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The Nanophone: Sensing sound with nanoscale spider silk

R. N. Miles and Jian Zhou
Department of Mechanical Engineering
Binghamton University
State University of New York
Binghamton, NY USA
Outline

1. Directional acoustic sensing based on pressure.

2. Sense sound with thin fiber. How thin should it be?

3. Sub-micron fiber provides ideal acoustic sensing

4. Electrostatic sensing for compliant electrodes
Nearly all microphones are designed to sense pressure Just like our ears

Engineers copy from biology (even without trying)
Typical hearing aids use two microphones to reduce interfering noises.

Process differences in pressure.

subtract
Typical Directional Microphones Sense Pressure

Directivity Pattern for First-Order Directional Microphone
Difference signal becomes smaller as wavelength increases (frequency goes down) or as D becomes small.
Directional microphones have terrible frequency response

Measured Sensitivity

- Single omnidirectional microphone
- Difference of signal from two omnidirectional microphones
Directional microphones for smart speakers
Most animals don’t sense sound pressure. They use sensory hairs to hear sound.

Mosquito antennae sense sound

https://www.microscopyu.com/galleries/digital-imaging

Spider hairs sense sound

Cricket cercal hairs sense sound
Previous work on biomimetic acoustic sensing: *Ormia ochracea*

**Tympanal ears sense pressure**

**Ideas for better directional microphones**

Patents based on *Ormia*

- At least 44 patents
- 22 patents issued on microphones to Binghamton
- *Ormia*-patents issued to others:
  - ATT
  - Siemens, Germany
  - University of Arizona
  - Corporation for National Research Initiatives (CNRI)
  - US Army
  - University of Tokyo
  - University of Maryland
  - Intel Corporation
  - US Navy
  - University of Texas, Austin
  - Shanghai Jiaotong University
  - Symphony Acoustics, Inc.
  - University of Wisconsin- Madison
sound is more than just pressure

Sound is:
- Fluctuating pressure
- Fluctuating velocity
- Fluctuating temperature
- Fluctuating density
Molecules in a gas
Plane wave propagation
Man-made flow velocity sensors have much lower response than those of animals


Velocity response of natural hair and best MEMS device[1]
Man-made flow velocity sensors have much lower response than those of animals.

Velocity response of natural hair and best MEMS device

References:
Light, thin objects move with the air.

Viscous forces can dominate.

How thin should a fiber be to move with the air in a sound field?
Analytical model: Motion of a fiber due to acoustic particle velocity

Assume flow is perpendicular to fiber axis

\[ u(y, t) = U e^{i(\omega t - ky)} = \frac{p(y, t)}{\rho_0 c} = \frac{Pe^{i(\omega t - ky)}}{\rho_0 c} \]

Plane sound wave
Thin fibers move with the flow

Model fiber as an elastic beam with circular cross section:

\[ E \frac{\pi r^4}{4} w_{xxxx} - E \pi r^2 w_{xx} \left( \frac{Q(L)}{L} + \frac{1}{2L} \int_0^L w_x^2 \, dx \right) + \rho_m \pi r^2 \ddot{w} = f_v(t) \]

Excitation is force from viscous flow (after Stokes 1851):

\[ f_v(t) = F_v e^{i \omega t} = \frac{\rho_0 c k r \pi i}{m} \left( \frac{K_1(mr)}{K_0(mr)} + mr \right) V e^{i \omega t} = Z(\omega) V e^{i \omega t} \]

As diameter gets small, right side dominates:

\[ 0 \approx f_v(t) = \frac{\rho_0 c k r \pi i}{m} \left( \frac{K_1(mr)}{K_0(mr)} + mr \right) (u(0, t) - \dot{w}(x, t)) \]

Approaches zero
\[ Z(\omega) = \frac{F_v}{V} = \frac{\rho_0 ckr \pi i}{m} \left( 4 \frac{K_1(mr)}{K_0(mr)} + mr \right) \]

\[ Z(\omega) = R(\omega) + i\omega M(\omega) \quad \text{Damping plus inertia} \]

Solution for finite length fiber:

\[
\frac{V_F(x)}{U} = i\omega \sum_{j=1}^{\infty} \frac{Z(\omega) \phi_j(x) \frac{2}{L} \int_0^L \phi_j(z) \, dz}{\left( EI p_j^A + EA p_j^2 Q(L) / L + i\omega (Z(\omega) + i\omega \rho_m \pi r^2) \right)}
\]

6 micron stainless steel
Blue Barn Fiber (Etsy)
Well-controlled plane wave, \( U = \frac{P}{(\rho_0 c)} \)

Experimental setup

Binghamton anechoic chamber
Binghamton University Anechoic Chamber

Robot

The interior wedge tip to wedge tip dimensions of the chamber are 13'-8" wide by 17'-8" long by 10' 6" high.

Anechoic for all frequencies above 80 Hz

0.5 dBA noise floor

Measured loudspeaker directivity
Promising results for 6 micron steel wire

The model says the response becomes flat as fiber diameter is decreased.
Try thinner wire/fiber-electrospun pmma
Spider silk

Materials

Tiny spider on its web

SEM image of spider silk
measured broadband flat response 1 Hz – 50 kHz

Submicron spider silk performs better than natural and artificial hair

Frequency response of 500nm spider silk


Excellent agreement with mathematical model

Effect of diameter on silk frequency response
Simple electrodynamic transduction
Flat frequency response measured 1 Hz - 10 kHz

$E = BLv$, $v = V_{air}$

Directional, passive, broadband acoustic sensor with flat response

Conductive silk by evaporating gold

3 Hz directional sound detection in miniature space

Directional sensor response at 3Hz
\[ e(t) = E_0 \cos(\theta) \]

3 Hz flow

Single sensor

\( \lambda \approx 114 \text{ m} \)

First-order directional response
Fiber microphone provides nearly ideal figure 8 directivity pattern at all frequencies

**Directionality and sensitivity are independent of frequency**

Fiber velocity microphone has flat frequency response
Response of pressure gradient microphones is proportional to frequency
Welcome to future of sound recording
Sound induced motion of a spider web

Spider and its web
Speakers

Anechoic chamber

Spider orb web

Laser vibrometer

2D linear stage

Microphone

Mounting plate
This is video!

100Hz

500Hz
4. Response to wing beat, cricket call, and bird song
New capacitive sensing as an alternative to electrodynamic sensing

Use with highly compliant electrodes
- Three electrodes
- Absolute stability

Sound pressure

Electrode velocity

Output voltage
0.5 volt/pascal
Bias has negligible effect on response but increases sensitivity

Primary innovations

- Sense sound using viscous force rather than pressure
  - Use thin, compliant element
    - Flat frequency response from infrasound to ultrasound
    - High temporal, spatial, and amplitude resolution
    - First-order gradient directivity independent of frequency
    - Low frequency sound localization in miniature space
    - Passive sensor, can also work as a nanogenerator

- Capacitive sensing for compliant electrodes
Thank you!
Thin fibers move with the flow

Model fiber as an elastic beam with circular cross section:

\[ E \frac{\pi r^4}{4} w_{xxxx} - E \pi r^2 w_{xx} \left( \frac{Q(L)}{L} + \frac{1}{2L} \int_0^L w_x^2 \, dx \right) + \rho_m \pi r^2 \ddot{w} = f_v(t) \]

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