Thermally Drawn Piezoelectric Fibers Impart Acoustic Functionality to Fabrics

by Grace Yang

November 13, 2023 at 8:45am in 6-104

Acoustic interactions with fabrics have predominantly revolved around their use as sound absorbers, leaving a broader spectrum of fabric-acoustic interactions relatively unexplored. This thesis investigates how the relationship between fabrics and acoustics can be leveraged for innovative applications through the use of a piezoelectric fiber. This acoustic fiber can be incorporated into traditional fabrics to transform them into microphones and loudspeakers. Various experiments and simulations are devised to understand how fabric properties influence fabric vibrations, which can be used to detect or emit sound. Once the fundamental working mechanisms are understood, fabric systems are engineered to optimize the performance of these acoustic fabrics for various applications.

The acoustic fiber is the key technology that enables this work, as fibers are the building blocks of fabrics. Thermal drawing allows for the scalable production of multimaterial fibers with complex architectures, providing functionality, such as that of an acoustic actuator. In the thermal drawing process, multiple viscoelastic materials flow in a laminar regime, maintaining the cross-sectional geometry of the macroscopic preform. In the fiber device, the piezoelectric domain of P(VDF-TrFE) with 20 wt% barium titanate (BTO) nanoparticles is sandwiched between two carbon-loaded polycarbonate electrodes. During the draw, two copper wires are fed into each electrode to preserve conductivity over long lengths of the fiber. The active layer and electrodes are encapsulated by an elastomer cladding. The measured d_{31} piezoelectric coefficient of the active domain of the fiber is 46 pC/N, which is more than double the values reported previously. Poling is a crucial step where high voltages align the piezoelectric dipoles, and breakdown must be prevented. The piezoelectric domain in the fiber, with an estimated breakdown strength of < 165 MV/m, is poled to an electric field of 133 MV/m. To enhance yield, a new method for terminating and connecting fibers for poling has been developed. The processing methods are investigated in detail to reliably create fibers with high piezoelectric performance.

When the acoustic fibers are incorporated into fabrics, sensitivity is enhanced, turning the fabric into a functional microphone. The fiber picks up nanometer-scale vibrations that arise in the fabric in response to incident sound. The acoustic sensitivity of a fabric woven with this fiber is comparable to typical handheld microphones, measuring 8 mV/Pa. Experimental and COMSOL simulation results show that the axial bending of the fiber predominantly contributes to the piezoelectric response, with longer wavelengths resulting in higher voltages due to charge accumulation on the same electrode. Moreover, the mechanical properties of the fabrics can be tuned to enhance performance, as demonstrated with fabrics with different Young's moduli.

Incorporating the acoustic fiber into clothing opens new possibilities in biometric monitoring. potential. The fiber reliably detects the heartbeat and breathing of adults when woven into the fabric, and an array of two fibers can accurately determine the direction of a sound source. Preliminary results suggest the possibility of using acoustic fibers for fetal monitoring during pregnancy, which would be a significant advancement in healthcare applications.

In addition to sensing, the acoustic fiber can also be used for emission. Applying a 1 kV AC voltage to a 6.7-cm fiber sewn onto an 8-cm diameter silk fabric generates micron-scale fabric vibrations, resulting in sound up to 70 dB measured 2.5 cm away. Different fabrics (muslin, canvas, silk, parachute) are tested and compared. Scanning 2D laser vibrometer measurements reveal that, despite the complexity of the fabric structure, its vibrational behavior is reminiscent of a classical thin plate. Additionally, the relative size of the pores compared to the viscous boundary layer effects the efficiency of the sound generation. Understanding how the fabric properties relate to acoustic performance is key for engineering acoustic fabrics.

In addition to emitting sound propagation, the fabric loudspeaker can be used for active noise canceling. In many instances, active noise canceling can save material costs and space while providing greater attenuation, particularly at lower frequencies compared to passive noise reduction using sound-absorbing panels. Active noise canceling is achieved by emitting sound waves that destructively interfere with the sound waves of the unwanted noise. The superimposed sound waves result in constant pressure, which means no sound. With just a single piezoelectric fiber device, the fabric loudspeaker can function as an active noise canceling device by emitting sound that is out of phase with the unwanted sound. The silk loudspeaker, with a thickness of just 0.13 mm, demonstrates effective sound cancelation at the point of detection (i.e., microphone), showing promise for noise-canceling applications.

This active noise canceling approach using just one speaker only achieves sound cancellation at particular points in space. Because active noise canceling only works locally, limiting the transmission of sound *into* a room is a way to reduce the noise in the entire room without requiring multiple transducers in different locations. In order to effectively limit acoustic transmission into a space, the structural vibrations which are transmitting the sound must be controlled. To achieve efficient vibration cancellation on fabric surfaces, the fabric loudspeaker generates vibration patterns similar to those caused by external sound sources. This vibration suppression is measured for the first time using scanning laser vibrometry, showing up to a 94% reduction in average surface displacement. When external sound waves impact the fabric, they are reflected back rather than propagating energy within the fabric. Thus, the acoustic reflectivity of the fabric increases, with SPL measurements showing an increase in SPL on the side of the unwanted noise and a decrease on the other side.

The integration of the fiber into textiles maintains the fabric's structural identity while enabling innovative acoustic applications. These acoustic fabric systems offer novel possibilities, including sound direction detection, biometric sensing, and noise control. This work marks a significant advancement in the intersection of textiles and acoustics, promising exciting potential ways in which fabrics interact with sound and can be reimagined as collectors of acoustic information and actuators to manipulate sound fields in useful ways.

Advisor: Yoel Fink, Ph.D.
Professor of Materials Science and Engineering
Professor of Electrical Engineering and Computer Science

Co-Advisor: William Tisdale, Ph.D.
Professor of Chemical Engineering