materials with different densities (ρ) were chosen so that the outer radius and thickness of the mesh disks remained constant. The materials used were brass for the 6 Hz mesh disk and ABS for the 19 Hz one.

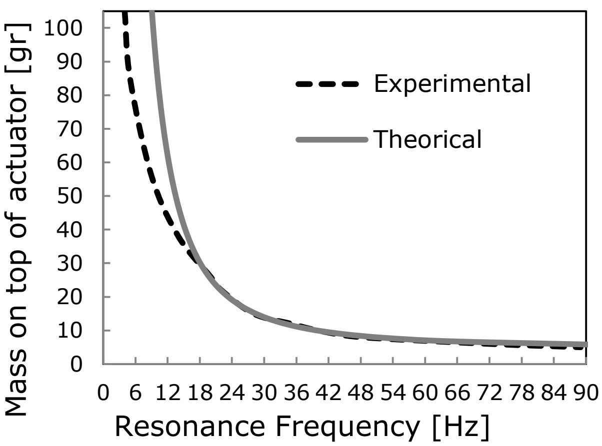

Figure 2

Each disk mesh was designed to have a different inner radius according to the needed *R* for the previously determined *P.* Considering the leak around the mesh disk, the device was design to have a gap between the mesh disk and the surrounding wall of less than 0.5 mm. The measured resistance of such gap was measured to be 1 $cmH_2O/l/s$. After this, the inner radius and mesh's open area can be tuned to match the resistance used in Eq. 1.

The piezoelectric actuator was always driven at the maximum AC amplitude recommended by the manufacturer (50 Volts p-p). Pressure and flow were measured using a modified off-the-shelf pneumotachometer with an extra pressure port (Figure 3) and a mesh resistance of 0.4 $cmH_2O/l/s$. Two ports, one on each side, were used for flow and the third for pressure. Both measurements are done using two highly symmetric 5 cmH_2O-range pressure transducers. The sensor data was acquired using a LABVIEW® acquisition card at 1000 Hz and *Zrs* and signal to noise ratio calculated using Bhatawadekar et al's algorithm [6].

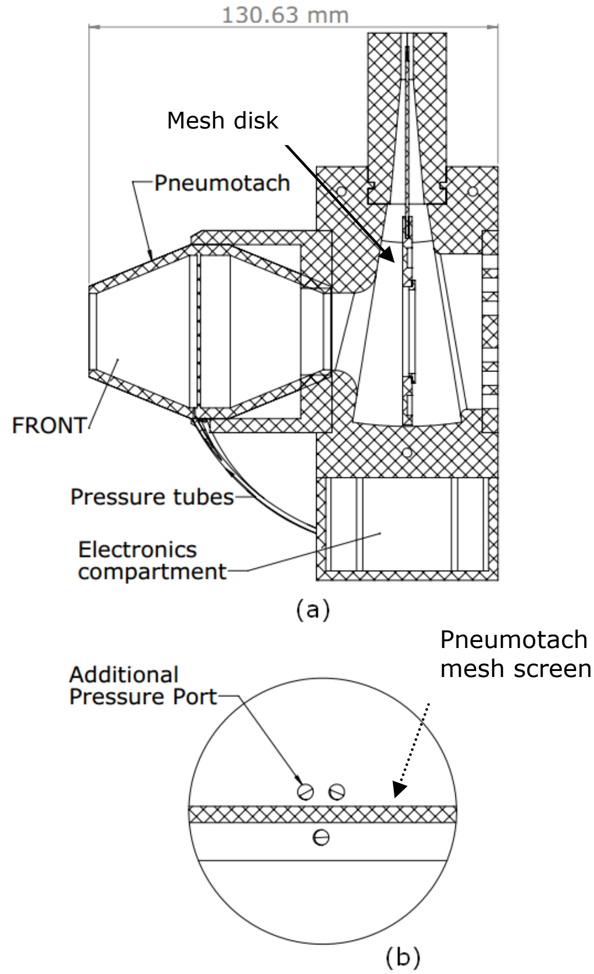

Figure 3

RESULTS

The novel OS device was built according to the design and then tested using three test loads with a resistance to flow value of 1 $cmH_2O/l/s$, 5 $cmH_2O/l/s$, and 15 $cmH_2O/l/s$. The device has two interchangeable mesh disks that allowed it to apply pleasure waves at 6 Hz or 19 Hz. Figure 4 shows a drawing from the 3D model. The body parts were made of ABS making it sturdy and light weighted.

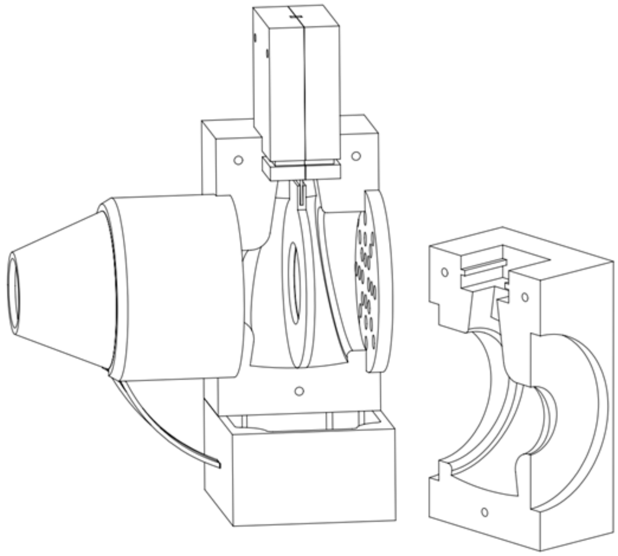

Figure 4

The traces in Figure 5 show the frequency response of the mesh disk's displacement during a frequency sweep chirp input from 0 to 30 Hz separately with each mesh disk. Since this underestimates resonant performance due to the rate of the frequency sweep we also measured the response at resonance indicated by the upper dots, together indicating adequate performance at resonance.

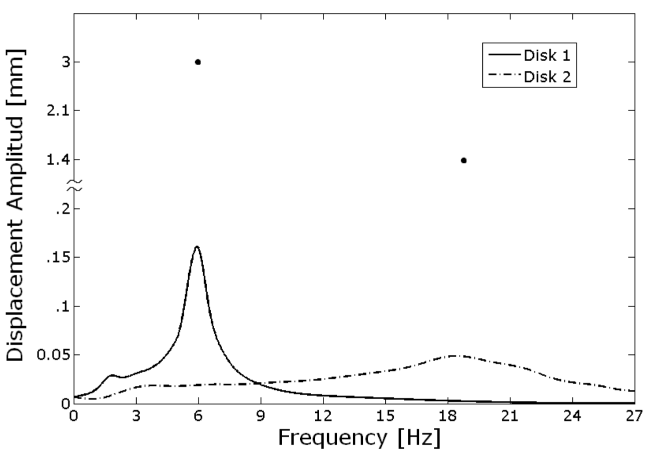

Figure 5

Table 1 shows the values of SNR in dB computed for flow and pressure, with the >30dB requirement exceeded for all test loads and frequencies.

Table 1

	1 cmH2O/l/s		5 cmH2O/l/s		15 cmH2O/l/s	
SNR (dB)	6 Hz	19 Hz	6 Hz	19 Hz	6 Hz	19 Hz
Flow	46.5	45.9	39.9	41.0	45.9	33.0
Pressure	56.3	56.8	59.6	58.3	56.8	61.9

CONCLUSION

This device is a proof of concept that an OS can be implemented in a compact, inexpensive, light-weighted and portable fashion with reliable performance. It represents a less expensive to manufacture and much simpler mechanical actuator design than any other approach.

The device takes advantage of the natural resonance of the actuator and thus requires very little power for operation; it could thus be battery operated. Given its characteristics and performance this device is particularly suited for easy assessment of respiratory mechanics for diagnosis and disease monitoring.

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