



Integrity ★ Service ★ Excellence

Embedded Sensors for Autonomous Air Systems

LRIR 09RW10COR

AFOSR Annual Meeting, PM:Les Lee
Mechanics of Multifunctional
Materials & Microsystems
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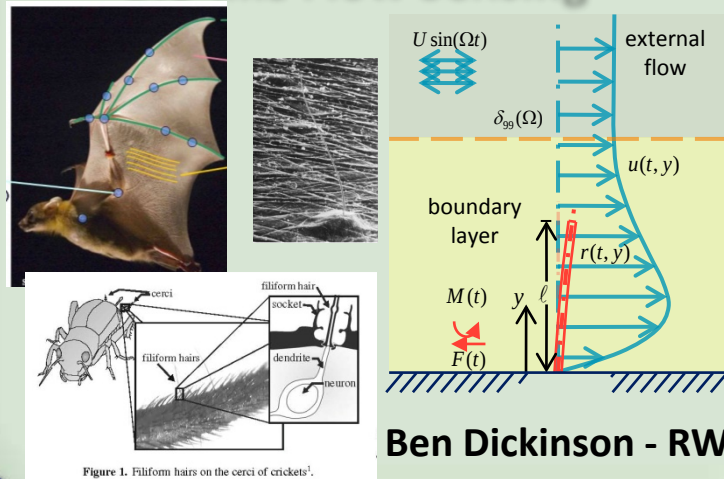
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Embedded Sensors for Air Vehicles

LRIR 09RW10COR – Dickinson (RW) / Baur (RX) / Reich (RQ)

Bio-like Flow Sensing

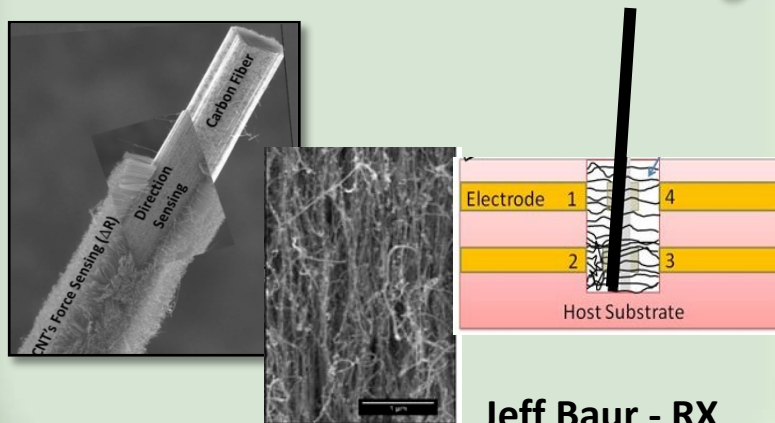


Ben Dickinson - RW



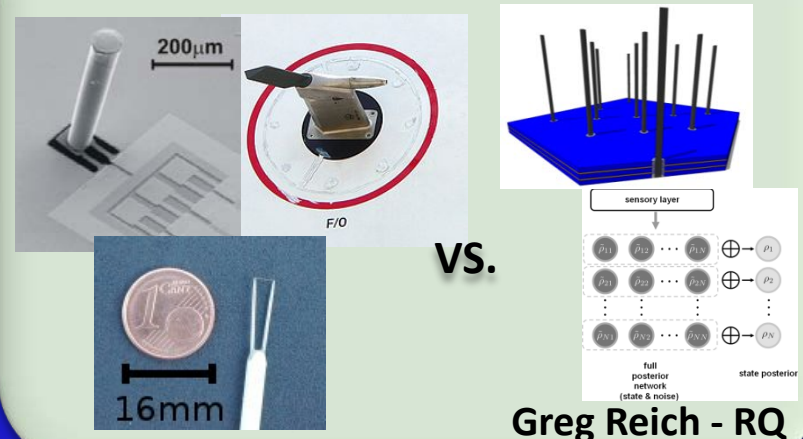
Can we enable
“fly by feel”
with
“insect grade” hair flow sensing
by understanding
Air Flow->
Hair Deflection ->
Nano-array transduction ->
Aero State Awareness

Hierarchical Fiber Nano-sensing



Jeff Baur - RX

“Insect Grade” Sensors to “Feel”



Greg Reich - RQ

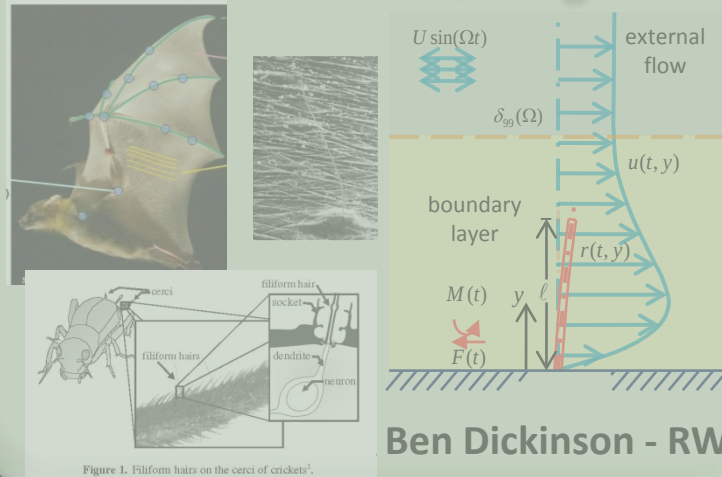


Embedded Sensors for Air Vehicles

LRIR 09RW10COR – Dickinson (RW) / Baur (RX) / Reich (RQ)



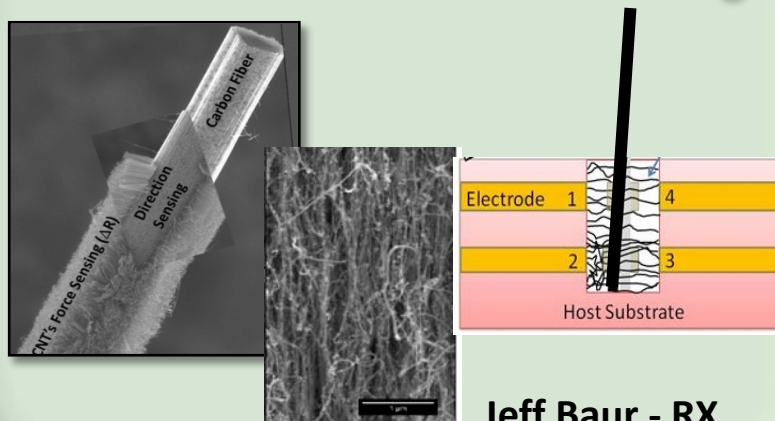
Bio-like Flow Sensing



Ben Dickinson - RW

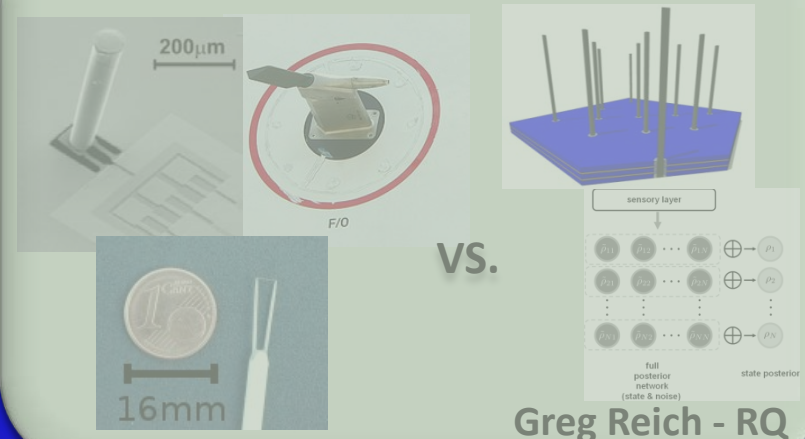
1. Origin/sensitivity of CNT arrays to force transduction?
2. Compression mechanics of CNT Arrays?
3. Best methods for quantifying CNT arrays mechanics?
4. Proof-of-concept as a artificial hair flow sensor?

Hierarchical Fiber Nano-sensing



Jeff Baur - RX

"Insect Grade" Sensors to "Feel"



Greg Reich - RQ

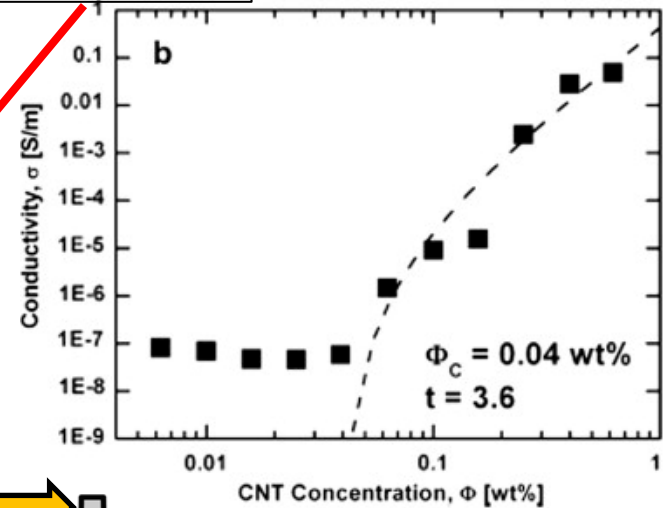
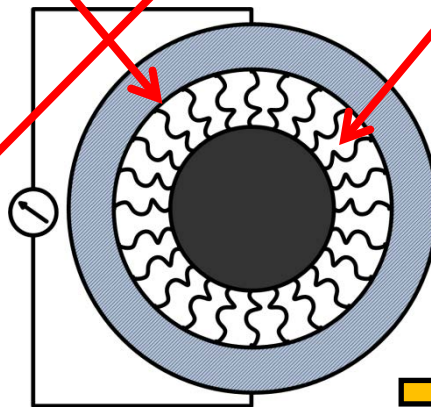
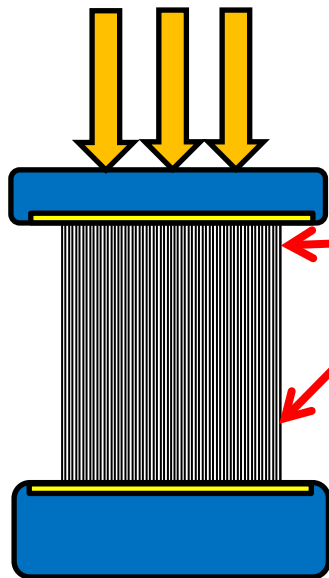


1. Origin of Mechano-Resistive Sensitivity

Effective Surface

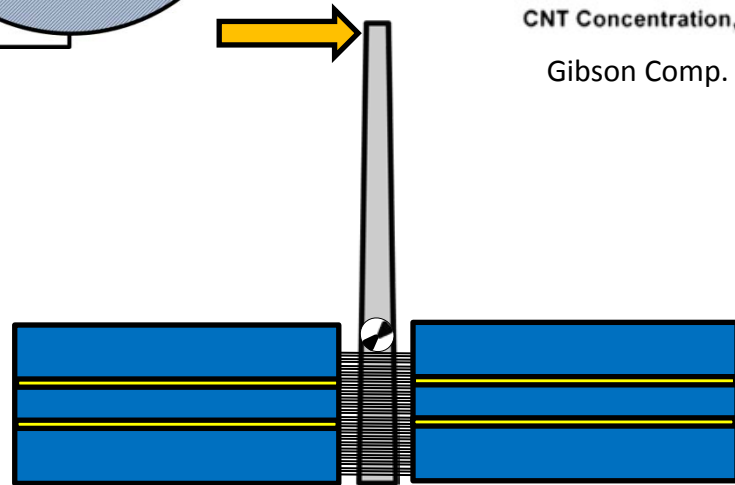
Modulation in Contact Resistance

Modulation in Bulk Resistance



Gibson Comp. Struct 2010

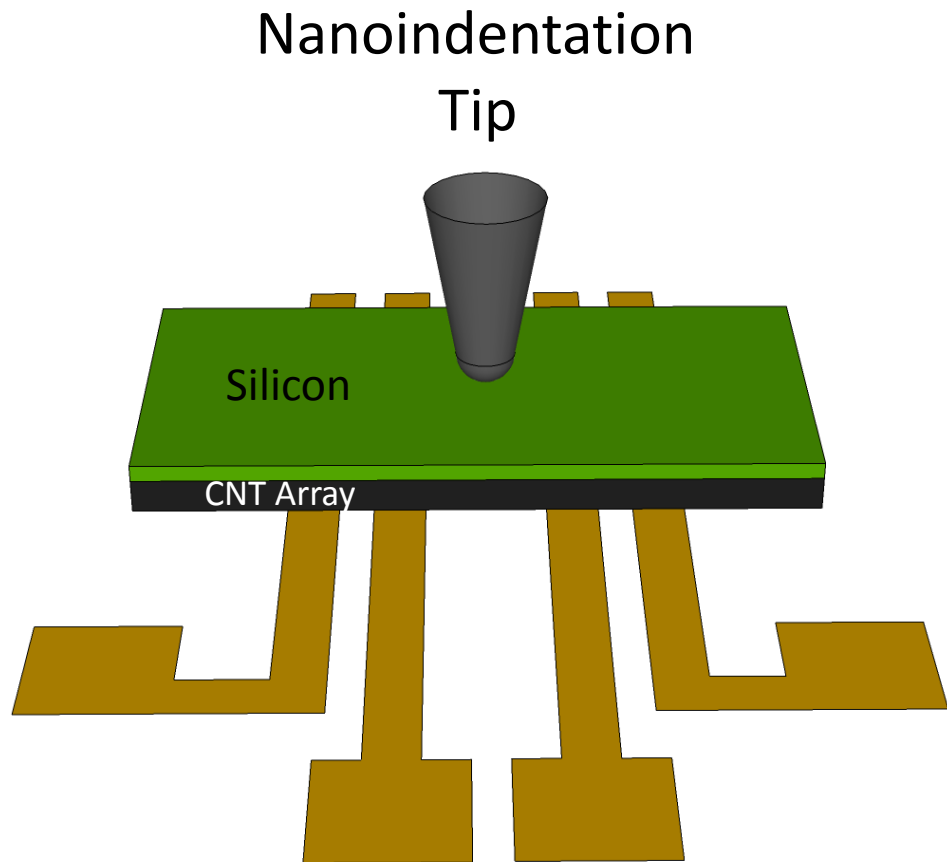
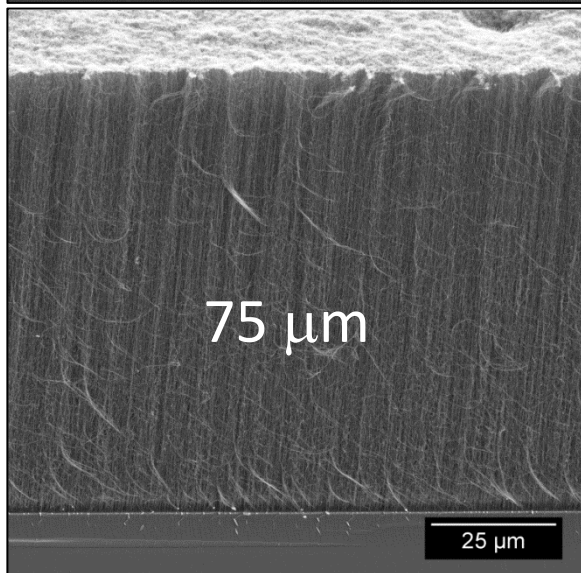
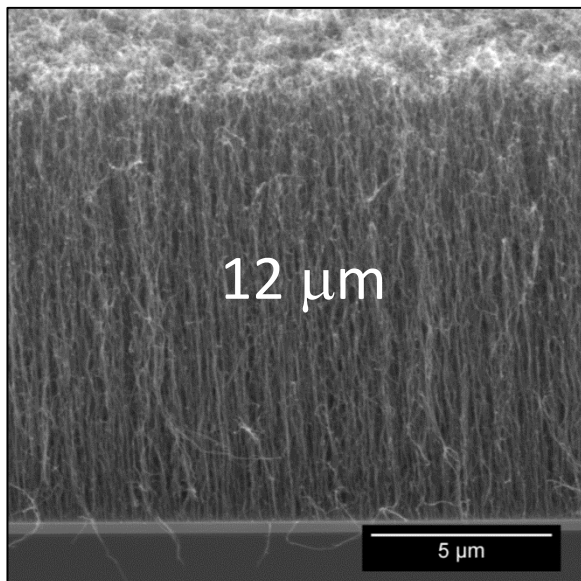
-  Support Material
-  Electrode
-  Carbon Nanotubes





Planar CNT Array

4-Wire Resistance Measurements

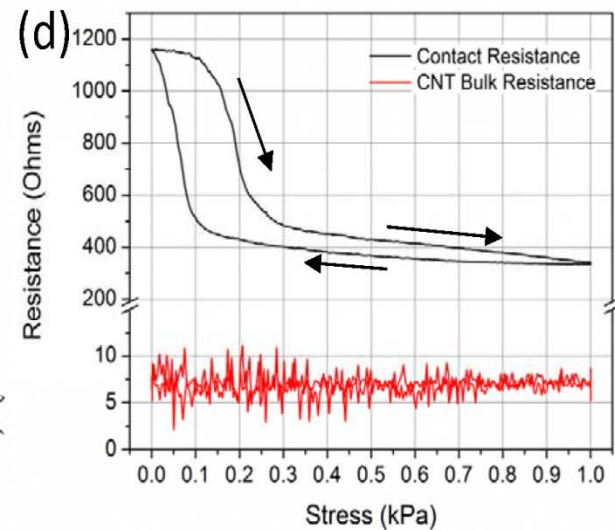
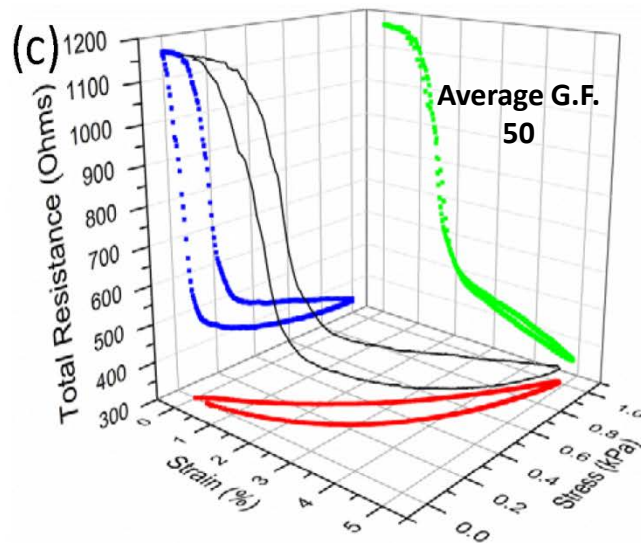
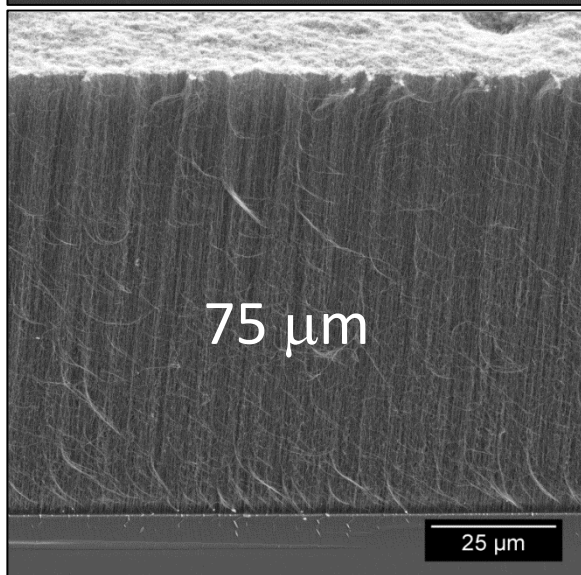
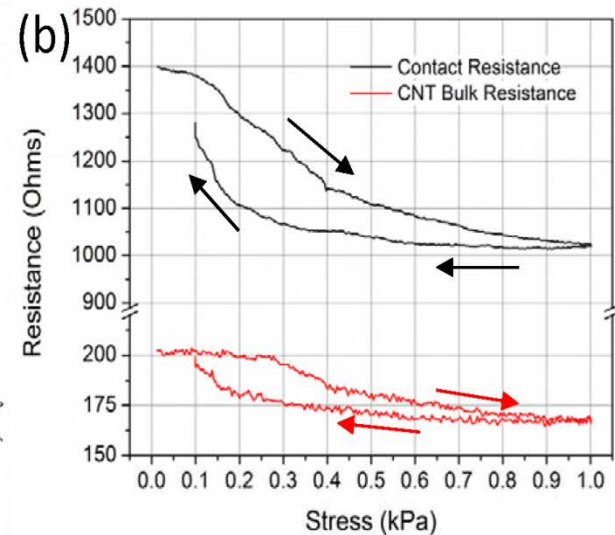
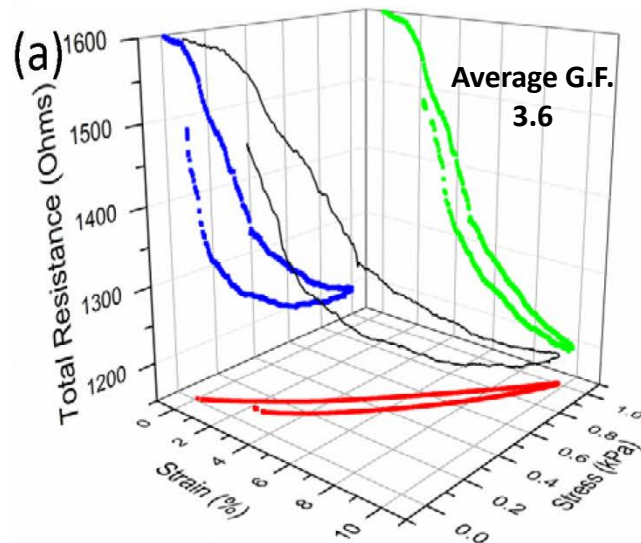
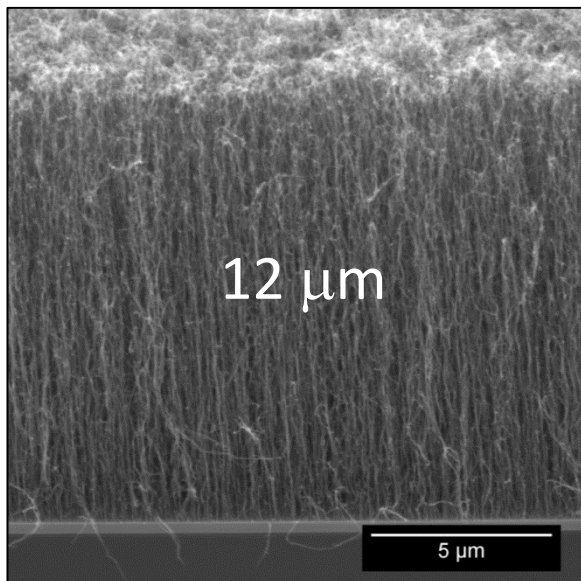


4-Wire Measurement



Planar CNT Array

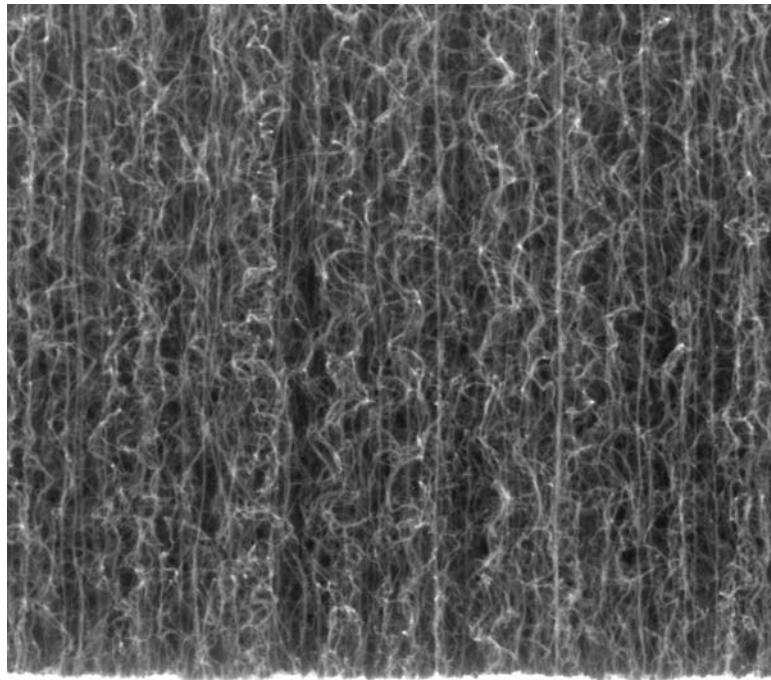
4-Wire Resistance Measurements





In Situ SEM Compression

CNT Array Columns



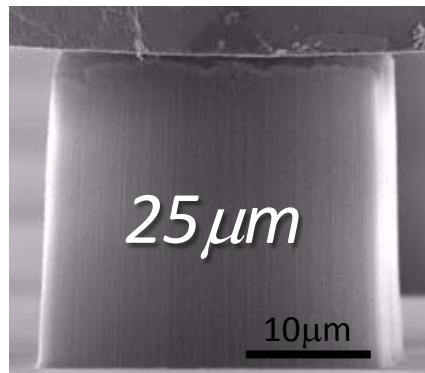
Array morphology enables traceability of individual CNT features during deformation
(Arrays from J. Hart)

Heights:

25, 50, and 75 μm

Widths:

10, 25, and 100 μm





In Situ SEM Compression

CNT Array Columns



Crushing

Bottom-Up Buckling

Bending

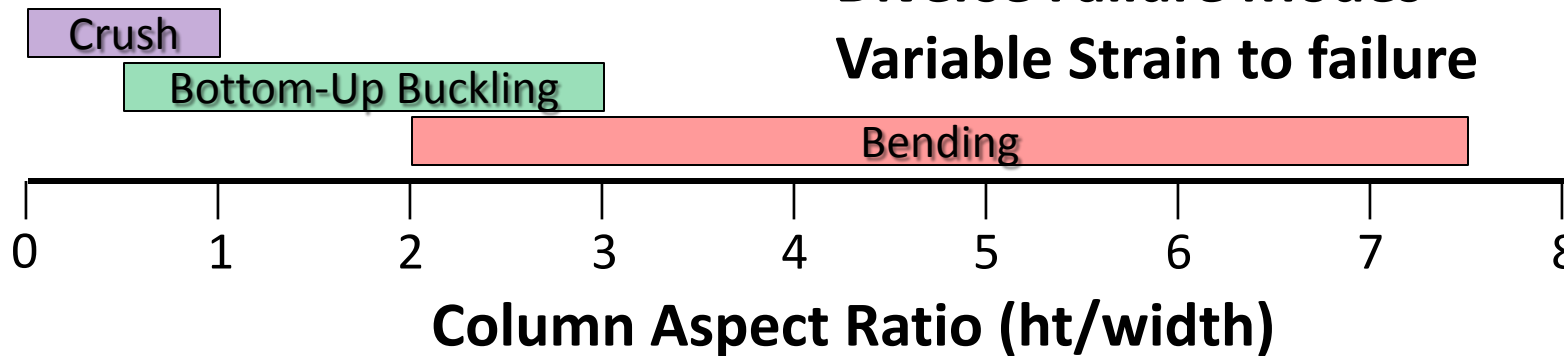
Indenter

10 μm

10 μm

5 μm

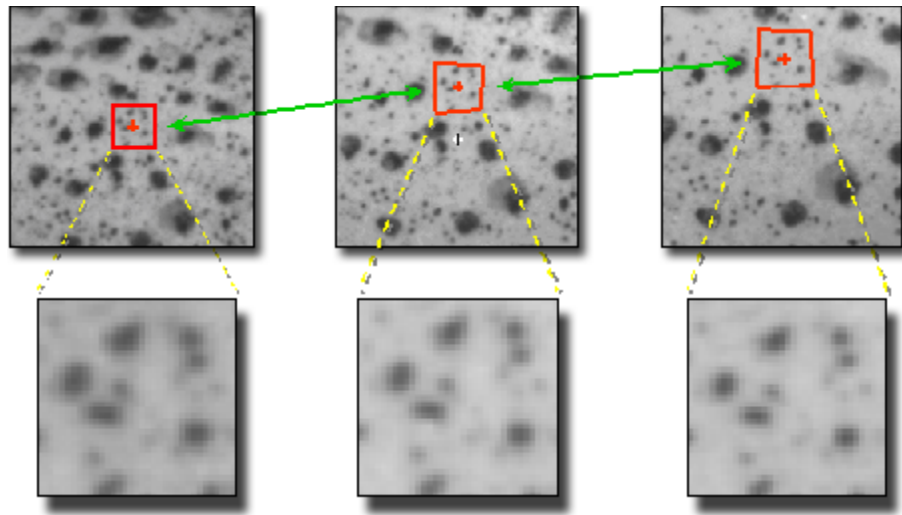
Diverse Failure Modes
Variable Strain to failure



M. Maschmann, G. Ehlert, S.J. Park, D. Mollenhauer, B. Maruyama, A.J. Hart, J. Baur, *in review*.

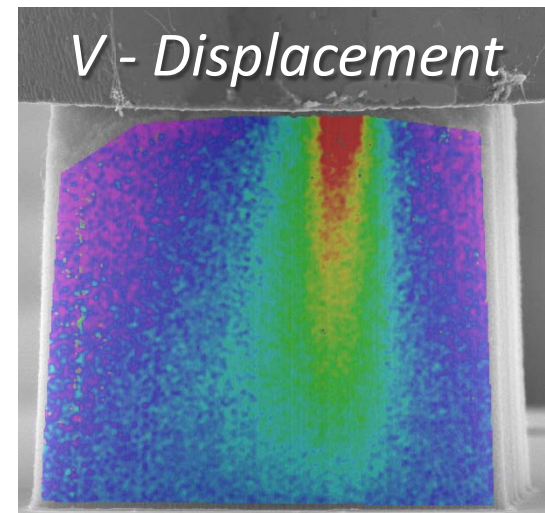
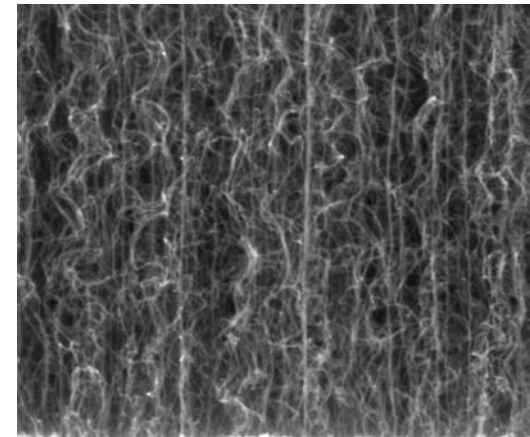


3. New Method for in-situ CNT Array Mechanics: Digital Image Correlation



Courtesy of Correlation Solutions, Inc.
<http://www.correlatedsolutions.com>

Tracking motion of CNTs enables
computation of full-field displacement
and strain maps



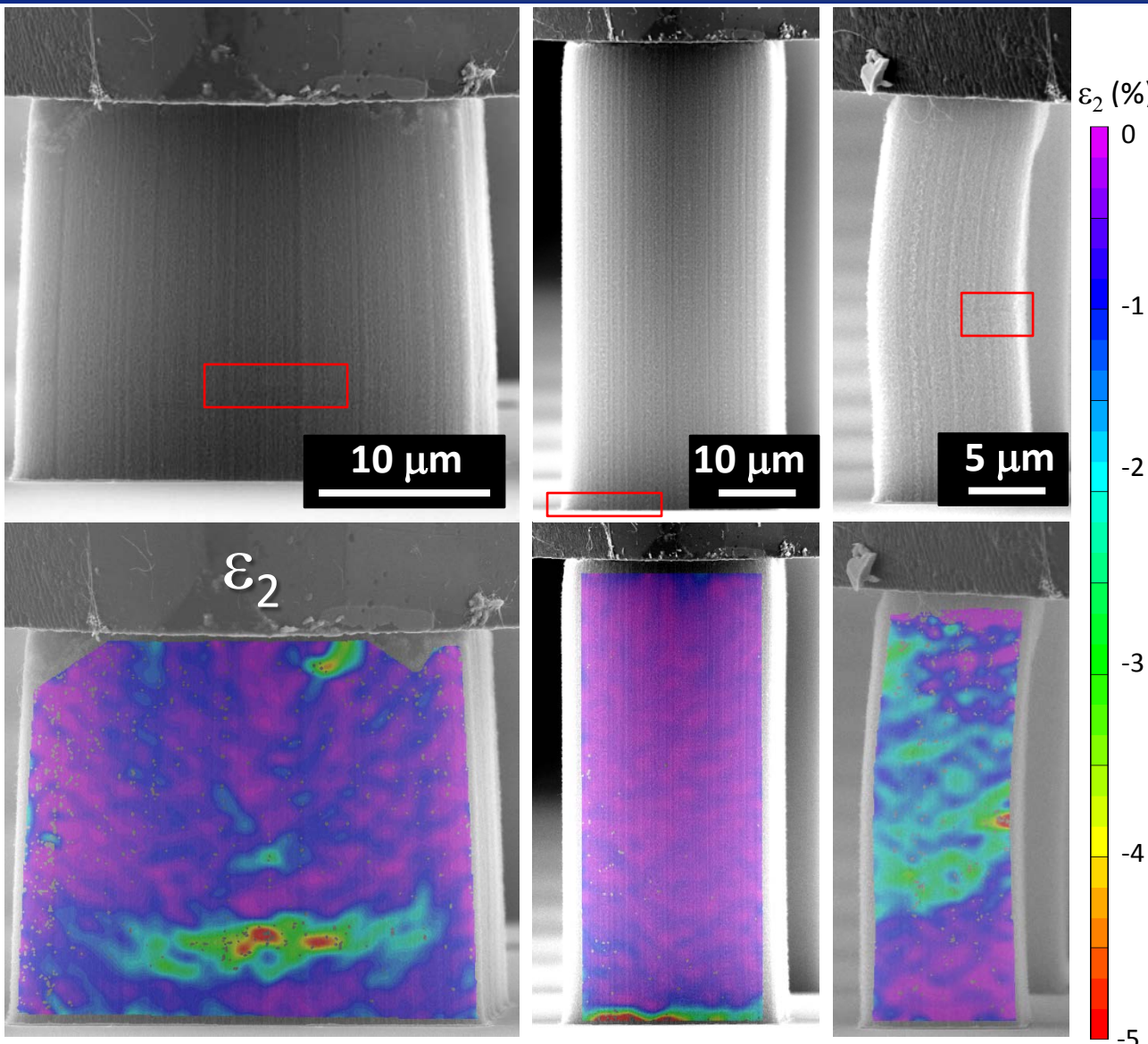
-0.16 -3.88
V(pixel)

M. Maschmann, G. Ehlert, S.J. Park, D. Mollenhauer, B. Maruyama, A.J. Hart, J. Baur, *in review*.



Digital Image Correlation

CNT Array Column Buckling



Without DIC:

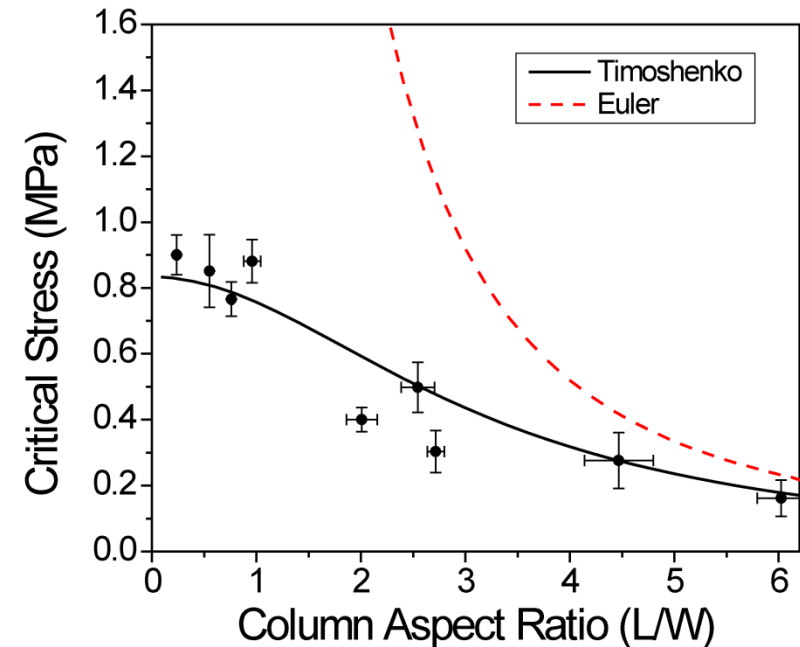
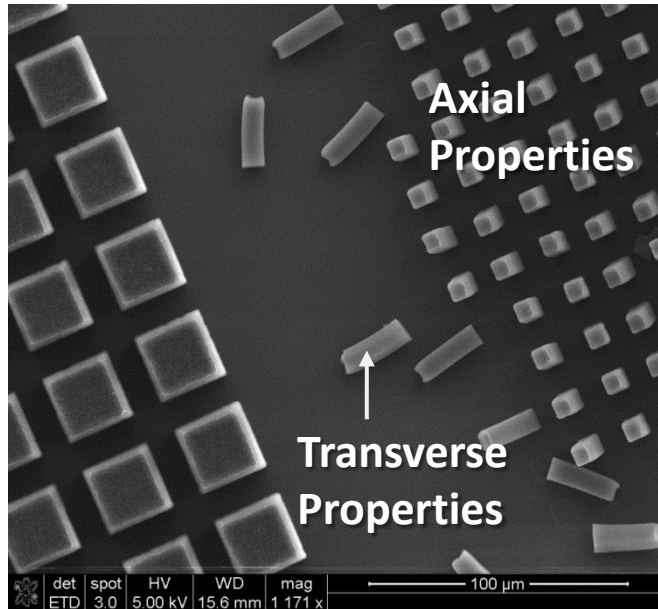
Column buckling is a strong function of column aspect ratio

With DIC:

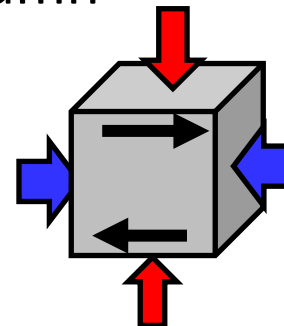
CNT array yielding is independent of column aspect ratio and initiates at 5% (ϵ_2)



Continuum-like CNT Properties



- DIC reveals *inelastic* column buckling
- Significant anisotropy reduces column strength
- Inelastic Timoshenko beam theory predicts critical stress of CNT array columns



$$E_{\text{Axial}} = 400 - 700 \text{ MPa}$$

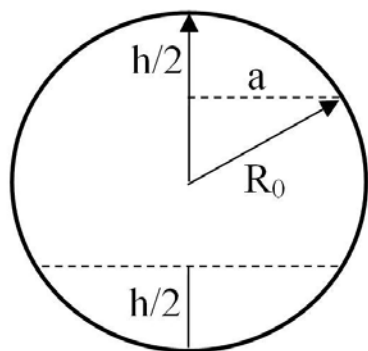
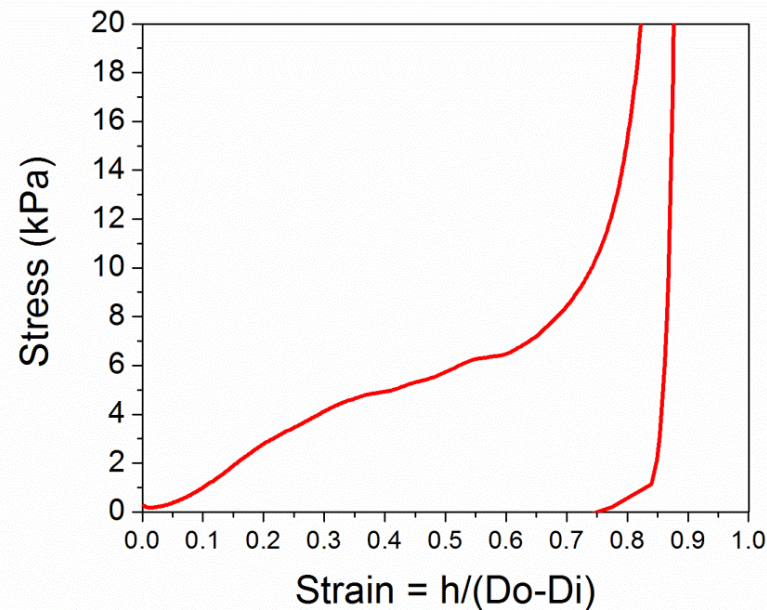
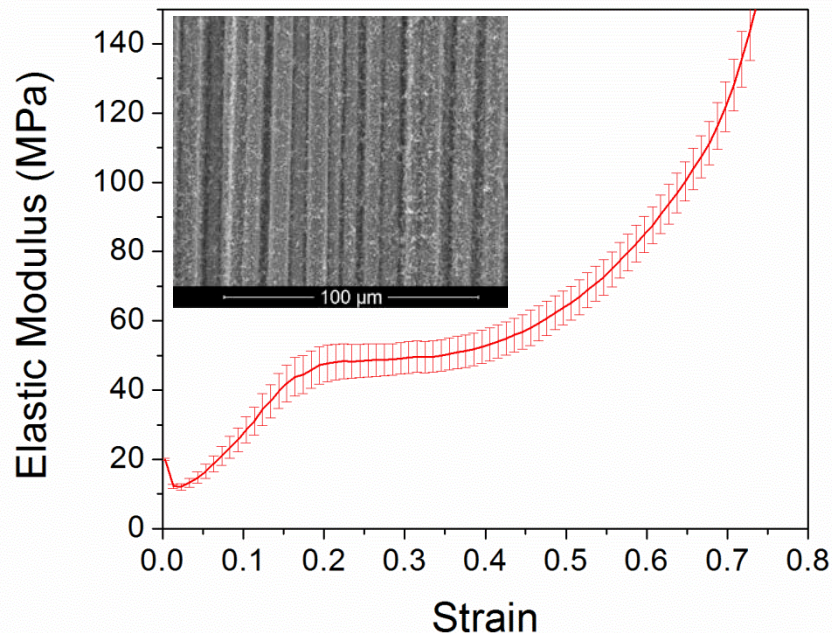
$$E_{\text{trans}} = 2.5 - 4.0 \text{ MPa}$$

$$G_{\text{trans}} = 0.8 - 1.6 \text{ MPa}$$

Strain <5% (elastic regime)



Compression of CNT Fuzzy Fibers



$$a = \sqrt{R_0 h - h^2/4}$$

$$\text{Contact Area} = 100\mu\text{m} * 2a(h)$$

$$E = \frac{\text{Contact Stiffness} * (D_0 - D_{CF})}{\text{Contact Area}}$$

h = indent depth

D_0 = CNT + CF Outer Diameter

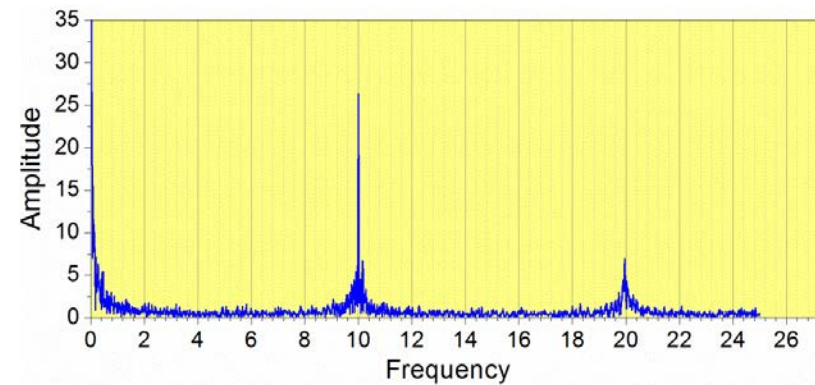
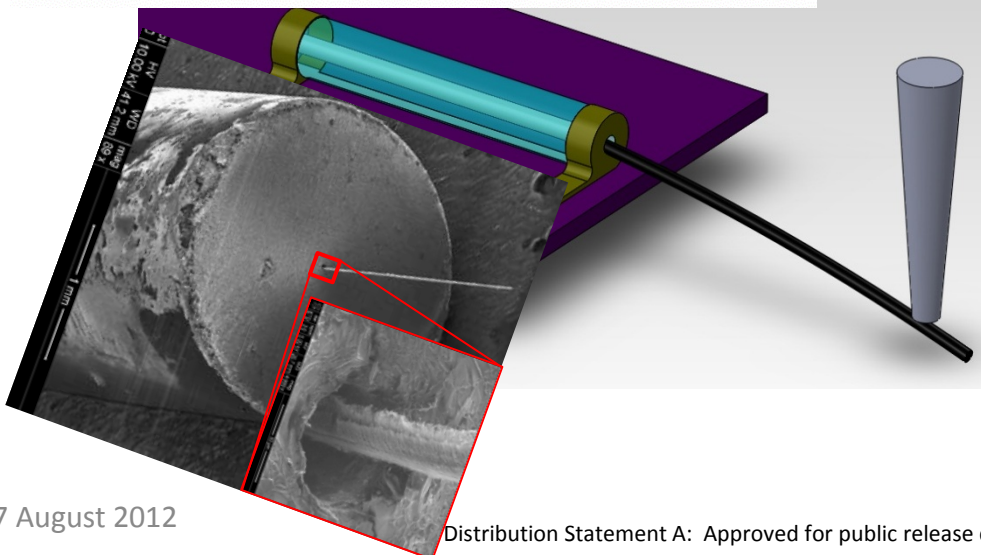
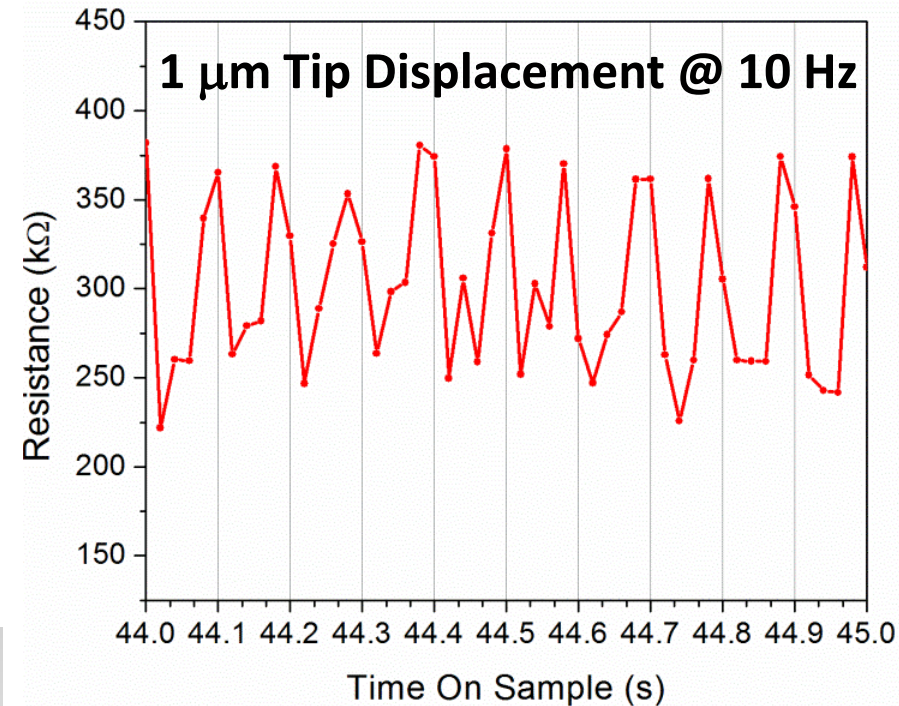
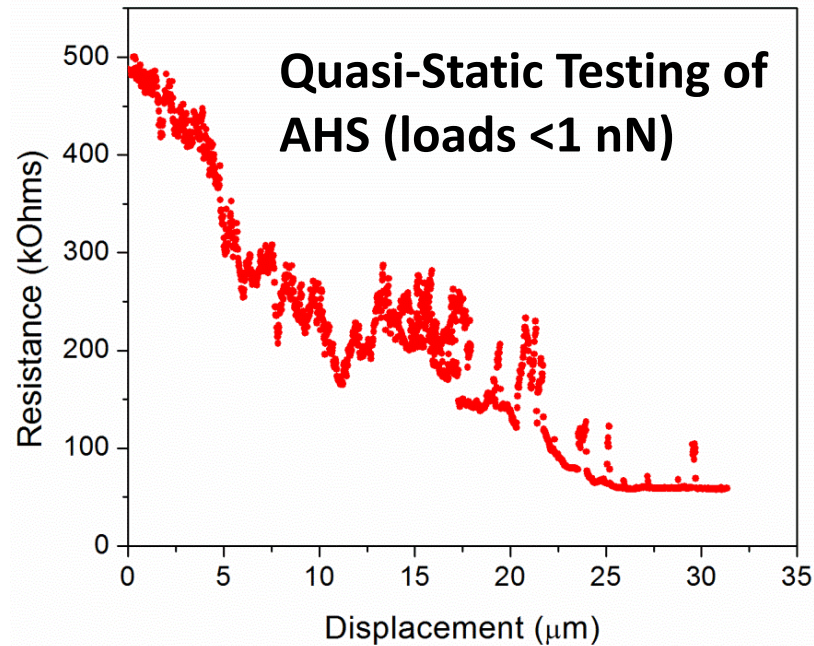
D_{CF} = CF Outer Diameter





4. Artificial Hair Sensor

Prototype Performance



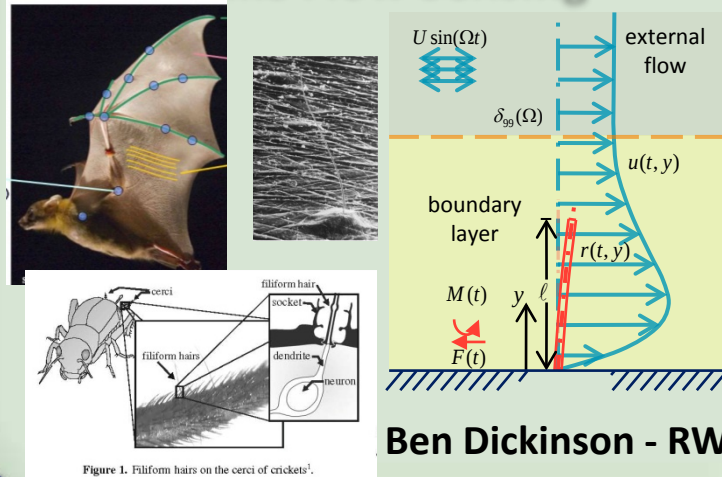


Embedded Sensors for Air Vehicles

LRIR 09RW10COR – Dickinson (RW) / Baur (RX) / Reich (RQ)



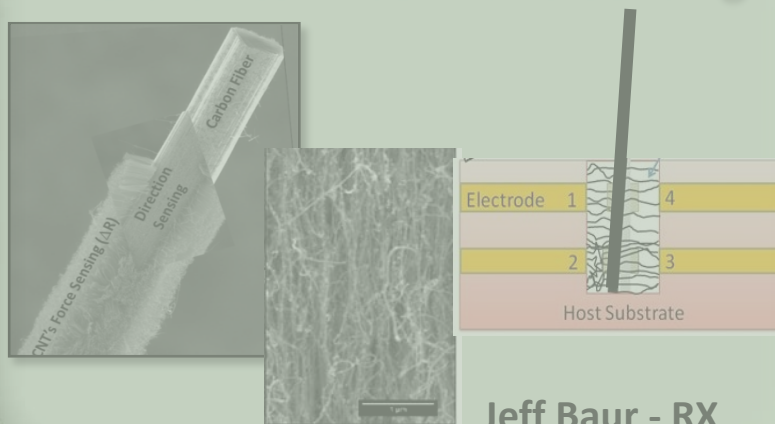
Bio-like Flow Sensing



Ben Dickinson - RW

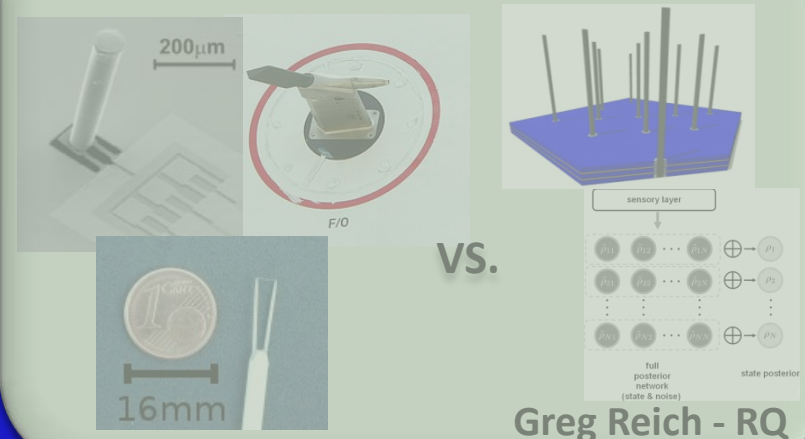
1. Response of carbon fiber hair in oscillating flow?
2. Why didn't we observe any vibration in the carbon fiber?
3. Frequency response of carbon fiber hair?
4. Forces involved in the dynamic response of the carbon hair?

Hierarchical Fiber Nano-sensing



Jeff Baur - RX

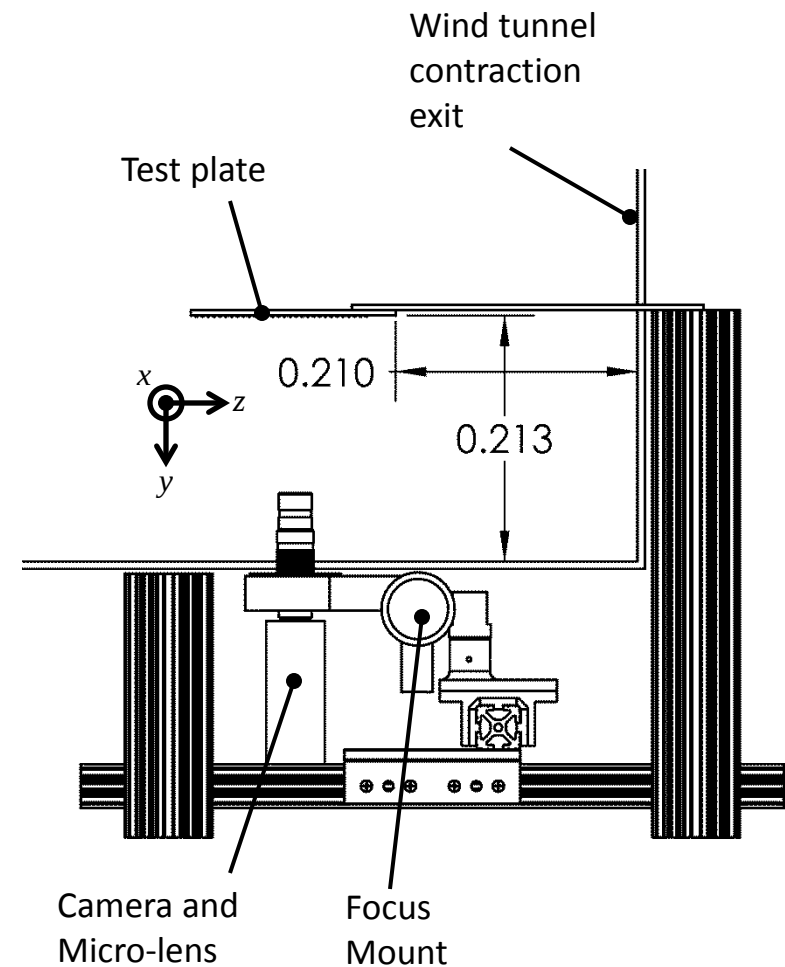
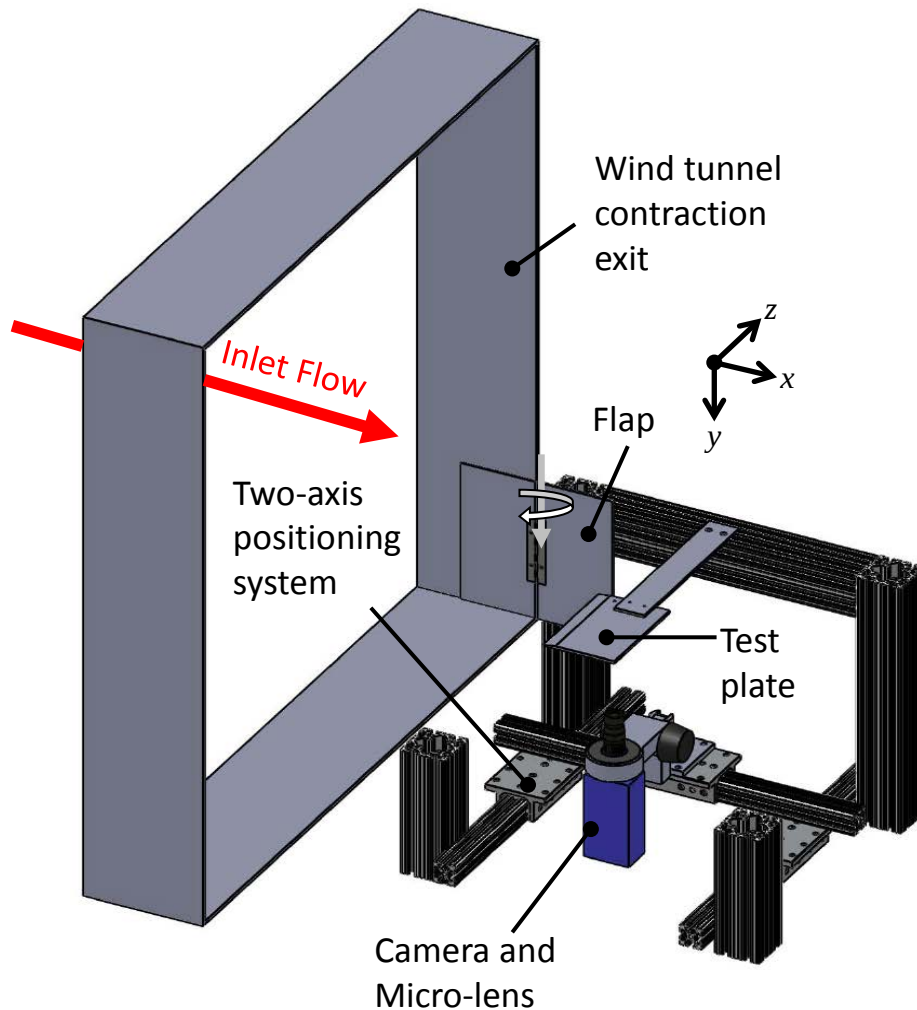
"Insect Grade" Sensors to "Feel"



Greg Reich - RQ



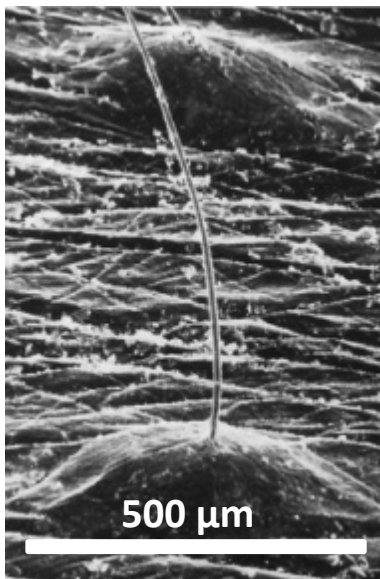
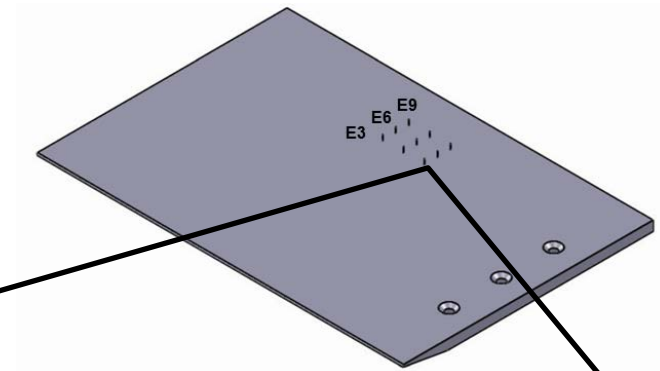
Wind tunnel setting, hair array fixed to flat plate



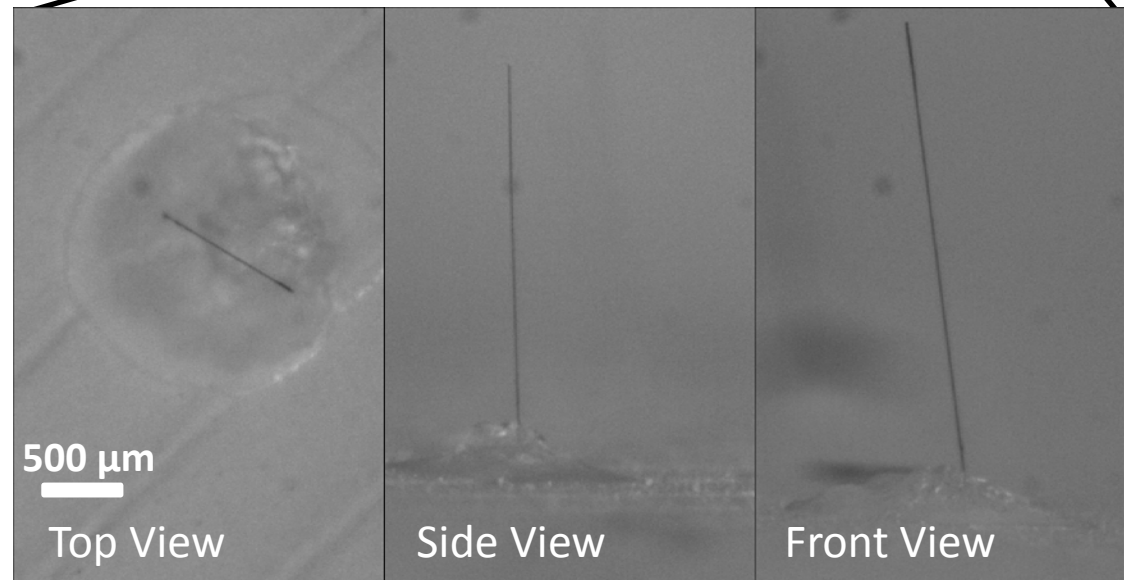


Hair array fixed to flat plate

Thornel T-650 pan based carbon fiber	
Density	1.77e3 kg/m ³
Aspect ratio	300:1
Elasticity	2.55e11 Pa



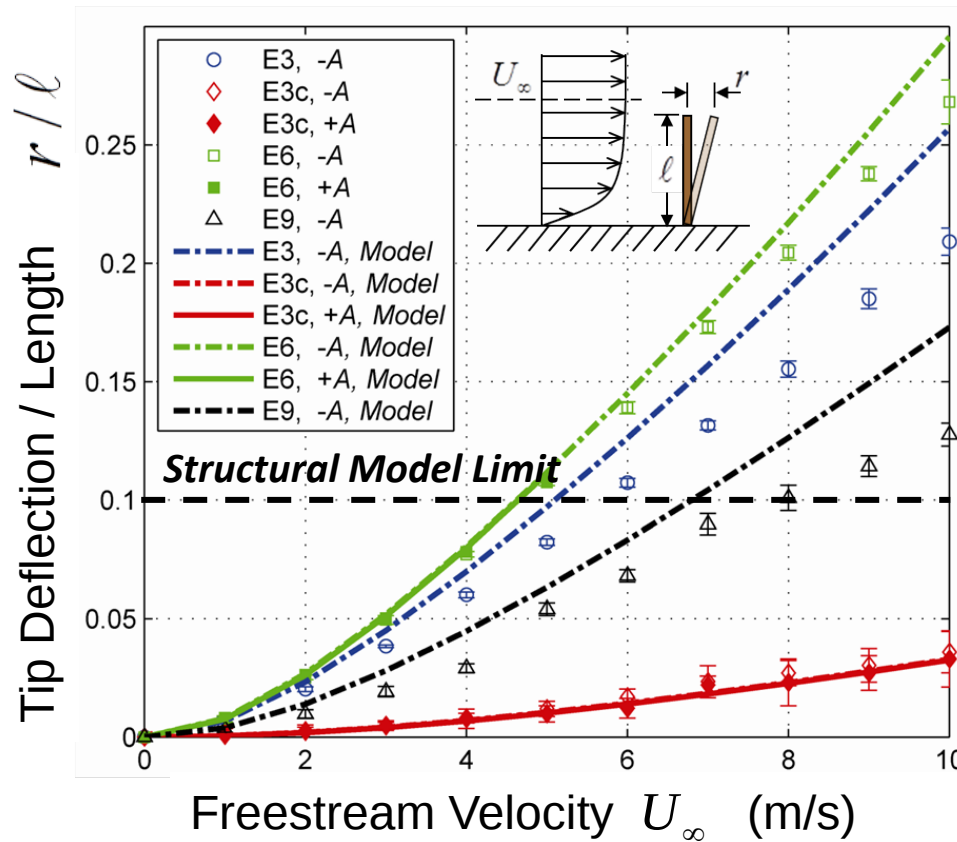
Bat wing hair receptor from
Hall, Aust J Zool, v 1994



McClain, Case, and Dickinson, submitted to AIAA Journal, 2012 .



Displacement predictions in steady laminar boundary layer vs experiment



- $Re_{\text{hair}} = 4$
- $Re_x = 50,000$

McClain, Case, and Dickinson, submitted to AIAA Journal, 2012.

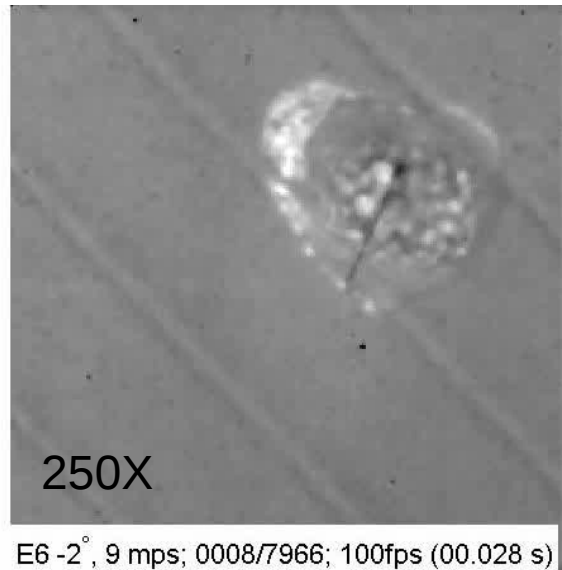
Distribution Statement A: Approved for public release distribution is unlimited. (88ABW-2012-4077)



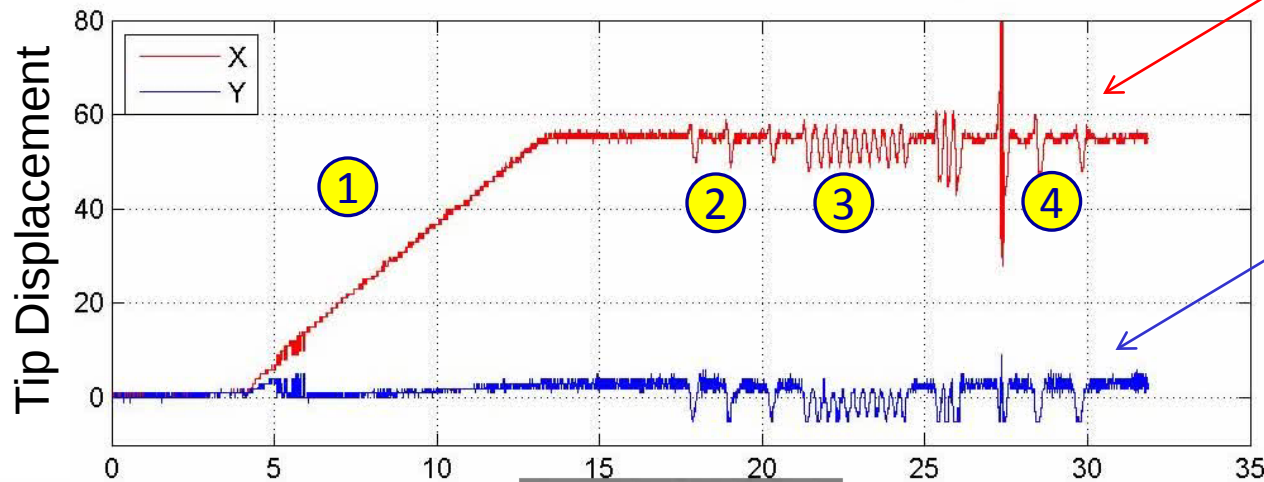
Preliminary observations of carbon hair-structure dynamic response



- ① flow ramp to 9 m/s
- ② 3 discrete gusts
- ③ Oscillatory gusts
- ④ 1 large gust with two small gusts



Streamwise Flow Dir

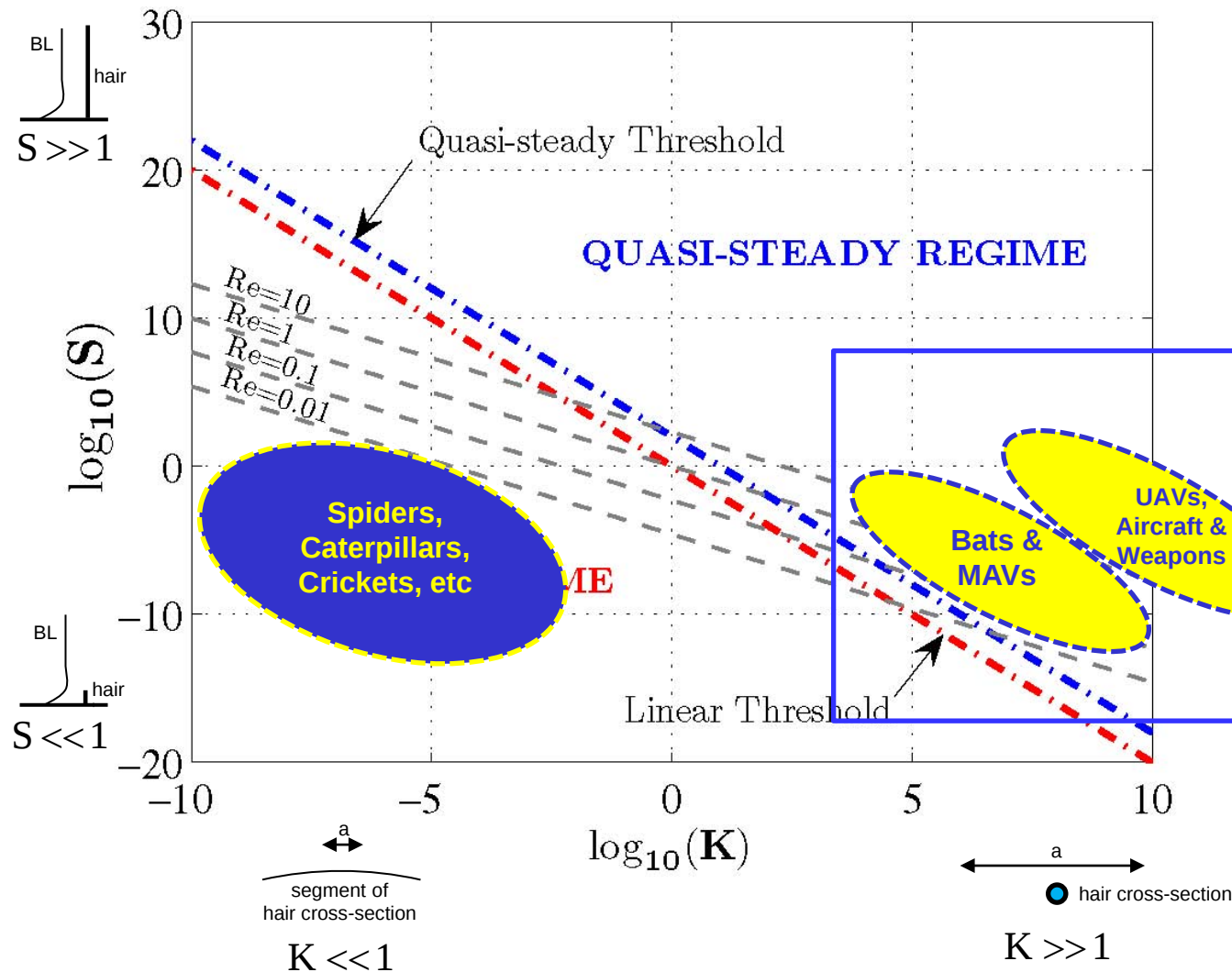


Streamwise def

Spanwise def



The Dynamic World of Hair-Structures



Creeping Flow Meas.

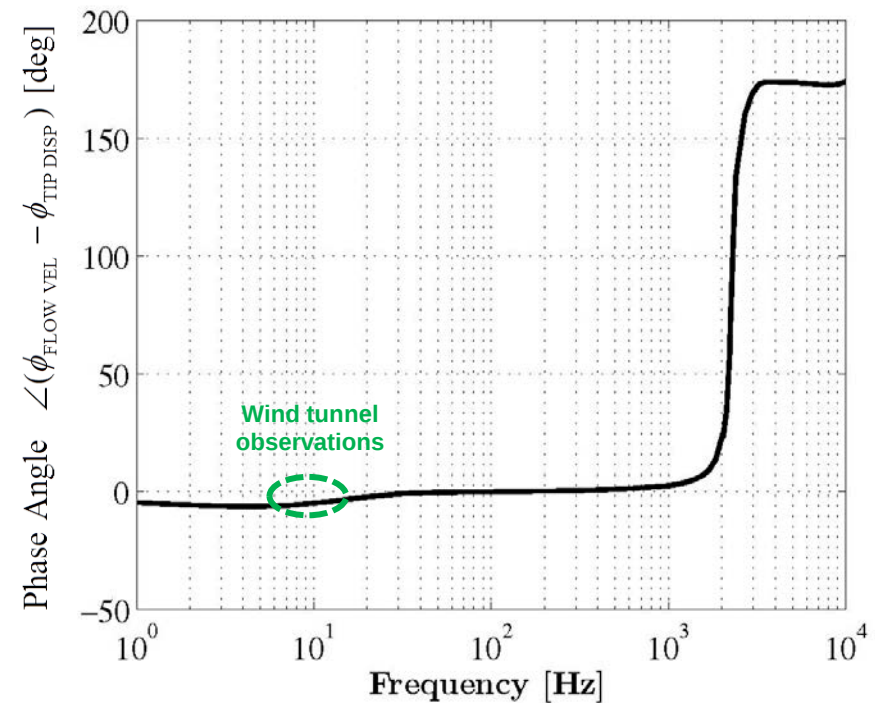
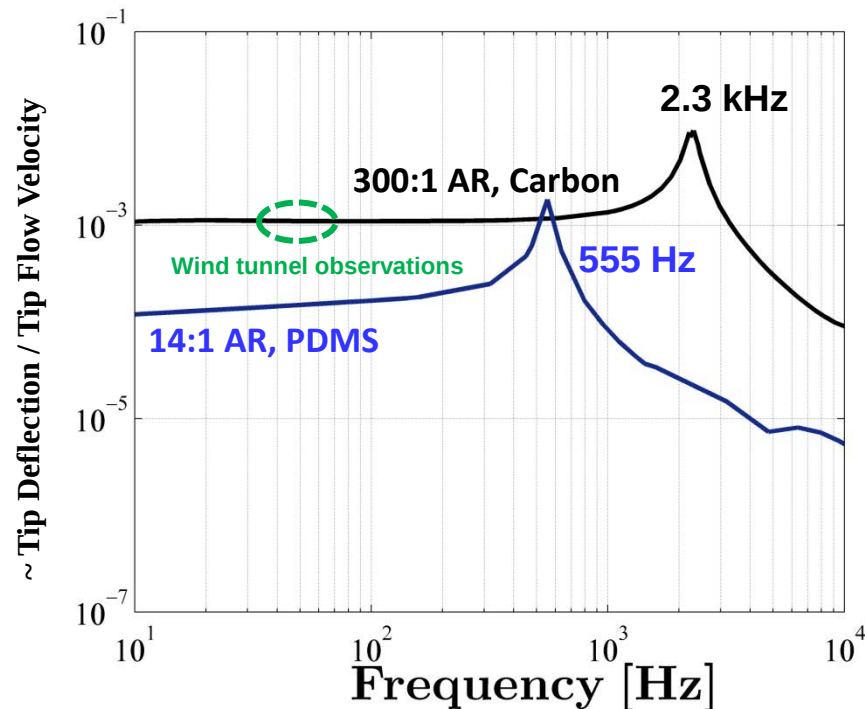
- Acoustic reception
- Environ. disturbance

Aero. Measurement

- Wall shear stress
- Critical aero. points
- Angle of attack meas.
- Disturbance rejection



Frequency response of carbon hair in oscillatory boundary layer



Hair structure response like 2nd order system

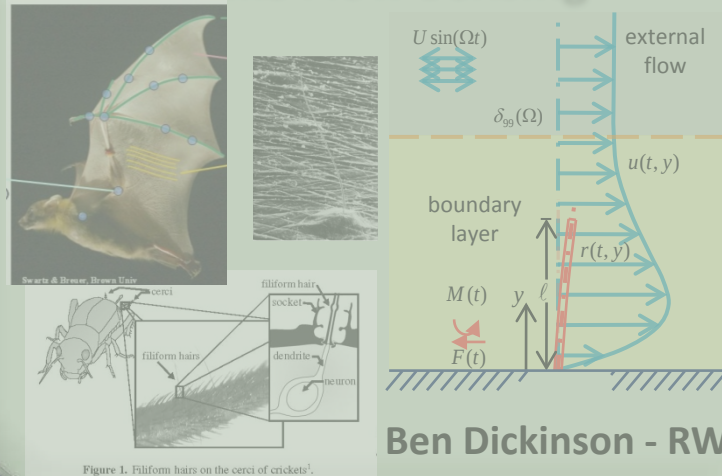
$$C(s) = \frac{Y(s)}{U(s)} = \frac{1}{(s/\omega_n)^2 + 2\zeta(s/\omega_n) + 1}$$



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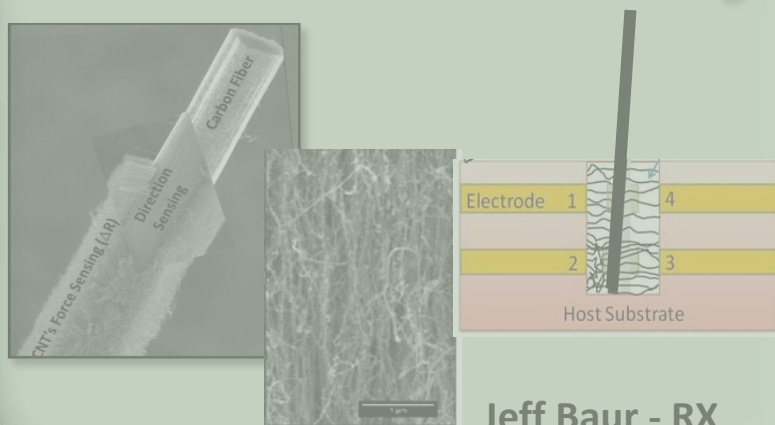
Bio-like Flow Sensing



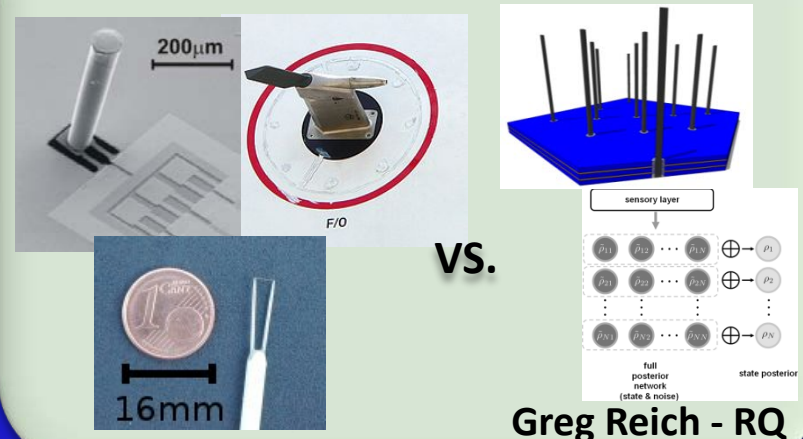
Ben Dickinson - RW

1. Limits of using arrays of “Insect Grade” noisy sensors ?
2. Methods for AHS arrays to provide flow state information for flight control or “feel”
3. AHS advanced estimation algorithms and approaches ?

Hierarchical Fiber Nano-sensing



“Insect Grade” Sensors to “Feel”

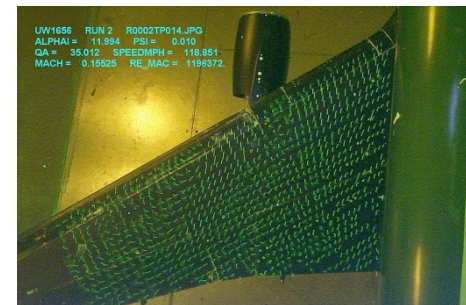
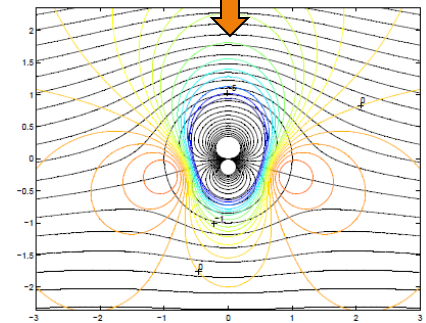




Future Work: AHS Control Investigation



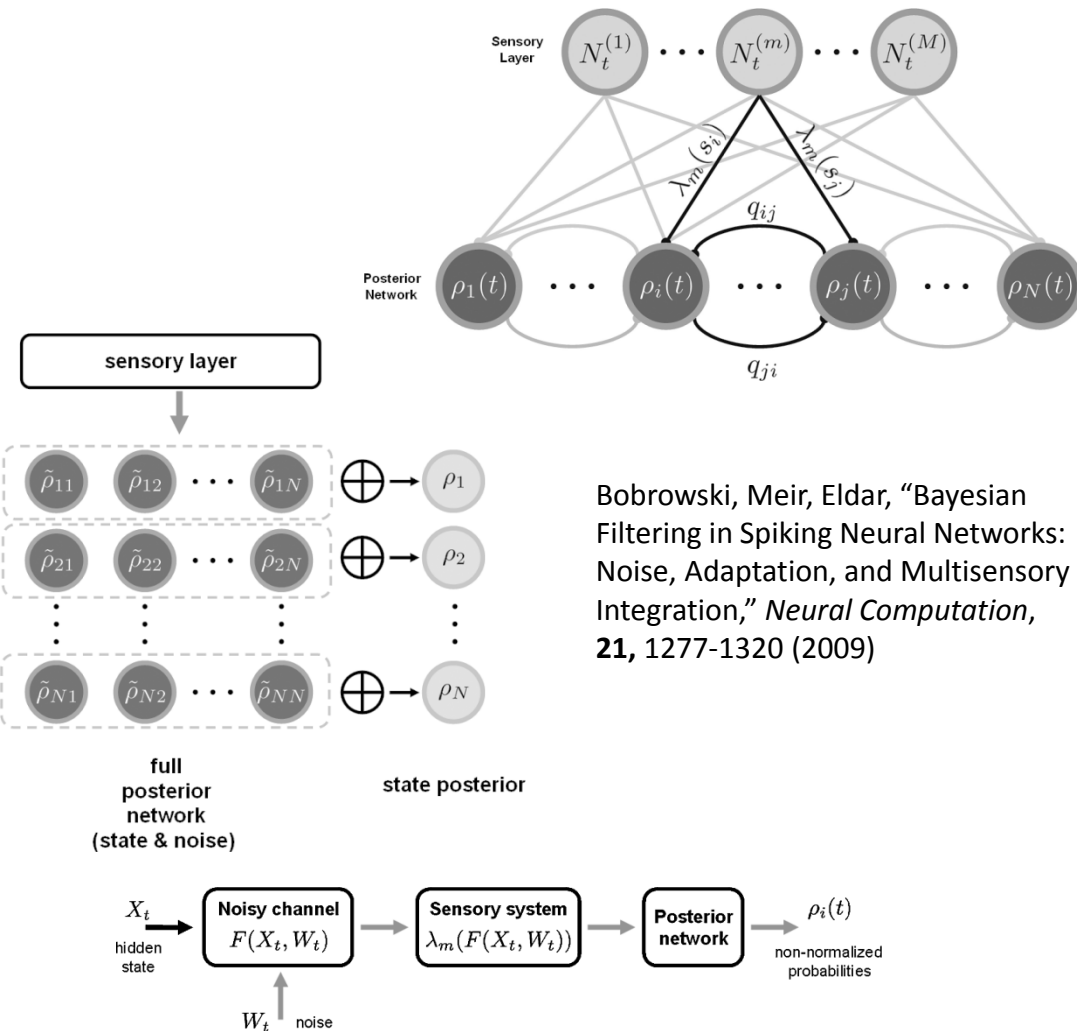
- **Flow state estimation**
 - Distributed arrays of sensors as an integrated solution rather than point sensors
 - Signal processing to collect information from array
 - Reduced-order modeling for estimation of potential flow
- **Flow and structure fusion**
 - Unmodeled dynamics, unsteadiness, etc
 - Time scales of AHS better than other sensors
 - Kalman Filter/Bayesian Estimation
- **Putting it together and demonstration with flight control**
 - Simulations, HIL, scaled flights





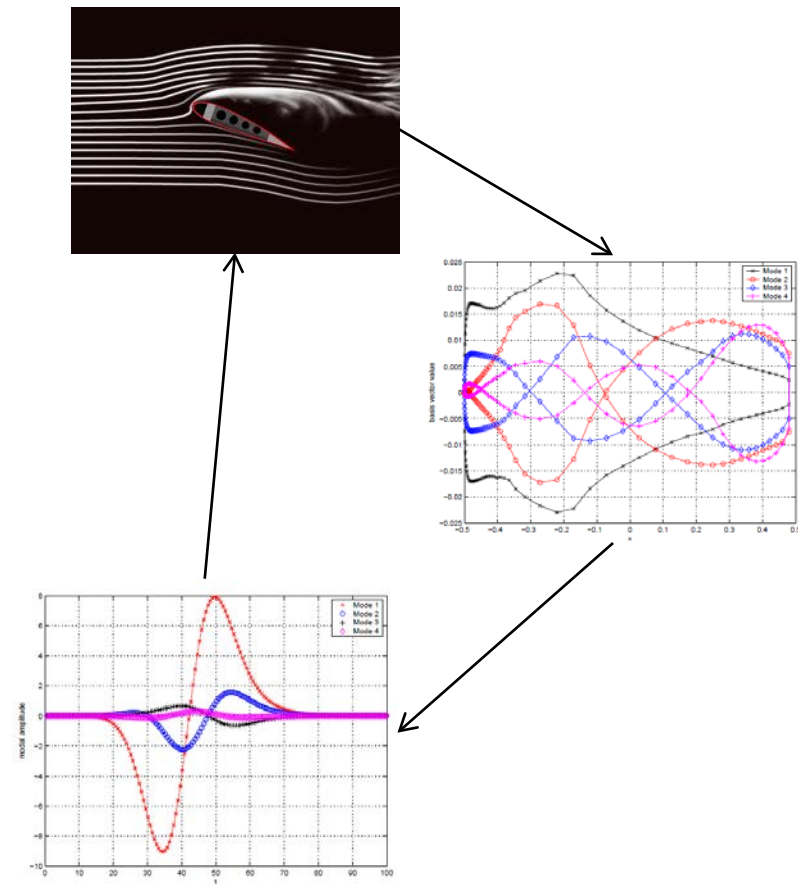
Insect-Grade (Noisy) Sensors

1. Bayesian Filtering (neuroscience)



Bobrowski, Meir, Eldar, "Bayesian Filtering in Spiking Neural Networks: Noise, Adaptation, and Multisensory Integration," *Neural Computation*, **21**, 1277-1320 (2009)

2. Process Decomposition (POD)

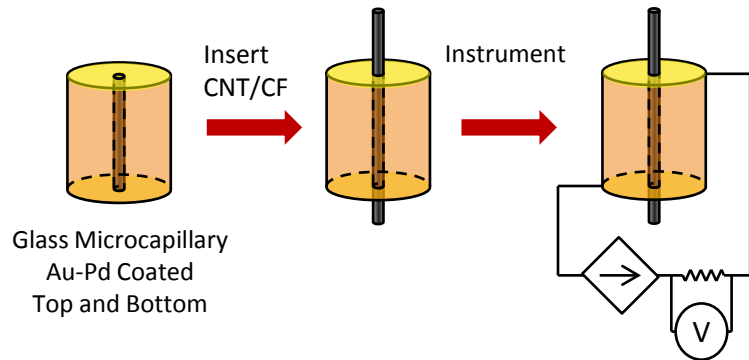


Willcox, "Unsteady Flow Sensing and Estimation via the Gappy Proper Orthogonal Decomposition," *Computers and Fluids*, **35/2**, 208-226 (2006)

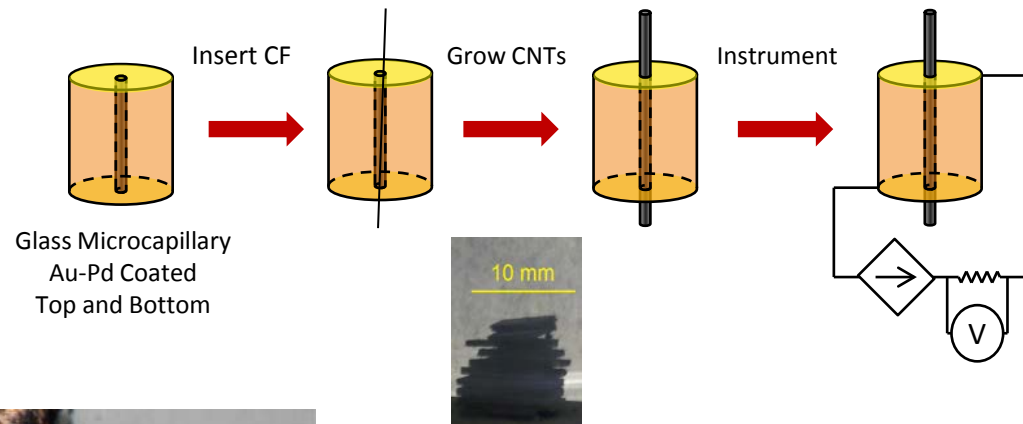


Next Steps - Prototype Design

Ex situ CNT Growth



In situ CNT Growth



Si Wafer Stack Expanded by *in situ* CNT Growth

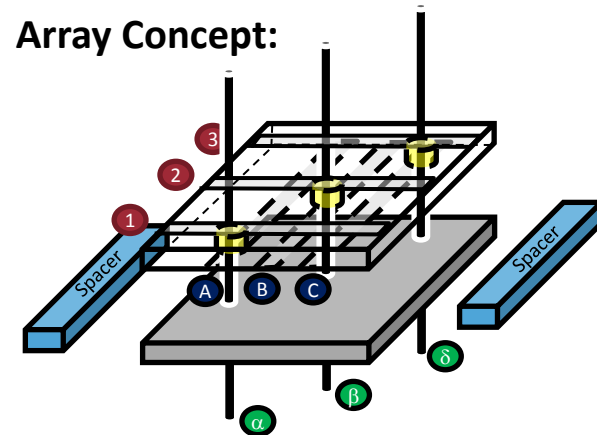
Step One: Structural Integration of a Single Sensor Pore

- Identify potential substrate materials for sensor integration as appliqué or surface-bonded treatment
- Address single CNT “hair plug” integration with electrical ingress/egress
- Demonstrate sensor viability on flexible substrate

Step Two: Array Development

- Identify direct write or alternative printing for application of array electronics on substrate
- Demonstrate interconnect of array leads to sensor pore

Array Concept:



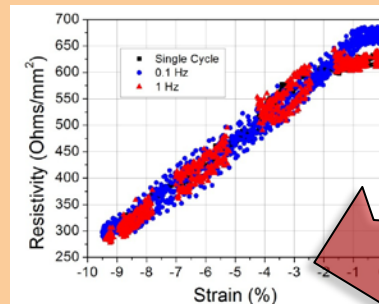
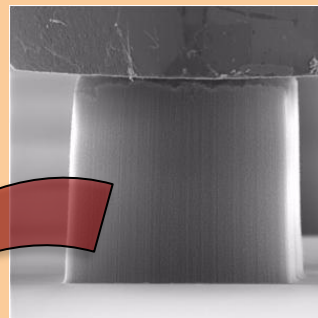


Sensitivities, Requirements, and Disciplines (OH MY!)



nm

Calculation of sensitivities/
performance

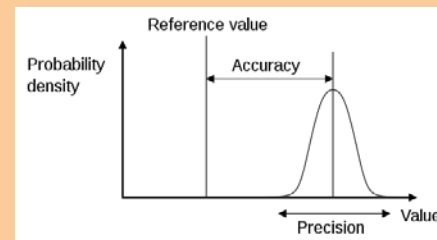
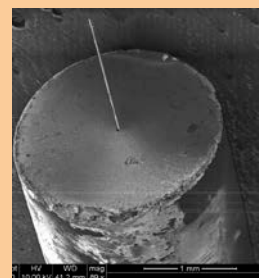
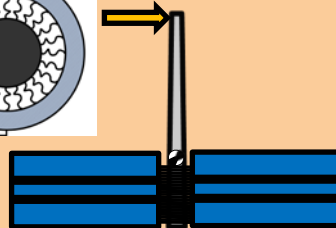
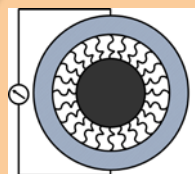


CNT gage factor

RX

Derivation of requirements

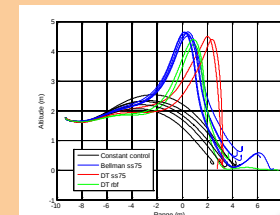
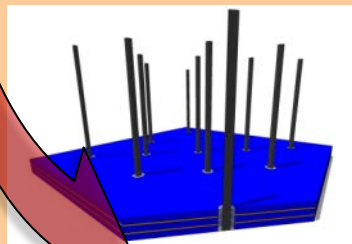
mm



Device accuracy and precision

RW

cm



System performance

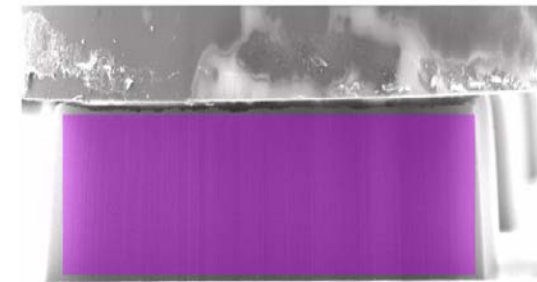
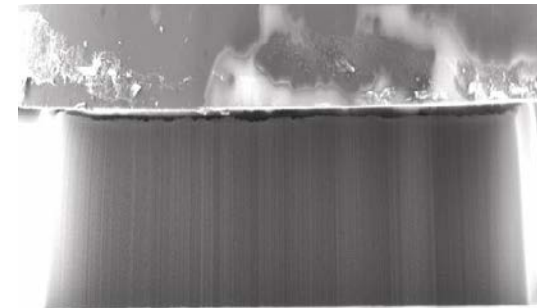
RQ



Summary



- **Proof-of-concept of Artificial Hair Sensor with CNT mechano-resistive elements demonstrated**
- **CNT arrays examined that initially appear mechanically different by length, but DIC reveal a common failure criteria**
- **Observed carbon hair deflection in-phase with gust-like disturbances without vibration - mapped the flow regime steady/ unsteady**
- **Computed frequency response plots for carbon hair structure in quasi-steady regime – 2nd order like response**
- **Found that elasticity and drag dominated the force balance in the carbon hair structure**
- **Established criteria based on dimensionless groups to control hair dynamic response through selection of material and geometric properties**





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- **Prof. Steve McClain (Baylor)**