Design and Fabrication of Piezoelectric Artificial Cilia for Airflow Sensing in Mobile Robot with Surface Mount

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Abstract. In order to realize the measurement of airflow velocity in narrow spaces, we fabricate, package and characterize a flexible and surface mount piezoelectric artificial cilia (PAC) for airflow sensing in a piezoelectric mobile robot (PMR). The diameter and height of the cilia are 0.3 mm and 5 mm, respectively, whose sensitivity is 30 (mV)/(m/s). Meanwhile, the PMR is 32.8 g in mass and 55 mm × 50 mm × 20 mm in size and it is capable of achieving a velocity of 200 mm/s. This sensing robot has advantages of light weight, miniature size, and low cost, which has potential to effectively evaluate air leakage in the pipeline.

Keywords: airflow sensor; artificial cilia; mobile robot; electrospinning.

1. Introduction
Air leakage can reduce the effective airflow in the coal seam, and accelerate the oxidation of the coal mine goaf, which is very easy to cause accidents such as coal spontaneous combustion and gas explosion [1, 2]. Therefore, it is particularly important to take effective and accurate methods to detect air leakage and find air leakage passages in coal mine safety. There is a positive correlation between air leakage and air velocity. Hence, the key to prevent coal seam spontaneous combustion is to monitor the airflow rate. Now, potential applications would include imaging and maneuvering control for autonomous mobile robots (AMRs), intrusion detection (ID) systems, and pipeline ventilation monitoring system [3, 4]. For example, the primary condition of coal seam spontaneous combustion is continuous oxygen supply, that is, air leakage. There is a positive correlation between air leakage and air velocity. It can be seen that accurate control of flow rate can effectively prevent coal seam spontaneous combustion. At present, the flow rate is measured manually, which requires a lot of personnel and time to collect the data [5, 6]. So, piezoelectric artificial cilia mounted on mobile micro robot can monitored and inspect the autogenous ignition area continuously in mine.

The traditional devices for measuring the velocity of flow in pipelines include ultrasonic anemometer and vortex street anemometer [7, 8], but they are too large to be located in narrow spaces. Fortunately, the cilia type of sensors is small and can detect the airflow in a space-limited environment. Some sensing cilia based on piezoelectric nanofibers have been reported and obtained by electrospinning method [9,
those piezoelectric sensing cilia on a flexible substrate had a high output voltage, whose maximum voltage can be 270 mV in bending mode [9]. The preparation of oriented piezoelectric nanofibers can greatly exert the positive piezoelectric properties. The sensitivity of oriented piezoelectric nanofibers is almost 40 times that of piezoelectric films [10]. Therefore, we design a type of piezoelectric artificial cilia with a copper core for airflow sensing, which can satisfy the demand of pipeline ventilation monitoring system [11, 12].

In this paper, a piezoelectric artificial cilia for airflow sensing in mobile robot with surface mount is designed and fabricated. The diameter and height of the cilia are 0.3 mm and 5 mm, respectively, whose sensitivity is $30 \text{ (mV)/(m/s)}$. Note that the PMR is 32.8 g in mass and $55 \text{ mm} \times 50 \text{ mm} \times 20 \text{ mm}$ in size and it is capable of achieving a velocity of 200 mm/s. At this point, the main design focus of this study would has advantages of light weight, miniature size, and low cost, which has potential to effectively evaluate air leakage in the pipeline.

2. Methods

Figure 1 shows an assembly process sketch of piezoelectric mobile micro robot. The equipment includes electrospinning instrument, power supply (including of signal generator and power amplifier), X-Y motion platform, collector in figure 1(a). The electrospinning solution was prepared following the method: first, a quantity of 1.68 g of PVDF-TrFE co-polymer power was dissolved in the solution of acetone, and the mixture has been heated at 50ºC for 1h. Then, this mixture solution was dissolved in the solution of 6 mL of dimethylformamide (DMF). The solution was transferred into a syringe for the electrospinning use. The micro/nano fibers array fabricated by the electrospinning can easily control fibers diameters (0.38 – 2.4 μm). Finally, a compact piezoelectric film is formed as shown in figure 1(b). Figure 1(c) shows the assembly process of piezoelectric artificial cilia (PAC). A copper wire acts as the supporting layer and the electrode of cilia, and then the PVDF nanofiber film is warped around the wire to form the PAC. Finally, the cilia are glued to the surface of the piezoelectric actuator to form the piezoelectric mobile micro robot (PMR).Figure 1(d) shows that the diameter and height of the cilia are about 0.3 mm and 5 mm, respectively. In addition, the PMR is 32.8 g in mass and $55 \text{ mm} \times 50 \text{ mm} \times 20 \text{ mm}$ in size.

Figure 2 shows the airflow velocity testing system. The PAC was connected to the charge amplifier and the NI data acquisition card through some electronic wire, and finally connected with the LabVIEW software interface in the laptop. When the airflow blows through the PAC, the vibration of the PAC results in the response charges generation of the piezoelectric fibers according to piezoelectric effect,
and this response charges were converted to response voltage (Um). Low-speed airflow can be perceived through this testing system, and the flow-rate range of the testing flow is from 1 m/s to 3 m/s.

Figure 3 presents the velocity characteristics of the PMR and the response voltage characteristics of a PAC with normal flow. In figure 3(a), the directional linear velocity changes when the amplitude Aw varies from 40 Vpp to 120 Vpp at a constant frequencies w1-path of 37930 Hz and w2-path of 14030 Hz, respectively. Both the directional linear velocities increase roughly in proportion to the amplitude of the applied voltages (Aw). Therefore, the multiple locomotion states of our proposed robot can be controlled by adjusting the resonance frequencies and applied voltages. According to Fig. 3(b), the response voltage is linearly following variation of the flow velocity, ranging from 1 to 3 m/s. The fitting curve can be achieved according to these data, and the relation between maximum voltage value (Um) and flow velocity is a linear relations. Meanwhile, the response voltage of a PAC shows a wave status and the Um is 60 mV as shown in Fig. 3(c) in first 0.1 s and at 2 m/s.

![Airflow velocity testing system](image)

**Figure 2.** Airflow velocity testing system: (a) schematic diagram of PMR; (b) photograph of measurement system.

### 3. Sensing model

The dynamic electromechanical equation of a PAC based on single degree of freedom is as follows:

\[ m\ddot{y}_t + c\dot{y}_t + ky_t - \theta U = F_y, \tag{1} \]

\[ \theta\dot{y}_t + C_p U + \frac{u}{R} = 0, \tag{2} \]

\[ F_y = \frac{1}{2}\rho\nu^2A_\xi \tag{3} \]

Where m is the mass of the oscillation of PAC, c is the structural damping, and \( k \) represents the stiffness. In addition, \( F_y \) represents the time-dependent excitation of the fluid flow applied on the PAC, \( \theta \) is the electromechanical coupling term, \( R \) is the electrical load resistance, \( U \) is the voltage across the load resistance, and \( C_p \) is the capacitance of the PAC, and \( y_t \) is the displacement of the PAC.
Meanwhile, $F_y$ is the drag force; $\rho$ is the fluid density in air; $v_{\text{normal}}$ is the normal flow velocity; $A$ is the projected frontal area of the cilia facing the flow; $L$ is the length of the cilia; $\xi$ is the drag coefficient that is a dimensionless constant and the value is 1.0–1.3 in airflow.

According to Eq. (1) ~ (3), the relationship between flow velocity ($v$) and response voltage ($U$) can be established.

![Figure 3](image1.jpg)

**Figure 3.** The velocity characteristics of the PMR and the response voltage characteristics of a PAC with normal flow: (a) The relationship between the amplitude of applied voltages ($A_w$) and linear velocity at a constant frequencies $w_{1\text{-path}} = 37930$ Hz and $w_{2\text{-path}} = 14030$ Hz, respectively; (b) relation between the response voltage and the flow velocity from 1 to 3 m/s; (c) time-domain curve of the response voltage at 2 m/s.

4. Conclusion

In order to effectively evaluate air leakage in pipeline of the coal seam autogenous ignition, a flexible and surface-mountable of piezoelectric artificial cilia are developed. A PAC mounted on mobile robot can sense flow velocity. At 2 m/s, the sensitivity of the cilia is 30 (mV)/ (m/s). The maximum speed of PMR can reach 200 mm/s when $A_w$ is 200 V. The sensing device is characterized by light weight, small volume, low energy consumption, and easy to the actuator surface. Such characteristics can move to the targeted point in a narrow environment and passively sense the airflow.

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