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Design and Fabrication of a Multi-electrode Metal-core Piezoelectric Fiber and Its Application as an Airflow Sensor

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Abstract

Crickets, similar to some other insects, have highly sensitive filiform hairs on their cerci that can detect miniscule changes in airflow. This study imitates the perception mechanism of these filiform sensory hairs of crickets by designing and fabricating a Multi-electrode Metal Core Piezoelectric Fiber (MMPF)-based airflow sensor. Four longitudinal conductive sheets were coated symmetrically on their surfaces with Metal-core Piezoceramic Fibers (MPF). The four fan-shaped piezoelectric ceramics with surface electrode covers were polarized. After successful polarization, the cantilevered MMPF could be used as an airflow sensor. The four electrodes on the surface were symmetrically divided into two groups. Therefore, two signals can be produced by a single fiber sensor. The theoretical model of an MMPF airflow sensor has been established. The model indicates that the ratio of the two signals is equivalent to the tangent of the airflow angle. Furthermore, the sum of the squares of the two signals is not dependent on the angle, but reflects the velocity of the airflow. Therefore, a single MMPF can be used to measure both the direction and amplitude for a given airflow. The theoretical model has been confirmed *via* experimental measurements.

Keywords: biomimetic sensor, piezoelectric fiber, airflow sensor, artificial hair, directional sensitivity

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1 Introduction

In nature, many animals have the capacity to sense their surroundings in many different ways, an essential requirement to survive[1]. More specifically, some insects can escape attack by sensing the location and movements of their enemies. Crickets sense airflow variations using their highly sensitive cerci systems[2]. A cricket has a pair of cerci that stretches out from its belly, and each cercus contains many sensory hairs with different lengths, as shown in Fig. 1a. The structure of the hairs is shown in detail in Fig. 1b. One end of a smooth straight bar is vertically aligned to the surface of the cercus, while the other end is free. When air flows through the hair, the cilia will bend and thus leads to the deflection of the root. This deflection will be passed on to the neurons, which will stimulate the neuron. This type of transformation travels to the nerve cells that are connected to the straight bar[3]. Subsequently, an impulse will be generated by the nerve cells and sent to the brain *via* the nerve fibers. This can help a cricket to sense the surrounding airflow and then take appropriate actions, such as running away from its enemy or hunting its own food[4]. The length of these sensory hairs are not equal but range from 150 μm to 750 μm[5]. A large number of sensory hairs of different sizes are essential to allow a cricket to sense the amplitude and direction of the impact airflow[6].

During the past decade, researchers have designed and fabricated artificial hair sensors by imitating the structures and functions of a cricket hair receptor. These sensors have been used in robots, intelligent vehicles and other systems to sense minuscule variations in the surrounding airflow[7]. Artificial hair sensors are typically employed with a cantilever structure where one straight bar is vertical to the surface of the substrate[8]. Airflow causes the cantilever to bend and transform. Both the amplitude and direction of the airflow can be determined through the bending transformation[9]. The extent of bending transformation of the cantilever can be measured either directly or indirectly[10]. With the indirect measurement method, the sensing element is connected to the fixed end of the cantilever. The degree of cantilever bending can be obtained by measuring the

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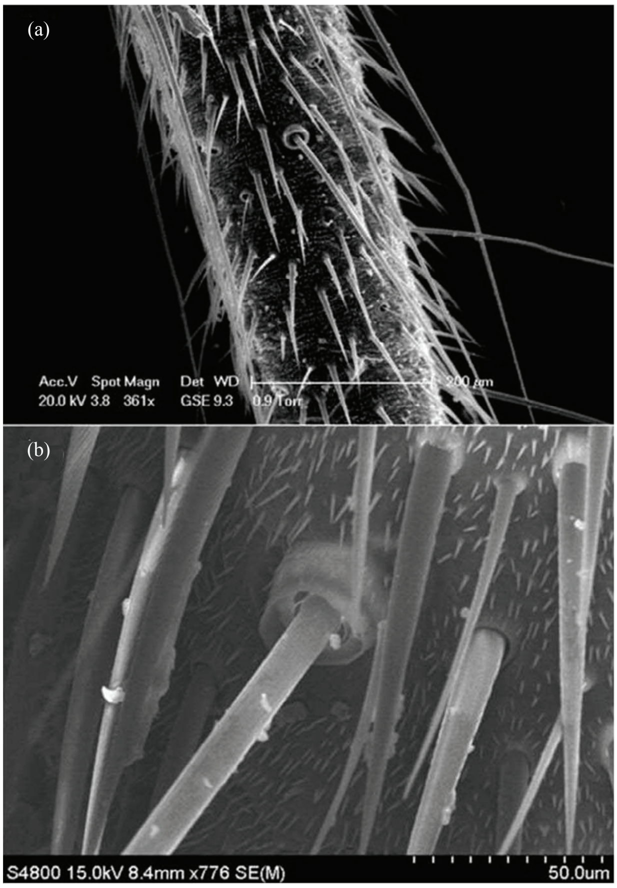

Fig. 1 (a) Amplified tail fibers of a cricket and (b) structure of a sensory hair.

transformation of the fixed end. A miniature capacitor or a piezo-resistance element is used as the sensing element in this method[11].

Droogendijk *et al* fabricated a capacitance bionic hair airflow sensor, where the fixed end of the cantilever and a movable miniature capacitor are connected[12]. When air flows through the cantilever, the airflow volume can be determined by measuring the variation across the movable capacitor[3]. These types of sensors can be combined into an array, which can then be used to measure entire airflow field distributions[13] and the distributions of flowing water[14]. The achievable resolution depends on the density of the sensor array[15].

Fan *et al* fabricated a piezo-resistance bionic hair airflow sensor, where the base of the cantilever is connected to a resistance strain gauge using Micro-electromechanical System (MEMS) technology[16,17]. The variation in resistance is determined using the known proportional behavior of a Wheatstone bridge. In addition, cantilever bending can also be measured and quantified. Furthermore, both the direction and velocity of airflow can also be measured if many bionic hair airflow sensors of this type are combined into an array[18]. In a bionic hair airflow sensor, the shape of each cantilever is either a sheet, a homogeneous cylinder or a heterogeneous cylinder[19]. Dickinson *et al*[20] and Rizzi *et al.*[21] also used a similar structure to fabricate bionic hair airflow sensors.

The above capacitance and piezo-resistance bionic hair airflow sensors all work by measuring a change of capacitance or resistance in relation to the fixed end of the cantilever. They both indirectly measure the bending and transformation of the cantilever. However, bending and cantilever transformation information can also be obtained using a more direct measurement method. In general, in these types of sensors, the cantilever is made of piezoelectric materials that convert mechanical movements into electric signals. Tao *et al.* coated the surface of a piezoelectric ceramic fiber with a metal layer[22]. Two surface electrodes were fabricated after removing the two narrow longitudinal bands through photolithography. A piezoelectric ceramic fiber sensor with a cantilever structure was produced after polarization. Their experiments shaw that this sensor has an excellent directional tip displacement sensing property of the cantilever.

The strength of the piezoceramic fiber increases if there is a metal core residing in the center of the piezoelectric ceramic fiber. This metal core serves as an electrode while the coated metal layer on the surface of the ceramic acts as the other electrode. This type of Metal-core Piezoceramic Fiber (MPF) can be produced using a hydro-thermal method[23]. Alternatively, a squeezing and pressing method[24] can also be used to achieve a similar fiber. Qiu *et al.* coated only half of the longitudinal surface with a metal layer, thus creating a Half-coated Metal-core Piezoelectric Ceramic Fiber (HMPCF)[25]. Only the piezoelectric ceramic section that was covered by electrodes can be polarized in the HMPF and shows piezoelectric properties. There are no piezoelectric properties shown along the surface area without the electrode. HMPCF can be used as an airflow sensor to detect the direction or the velocity of the airflow.

One disadvantage of the artificial hair sensors discussed above is that each single sensor can only detect one parameter (the amplitude or the direction of the airflow), but not both at the same time[26]. A combination of sensors is required to measure both the size and di-