Aerospace Applications of Elastomers for Extreme Environments: Challenges & Opportunities

JASON R. FOLEY, PH.D., INTERNATIONAL PROGRAM OFFICER (MATERIALS & PHYSICS)

HIGH STRAIN RATE BEHAVIOUR OF ELASTOMERS, RIEG, UNIVERSITY OF OXFORD, 13 MAR 2020

Outline

- Extreme Environments in Air Force Applications
- Elastomeric Materials
  - Dynamics of energetic materials
  - Shock mitigating systems
  - Novel applications
- Closing Thoughts & Acknowledgements
- Discussion

Air Force Applications: Extreme Environments

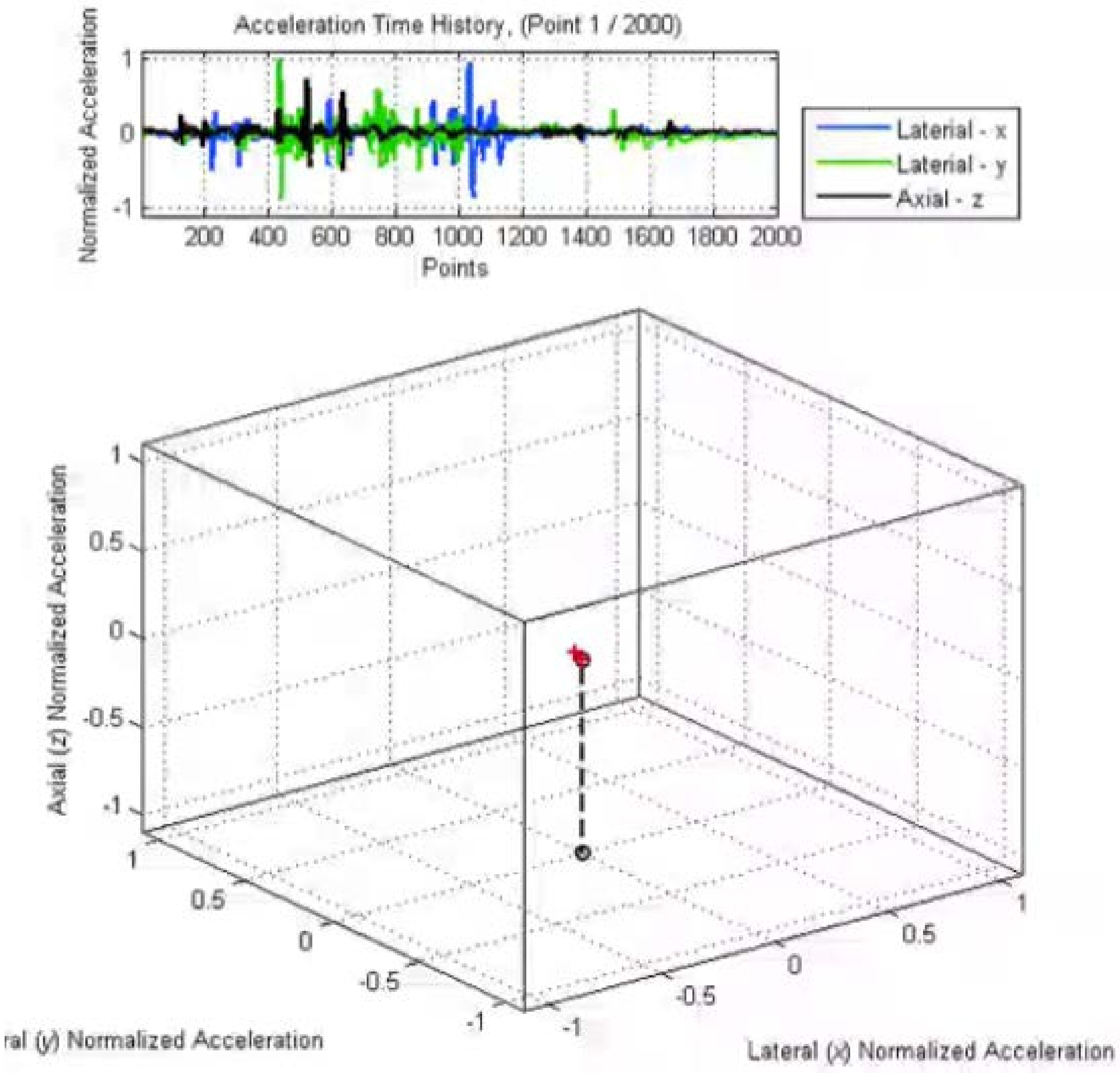
Air Force Weapons: Extreme Operating Environments

Multiaxial Dynamics

Representative Sled Test Data
Similar to video on previous slide

- Linear triaxial data
- Aspects of environment:
  - Multiaxial…
  - Repeated loading…
  - High rate…
  - Broadband…
  - Stochastic!

Resultant acceleration “lissajous”
Vector triaxial accelerometer data from full-scale penetration event



From Bad to Worse…

Stress/Pressure

Vacuum — Impact Stress — Detonation

~0 Pa — >50 MPa — >1 GPa

Shock/Vibration

Flight Operations — Rocket Launch — Hard Target Penetration — Explosively-Driven Shock

100 m/s² — ~1 km/s² — >10⁶ m/s² — >10⁸ m/s²

Temperature

Cryogenics — Solid Oxide Fuel Cells — Shock Heating — Nuclear Sources

77 K — ← Mil Std → — ~1200 K — >2000 K — >2500 K

Erosion/Corrosion/Wear

Humidity — Saltwater Corrosion — Penetration Erosion — Blast Ablation

← Eglin → — >10 mm — >1 mm/us

Power and Fields

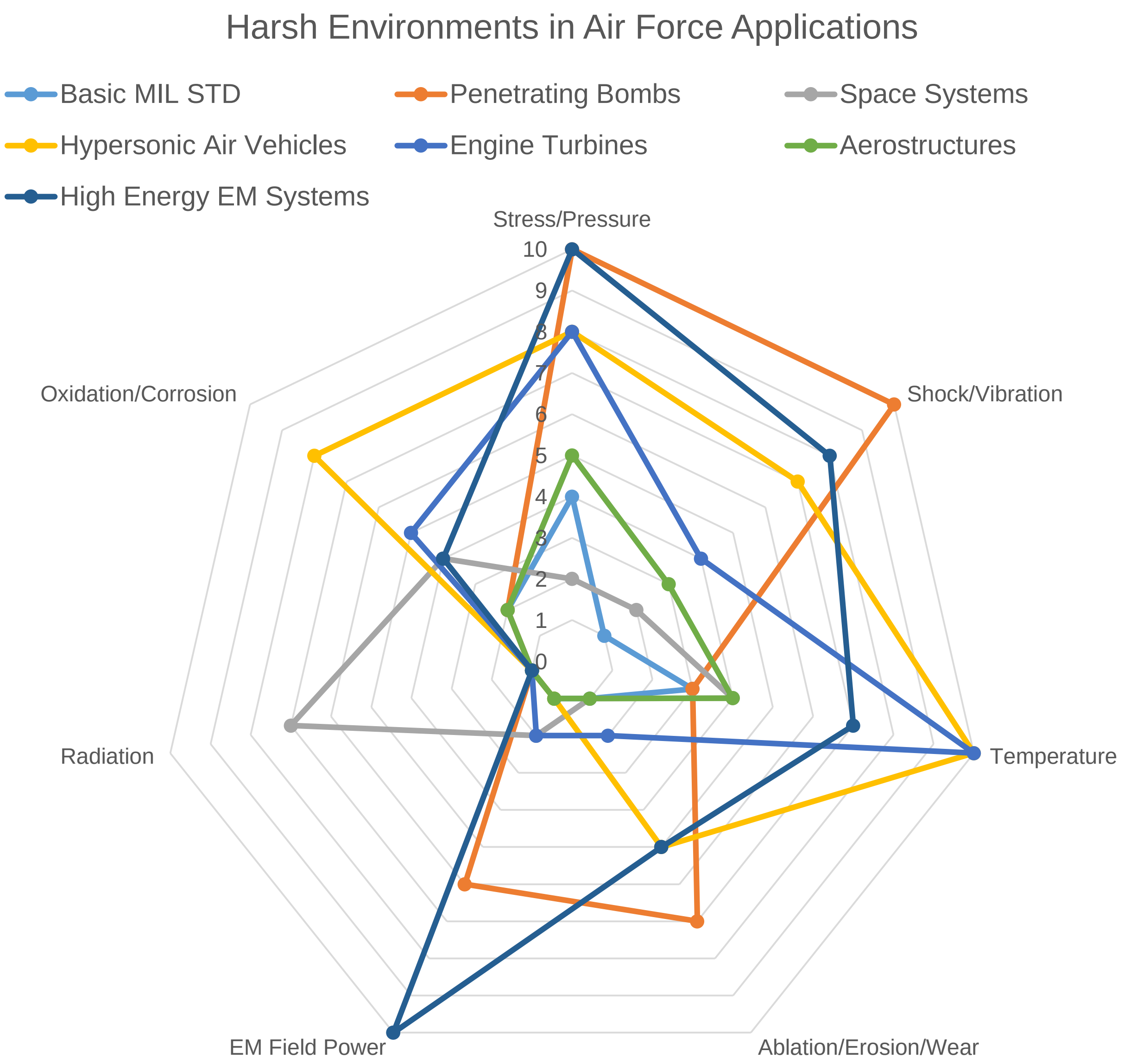
Persistent Power Sources — RF and High Speed Electronics — Capacitive Discharge

$>10^3$ W·h/kg — >100 GHz·100mA = 10^7 A/s — $>10^9$ A/s

Radiation

Geologic Background — Space Environment — Nuclear Reactor

~360 mrem/yr — $\sim10^{10}$ cm^{-2} — 10^{14} cm^{-2} s^{-1}



** Radar plot prepared using relative scale of environmental severity*

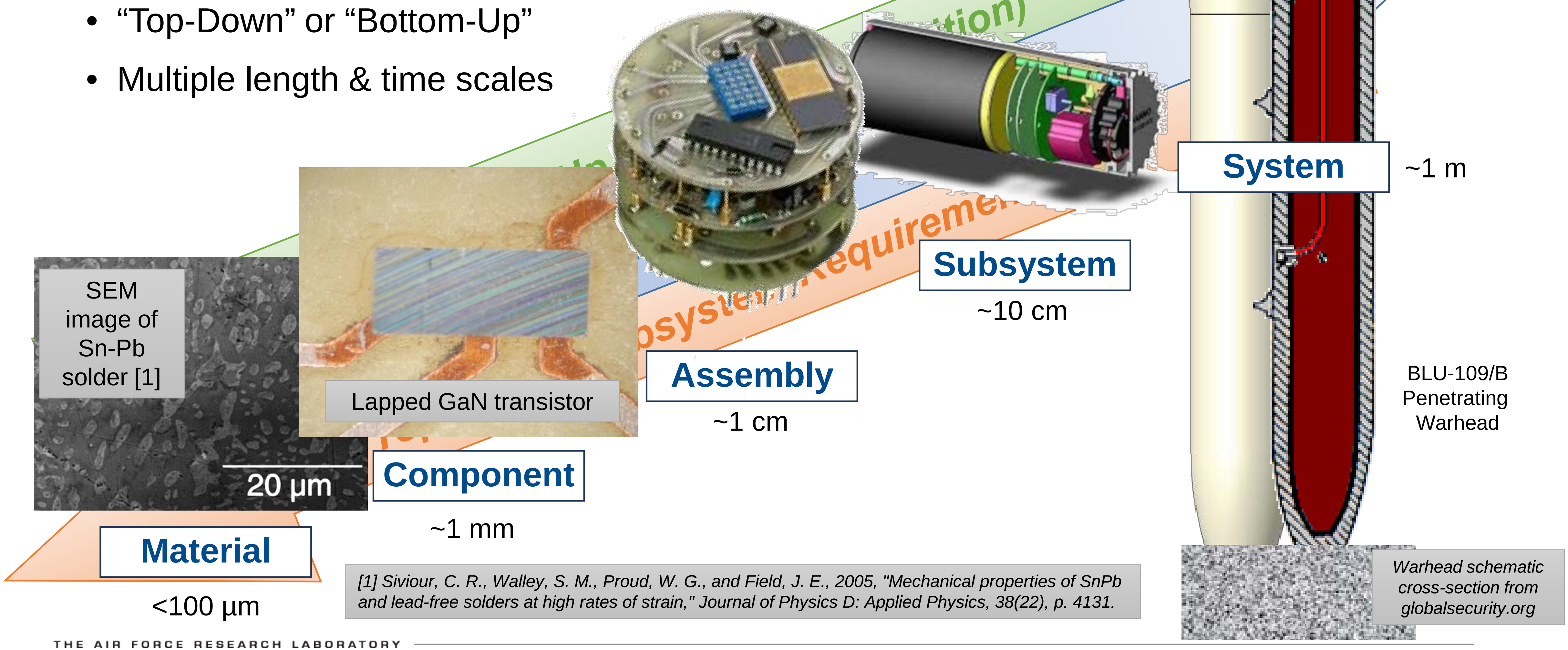
Dynamics of Elastomers for Energetic Materials

Motivation: Dynamic Response of Energetic Composites

Complex Multiscale Structure of Military Systems

Dynamic response can be considered in multiple ways:

- “Top-Down” or “Bottom-Up”
- Multiple length & time scales



[1] Siviour, C. R., Walley, S. M., Proud, W. G., and Field, J. E., 2005, "Mechanical properties of SnPb and lead-free solders at high rates of strain," Journal of Physics D: Applied Physics, 38(22), p. 4131.

Wave Propagation in Viscoelastic Media

Stress-Strain Relation for Viscoelastic Materials

$$\sigma(t) = \int_0^t Y(t-\tau)\,\frac{d\varepsilon(\tau)}{d\tau}\,d\tau\,,$$

Frequency Domain

$$\tilde{\sigma}(\omega) = \tilde{E}^*(\omega)\tilde{\varepsilon}(\omega)$$

Complex Stress-Strain

$$\tilde{E}^*(\omega) = i\omega\tilde{Y}(\omega) = \tilde{E}'(\omega) + i\,\tilde{E}''(\omega)$$

1D* Equation of Motion

$$\tilde{E}^*\frac{\partial^2\tilde{\varepsilon}}{\partial x^2} + \rho\omega^2\tilde{\varepsilon} = 0. \qquad \gamma(\omega) \equiv i\omega\sqrt{\frac{\rho}{\tilde{E}^*}},$$

Attenuation Coefficient

Wavenumber

$$\gamma(\omega) = \alpha(\omega) + ik(\omega)$$

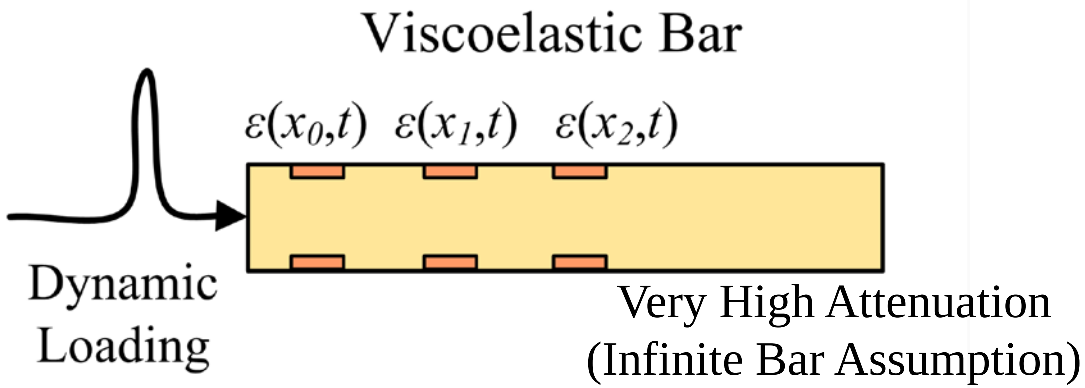
$$\tilde{\varepsilon}(x,\omega) = \tilde{P}(\omega)e^{-\gamma(\omega)x} + \tilde{N}(\omega)e^{\gamma(\omega)x}$$

Frequency domain formalism has significant advantages for wave-based sensing, etc.: but what about the materials properties?

* *Similar results for axisymmetric 3D*

Bonakdar, M., Seidel, G.D., Inman, D.J., *Damping characterization of viscoelastic composites using a micromechanical approach,* Behavior of Mechanics of Multifunctional Materials and Composites 2011, Proc. of SPIE Vol. 7978, 797810

Wave-Based Estimation via "Direct" Impact Test



$$\frac{\tilde{\varepsilon}(x_1,\omega)}{\tilde{\varepsilon}(x_0,\omega)} = R(\omega)e^{-i\phi(\omega)}$$

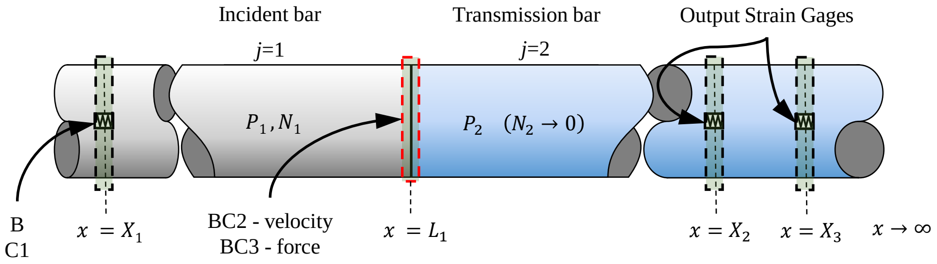
Attenuation Coefficient

$$\alpha(\omega) = -\frac{1}{\Delta x}\ln(R(\omega))$$

Wavenumber (propagation constant)

$$k(\omega) = \frac{\phi(\omega)}{\Delta x}$$

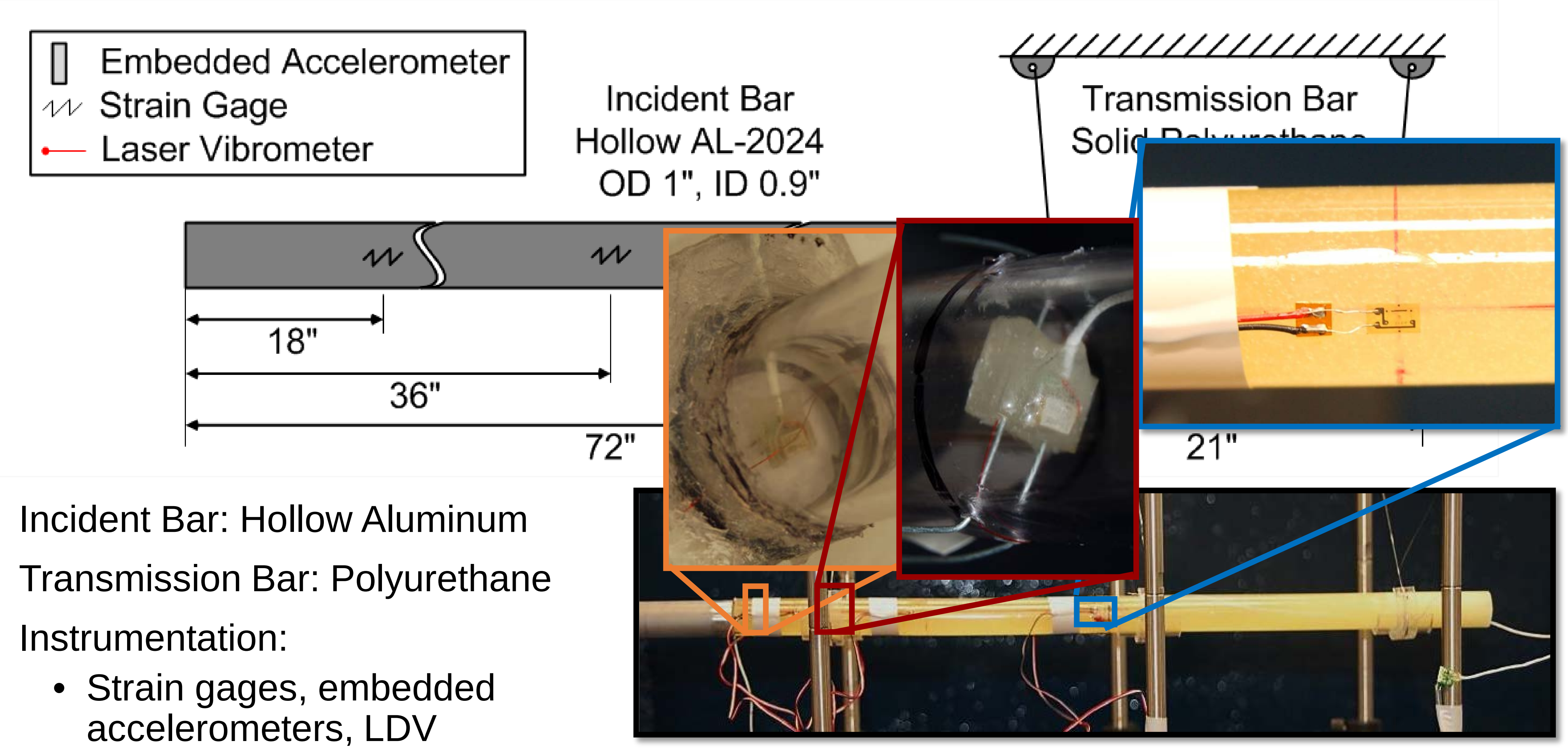
- Pseudo-direct impact SHPB apparatus
- Solve coupled equations for embedded strain gages



$$\begin{bmatrix} e^{-\gamma_1 X_1} & e^{\gamma_1 X_1} & 0 \\ -\gamma_2 e^{-\gamma_1 L_1} & \gamma_2 e^{\gamma_1 L_1} & \gamma_1 e^{-\gamma_2 L_1} \\ A_1 \tilde{E}_1^* e^{-\gamma_1 L_1} & A_1 \tilde{E}_1^* e^{\gamma_1 L_1} & A_2 \tilde{E}_2^* e^{-\gamma_2 L_1} \\ 0 & 0 & e^{-\gamma_2 X_2} \\ 0 & 0 & e^{-\gamma_2 X_3} \end{bmatrix} \begin{Bmatrix} \tilde{P}_1 \\ \tilde{N}_1 \\ \tilde{P}_2 \end{Bmatrix} = \begin{Bmatrix} \tilde{\varepsilon}_1 \\ 0 \\ 0 \\ \tilde{\varepsilon}_2 \\ \tilde{\varepsilon}_3 \end{Bmatrix}$$

Lundberg, B. and R.H. Blanc, *Determination of mechanical material properties from the two-point response….* Journal of Sound and Vibration, 1988. **126**(1): p. 97-108.
Bacon, C., *An experimental method for considering dispersion and attenuation in a viscoelastic Hopkinson bar.* Experimental Mechanics, 1998. **38**(4): p. 242-249.

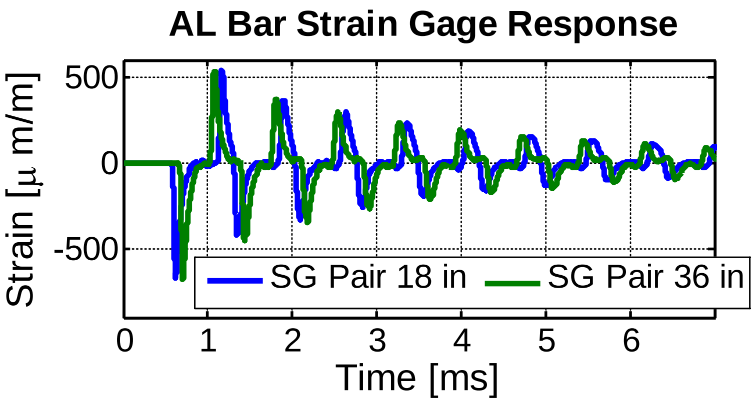
Experimental Setup

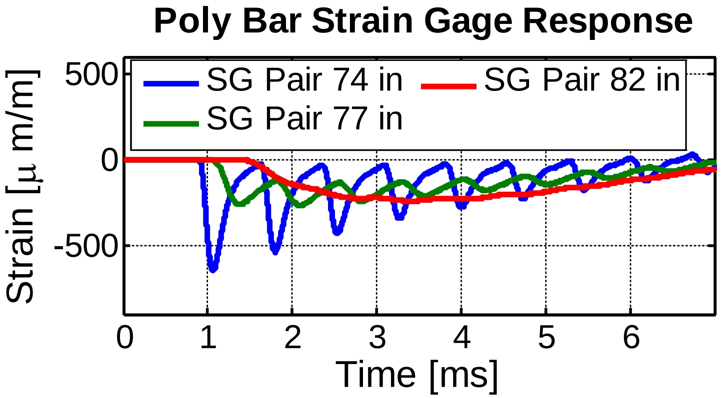


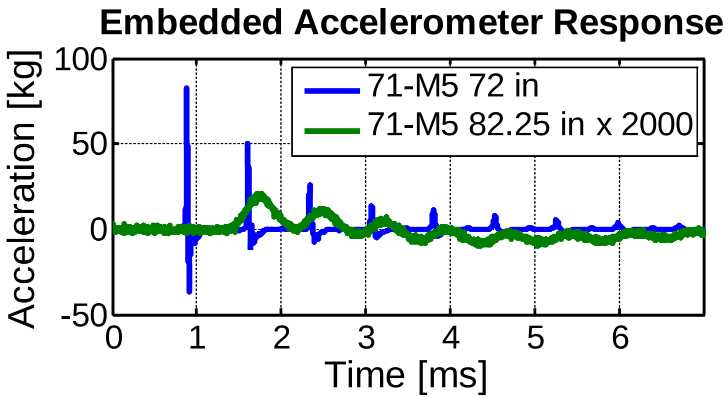
- Incident Bar: Hollow Aluminum
- Transmission Bar: Polyurethane
- Instrumentation:
  - Strain gages, embedded accelerometers, LDV

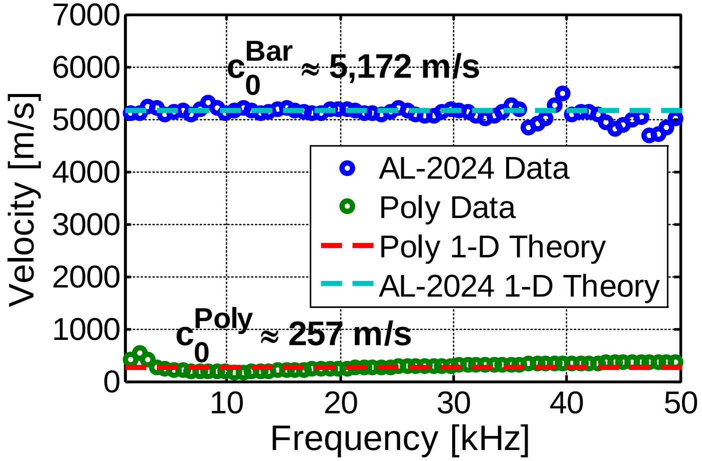
Data & Analysis

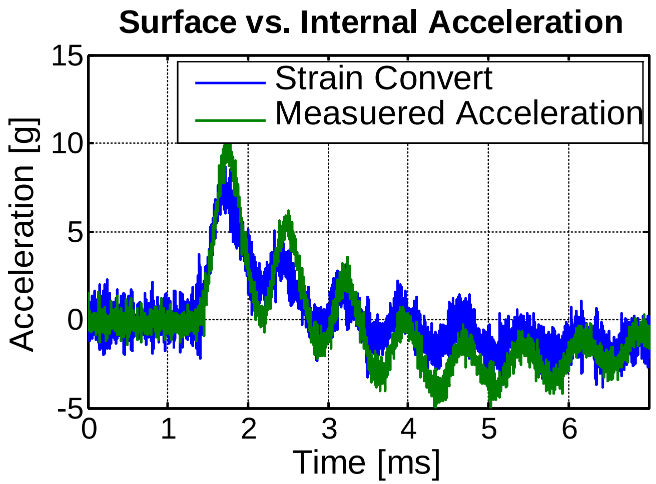
- Observed strain agrees with acceleration
  - High attenuation = low signal
  - Data noisy
- Wave speeds within expectation
- Strain used as boundary conditions for estimating 1-D propagation behavior
  - *Next slide*











Complex Properties

- Model-based estimation using moduli
  1. Freq-independent

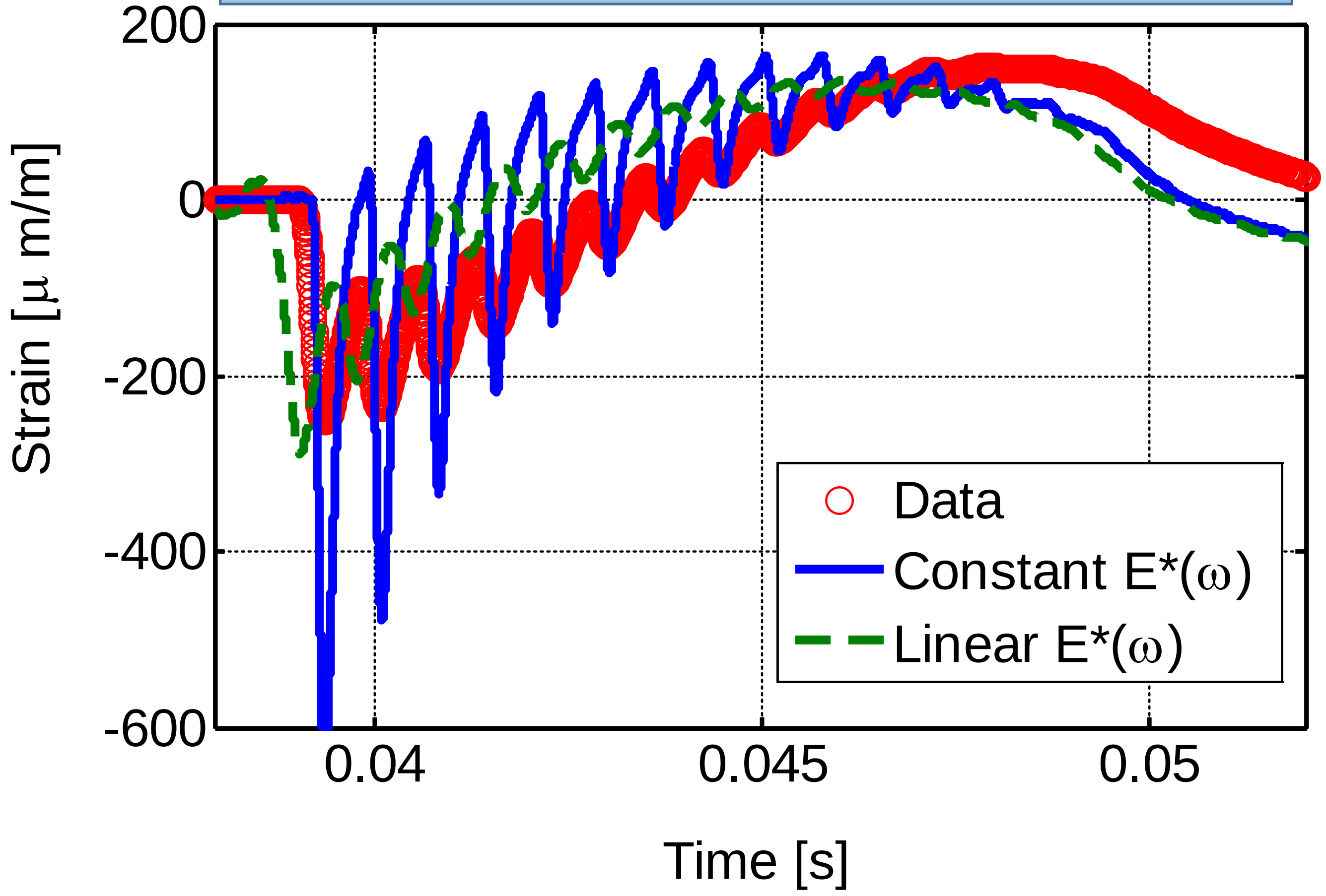
$$E^*(\omega) = A_1 + A_2 i$$
$$E^*(\omega) = 66.9 + 0.140\, i \text{ MPa}$$

  2. Linear wrt freq.

$$E^*(\omega) = (A_1 + A_2\omega) + (A_3 + A_4\omega)i$$
$$E^*(\omega) = (15.5 - 0.0049\omega) + (1.21 + 0.00314\omega)i \text{ MPa}$$

- Linear model better fit
  - Higher order or nonlinear: improved results?

Strain vs. Time in Polyurethane Bar (*x* = 77 in)



- Next steps:
  - Comparison of dynamic complex elastic moduli with other test methods (e.g. DMA)
  - Global optimization of moduli with multiple random initial conditions

FY19 MURI Topic 24: Microstructurally-Aware Continuum Models for Energetic Materials

- Objective:
  - Transform current continu models by incorp structural features together with mechanical and predict & validate predictions for continuu ion transition in energ ls with a range of microstruc
- Research Concentr ontinuum models that
  - Inc ostructural features and
  - Contains mechani hemical energy release rates that lead to
  - ounts for uncertainty (e.g., f ation & computational methods), and
  - Provi nced effort that culminates wit

Hot Spots

Growth to detonation → DDT

Mesostructural influences → Stochasticity

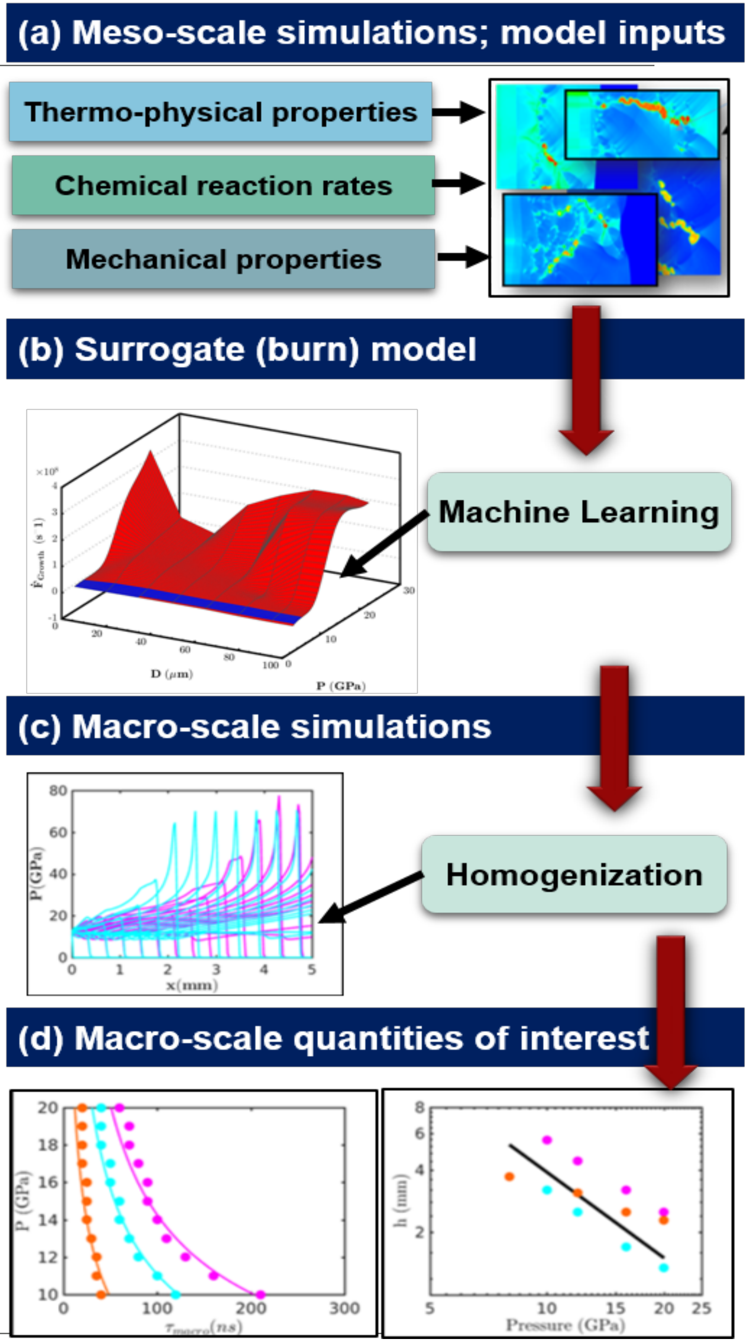
Obligatory AI & Machine Learning References

#ChemistryInside™

Quantitative Structure-Processing-Properties-Performance

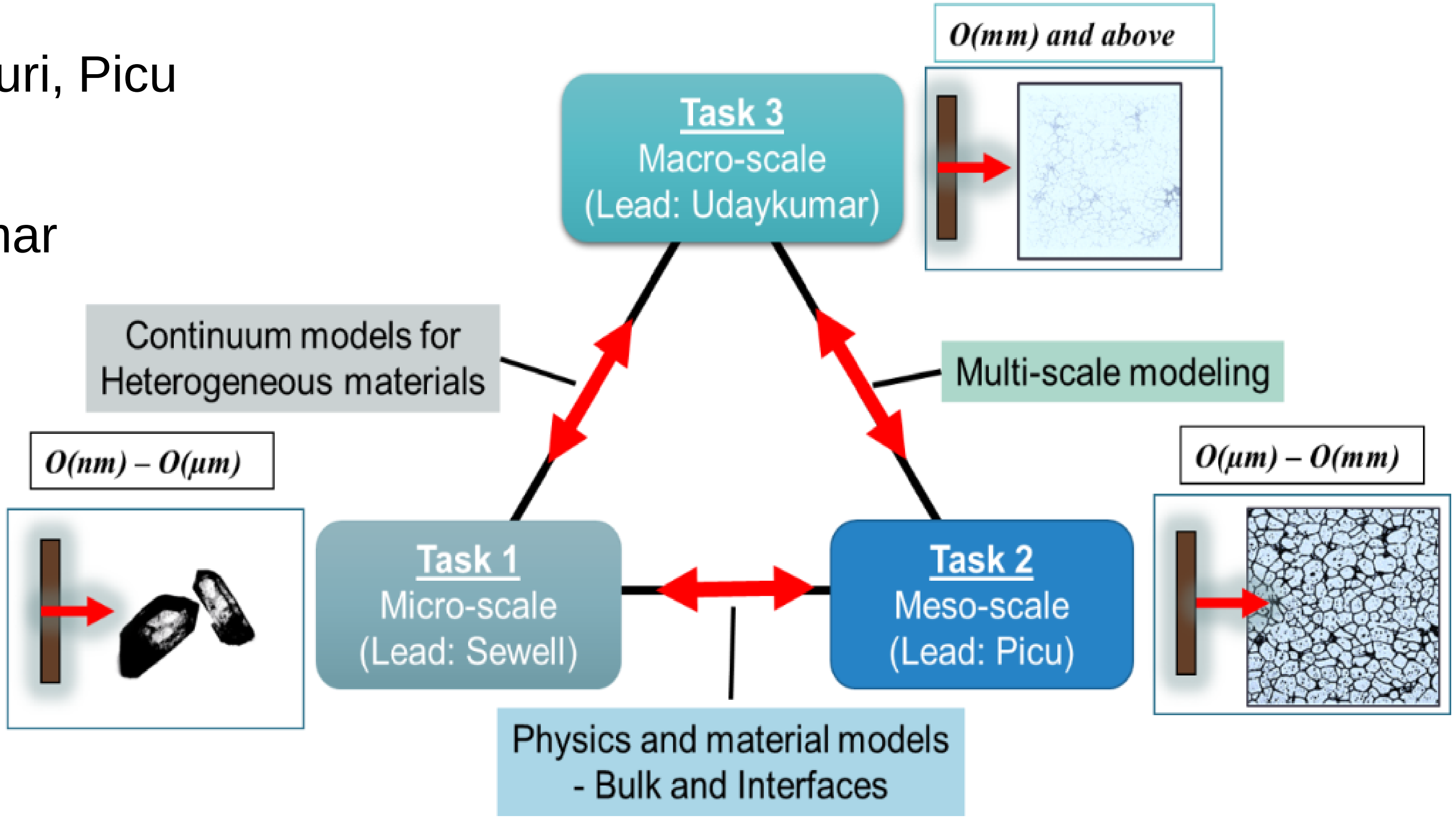
US MURI Team

- PI: Tommy Sewell (U of Missouri)
- Goal: A machine-learned, microstructure-informed surrogate surface for energy localization (MISSEL)
- MISSEL will be used to predict the response of energetic materials for loading conditions ranging from weak impact to strong shocks, including corner turning & re-shock.
  - James convex hull, go/no-go under impact loading
  - Pop plot under shock loading
- Materials:
  - HMX, PDMS and HTPB binders
  - Micro-structures of pressed HMX & other PBXs
- Fundamental science and engineering deeply augmented & integrated via machine learning



MURI Effort Organized into Three Integrated Tasks

- Task 1: Micro-scale
  - Sewell (lead), Dlott, Chaudhuri, Picu
- Task 2: Meso-scale
  - Picu (lead), Tomar, Udaykumar
  - And the rest of the team!
- Task 3: Macro-scale
  - Udaykumar (lead), Sun, Picu, Dlott

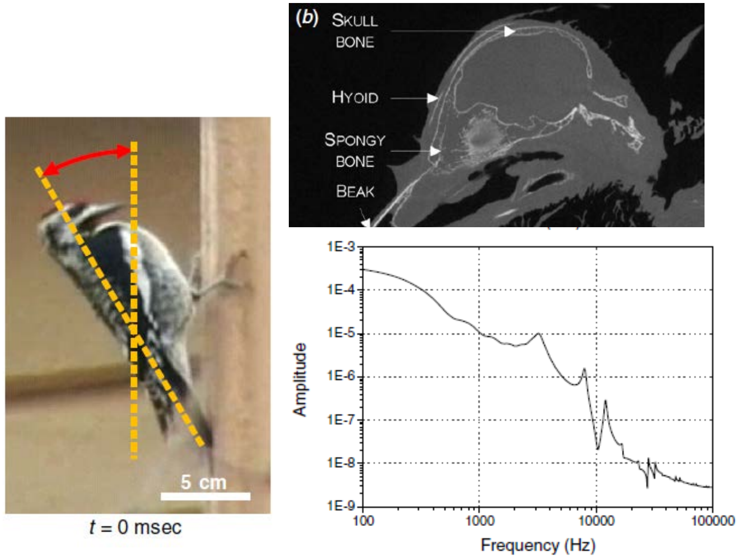


Shock Mitigation

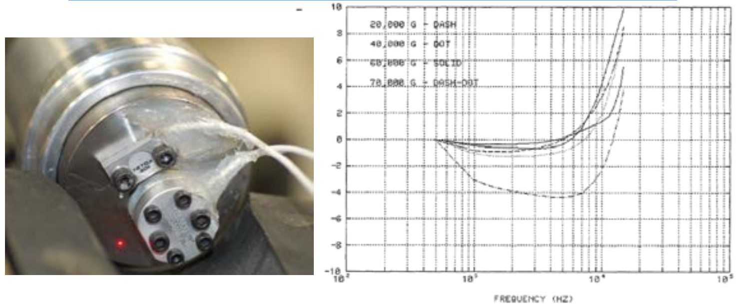
State of the Art in Shock Mitigation

<u>Classes</u> *(by dissipation mechanism)*

- Mechanical deformation
  - Automotive “crumple zones”
- Constrained layer damping
  - Woodpecker skull (biomimetic) [1]
- Energy localization
  - Functional polyurea nanoparticles [2]
- Viscoelastic/viscoplastic
  - Polysulfide-isolated mount [3]
- Superelastic
  - NiTi shape memory alloy [4]
- Multilayered mechanical filter
  - Metal & polymer “bandstop” filter [5]



Woodpecker brain isolation [11]

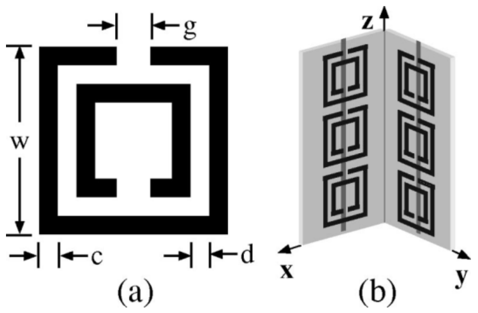


Polysulfide filter [13]

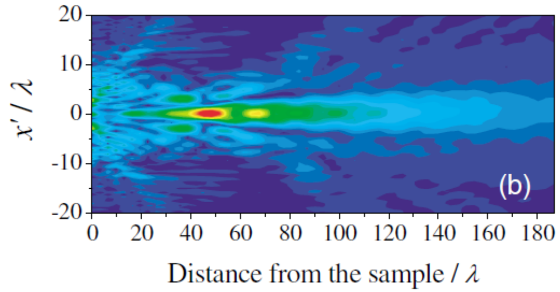
[1] Yoon, S.-H., and Park, S., 2011, "A mechanical analysis of woodpecker drumming and its application to shock-absorbing systems," Bioinspiration & Biomimetics, 6(1), p. 016003.
[2] Holzworth, K., Williams, G., and Nemat-Nasser, S., 2012, "Hybrid Polymer Grafted Nanoparticle Composites for Blast-induced Shock-wave Mitigation," Proc. SEM International Conference & Exposition on Experimental and Applied Mechanics, Costa Mesa, CA.
[3] Bateman, V. I., Brown, F. A., and Nusser, M. A., 2000, "High Shock, High Frequency Characteristics of a Mechanical Isolator for a Piezoresistive Accelerometer, the ENDEVCO 7270AM6," Report SAND2000-1528 Sandia National Laboratory
[4] S. Nemat-Nasser and W.-G. Guo, 2006, “Superelastic and cyclic response of NiTi SMA at various strain rates and temperatures”, *Mech Materials* 38, pp 463-474.
[5] N.A. Winfree et al, 2010, “Mechanical filter for sensors”, US Patent 7706213

Metamaterials & Related Metastructures

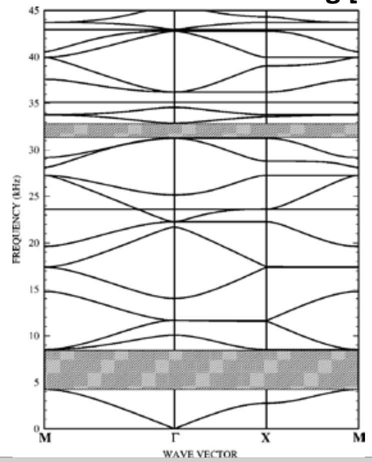
- *Metamaterials* [1]
  - Definition: Engineered materials designed w/properties not occurring naturally
  - “Effective” macroscopic properties strongly dependent on (nano-/micro-) structure & material (vs. “unobtainium”)
- *Phononic Crystals (PC)/Band Gap (PBG) Materials*
  - Definition: Artificial periodic (crystalline) composites where structure influences wave propagation [2]
  - Interactions: Bragg (lattice) + Mie (geometric) scattering
    - Generally constant “single scatterer” assumption
- *Acoustic Band Gap (ABG) Materials*
  - Definition: Composite materials with defined band baps in or near the acoustic range (~20 Hz to 20 kHz)
  - Interactions: Elastic wave propagation + Bloch periodicity (pressure)
- *Superlattices (SL)*
  - Definition: Multilayered periodic heterostructures (i.e., a microstructure with different materials) made of thin crystalline films,
    - Individual film thicknesses ranging from less than 1 nm to over 100 nm
    - Period: Characteristic pattern of crystalline films (e.g., a pair of different films called a “bilayer”) that is repeated many times
  - Interactions: Phonon (elastic) propagation on lattice (band-folding, scattering)



Split Ring Resonators [1]

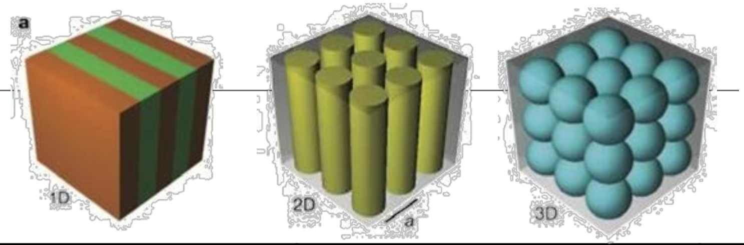


3D acoustic wave focusing [3]



Acoustic band structure [4]

[1] Shelby, R. A., Smith D.R., Shultz S., and Nemat-Nasser S.C., 2001, “Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial”, *Applied Physics Letters* 78 (4), pp. 489-491.
[2] Lu, M.-H., Feng, L., and Chen, Y.-F., 2009, "Phononic crystals and acoustic metamaterials," Materials Today, 12(12), pp. 34-42.
[3] Yang, S., Page, J. H., Liu, Z., Cowan, M. L., Chan, C. T., and Sheng, P., 2004, "Focusing of Sound in a 3D Phononic Crystal," Physical Review Letters, 93(2), 024301.
[4] Vasseur, J. O., Deymier, P. A., Khelif, A., Lambin, P., Djafari-Rouhani, B., Akjouj, A., Dobrzynski, L., Fettouhi, N., and Zemmouri, J., 2002, "Phononic crystal with low filling fraction and absolute acoustic band gap in the audible frequency range: A theoretical and experimental study," Physical Review E, 65(5), p. 056608.



Sample of Metamaterials Work

First Author	Year	Materials/ Geometry	*N*-D	Feature Size *r* or *l* [m]	Lattice Spacing *a* [m]	Freq Range/ Bandwidth $\Delta\omega$ [Hz]	Notes/Comments	Ref.
Liu	2000	Cubic array of Pb/silicone spheres	3D	~5 mm	30 mm	250 to 2k		[5]
Vasseur	2002	Square planar array of filled/hollow Cu tubes in air	2D	14 mm	30 mm	0 to 50k		[4]
Tanaka	1999	Square lattice of AlAs cylinders in GaAs matrix	2D	*A* (arbitrary)	*a* (arbitrary)	~ *a/v* (normalized)	Surface acoustic wave (SAW) theory	[6]
Pennec	2004	Square planar array of steel tubes w/air, Hg in air	2D	0.9-1.4 mm	5 mm	0 to 300k	ABG w/ tunability and multiplexing	[7]
Tang	2004	Thin film sandwiches w/ electrorheological material	1D	0.1 mm	0.1 mm	80 to 200	Simple transmission experiments	[8]
Dhar	1999	Lithographically patterned Al film on glass substrate	1D	~1 μm	3-3.75 μm	100-800 MHz	Measured w/ ps transient grating	[9]
Yang	2004	FCC cubic array of WC beads in water	3D	0.4 mm	0.8 mm	0.98-1.2 MHz	3-D focusing of waves	[1]
Lu	2009	(Review article)					Review article (PC and AMM)	[2]

[5] Liu et al., 2000, “Locally Resonant Sonic Materials,” *Science* 289 (5485), pp 1734-1736.
[6] Tanaka, Y., and Tamura, S.-I., 1999, “Two-dimensional phononic crystals: surface acoustic waves,” *Physica B: Condensed Matter* 263-264, pp. 77-80.
[7] Pennec, Y., Djafari-Rouhani, B., Vasseur, J. O., Khelif, A., and Deymier, P. A., 2004, "Tunable filtering and demultiplexing in phononic crystals with hollow cylinders," Physical Review E, 69(4), p. 046608.
[8] Hong, T., Chunrong, L., and Xiaopeng, Z., 2004, "Tunable characteristics of a flexible thin electrorheological layer for low frequency acoustic waves," Journal of Physics D: Applied Physics, 37(16), p. 2331.
[9] Dhar, L., and Rogers, J. A., 2000, "High frequency one-dimensional phononic crystal characterized with a picosecond transient grating photoacoustic technique," Applied Physics Letters, 77(9), pp. 1402-1404.

Top right images from M. Maldovan, “Sound and Heat Revolutions in Phononics,” *Nature*, 503, p. 209-217 (2013).

Wave Properties in Various Media

$Z = F/v = \rho A c$

$c = \sqrt{E/\rho} = f\lambda$

	Material	Elastic Modulus E [GPa]	Density P [kg/m^3]	1-D Impedance $Z'' = Z/A$ [x 10^6 kg/m^{2}s]
Metals	6/4 Titanium	104	4420	21.4
	Maraging Steel	188	8080	39.1
	Tungsten	329	16920	75.3
	Copper	115	8960	32.1
Polymers	Polycarbonate	2.3	1200	1.86
	Epoxy	2.3	1140	1.62
	PVC	1.6	1380	1.48
Composites	PBX[1]	~0.5 (0.1-2.9+)	~1800	1.89
	G10[2]	~18.8 (*x*) ~7.8 (*z*)	~1700	5.64 (*x*) 3.64 (*z*)
	CFRP	~1.5	~1500	1.50

Frequency f [Hz]	Wavelength λ [m]
1	4800
100	48
10k	0.48
1M	4.8m
100M	48m

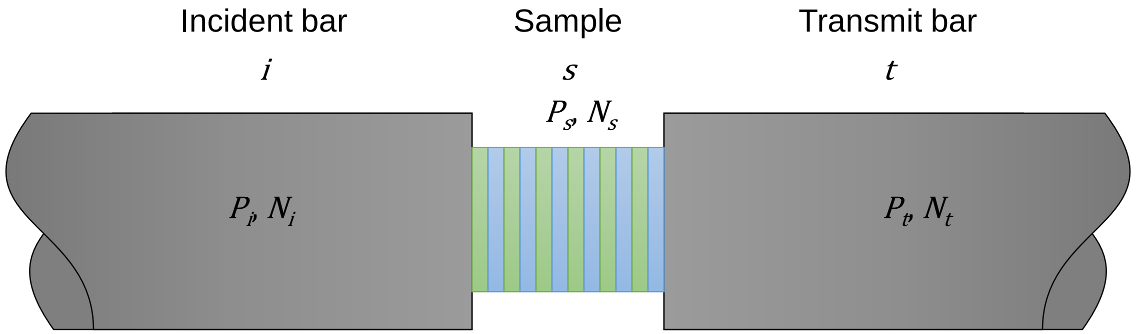
Frequency f [Hz]	Wavelength λ [m]
1	1077
100	1.1
10k	0.11
1M	1.1m
100M	11m

(1) Generalized from several open literature values for PBX-9501 properties

(2) K. Ravi-Chandar and S. Satapathy, 2006, “Mechanical Properties of G-10 Glass–Epoxy Composite”, Institute for Advanced Technology, The University of Texas at Austin, IAT.R 0466

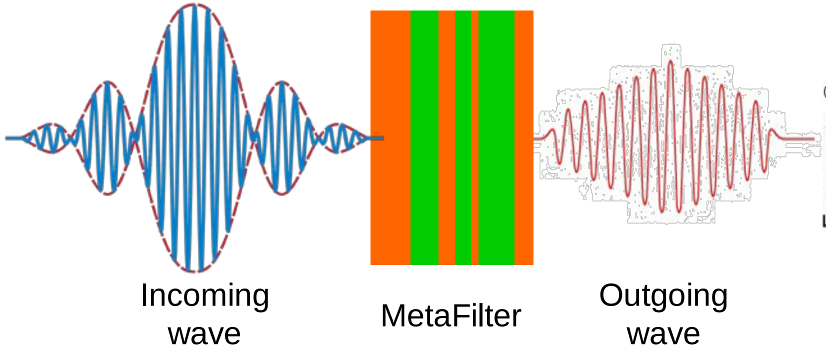
Initial Shock “MetaFilter” Design Optimization Problem

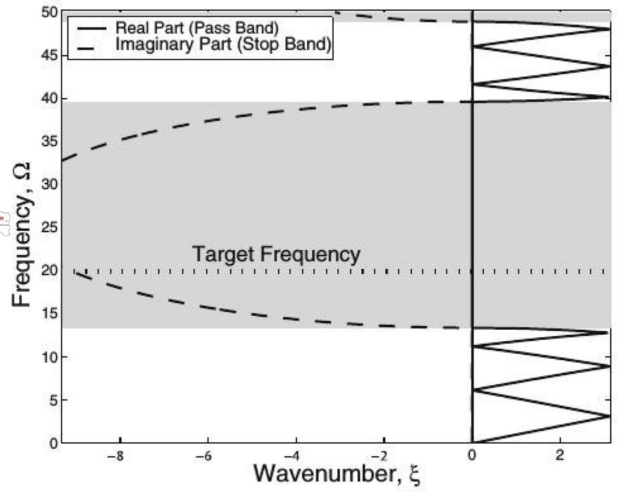
- Design goals/objectives:
  - Spectral energy isolation (transmission rejection ratio)
  - Minimum complexity (N_{layers}, L_{system})
- Constraints:
  - Discrete material set (non-continuous property variables)
  - Defined layer pattern
  - Constant layer sizing (L_A, L_B)
- Initial guess:
  - Polysulfide/steel stack
- Method:
  - Heuristic discrete genetic algorithm w/ local gradient-based improvement



$$t_{12}(\omega) = \frac{\sigma_1(\omega)}{\sigma_2(\omega)}$$

$$\tau_{12} = \frac{\text{transmitted vibrational power}}{\text{incident vibrational power}} \propto {t_{12}}^2$$





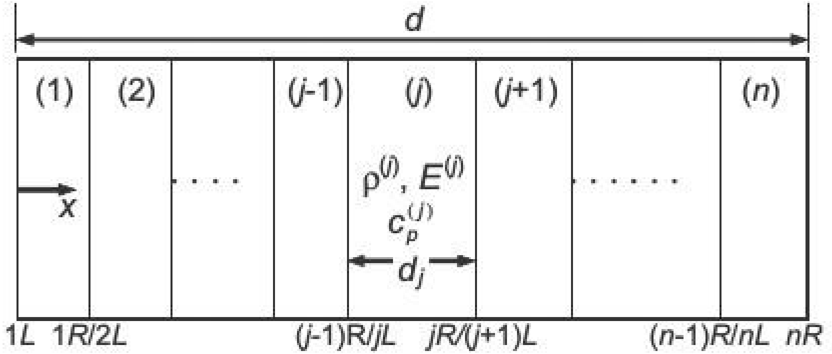
Hussein, M.I., Hamza, K., Hulbert, G.M., Scott, R. A., and K. Saitou, “Multiobjective evolutionary optimization of periodic layered materials for desired wave dispersion characteristics,” *Structural and Multidisciplinary Optimization*, 31, p. 60-75 (2006).

Theoretical Framework

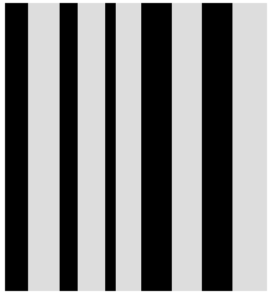
- Transfer matrix method:
  - Assume infinitely periodic layered material consisting of a repeated unit cell
  - Solve elastodynamic equation for the unit cell consisting of n layers
  - Use periodicity of the material to compute band structure

$$\rho(\boldsymbol{r})\,\frac{\partial^2 \boldsymbol{u}(\boldsymbol{r})}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma}(\boldsymbol{r})$$

$$\mathbf{T}_j = \begin{bmatrix} \cos(k^{(j)}d^{(j)}) & (1/Z^{(j)})\sin(k^{(j)}d^{(j)}) \\ -Z^{(j)}\sin(k^{(j)}d^{(j)}) & \cos(k^{(j)}d^{(j)}) \end{bmatrix}$$

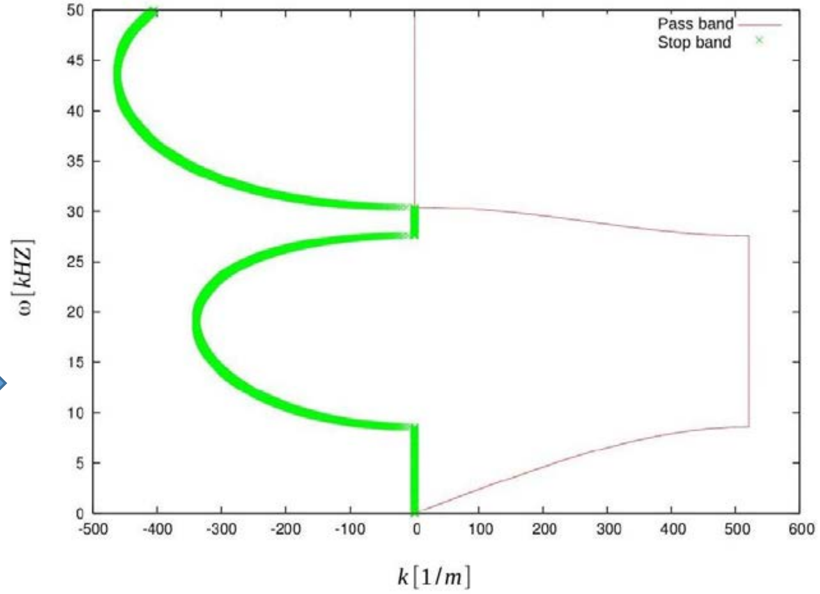


Unit Cell



HDPE and Aluminum MetaFilter

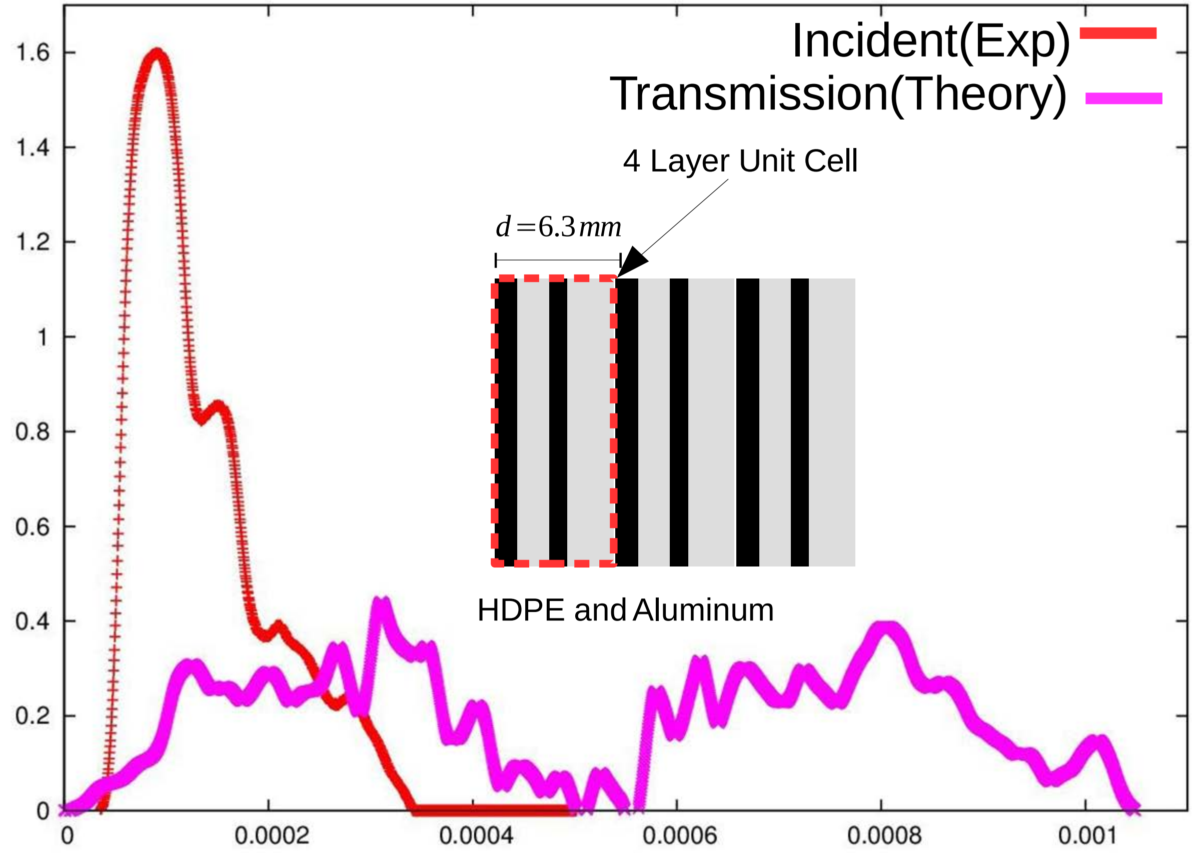
10 layer unit cell of HDPE & Al layers (thickness ~1 mm)

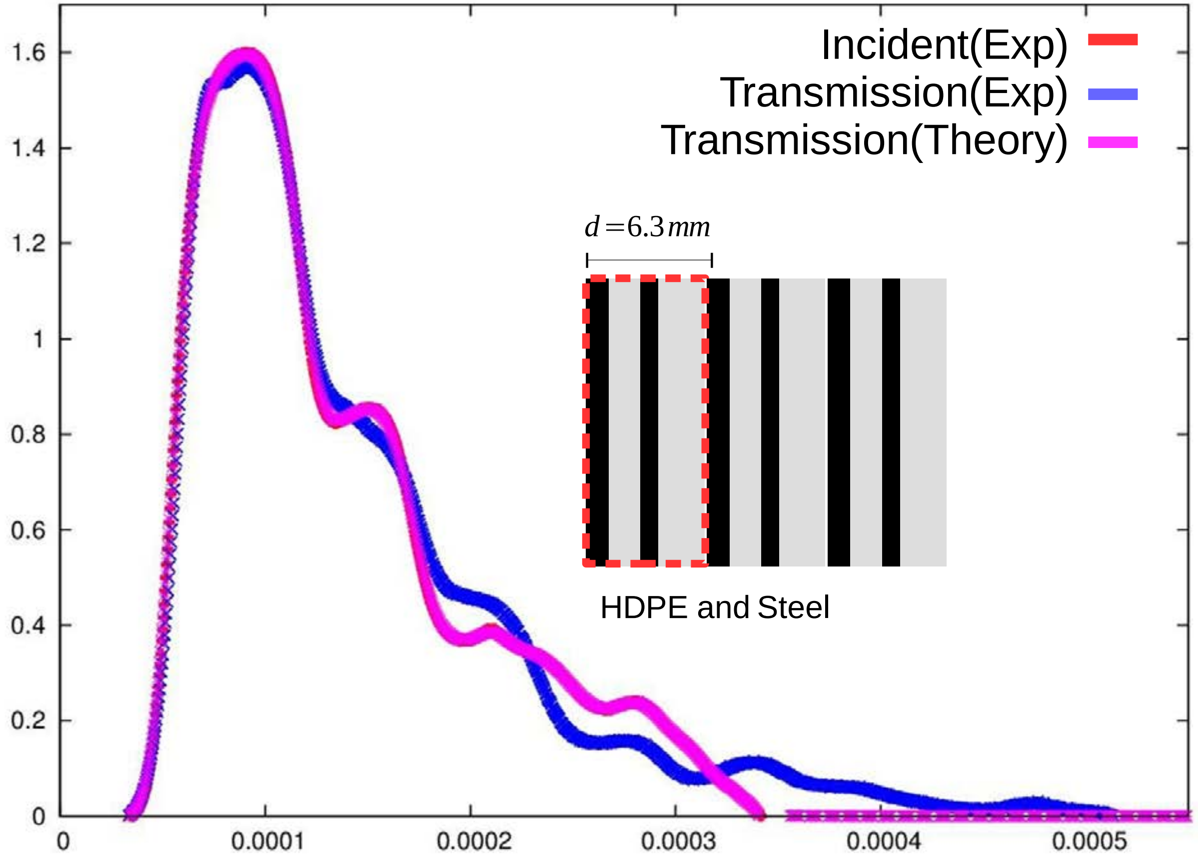


Calculated band diagram

Mahmoud I. Hussein, Gregory M. Hulbert, and Richard A. Scott, “Dispersive elastodynamics of 1D banded materials and structures: analysis”, Journal of Sound and Vibration 289 (2006) 779–806

Shock MetaFilter: Predictions & Observed Response





Further studies

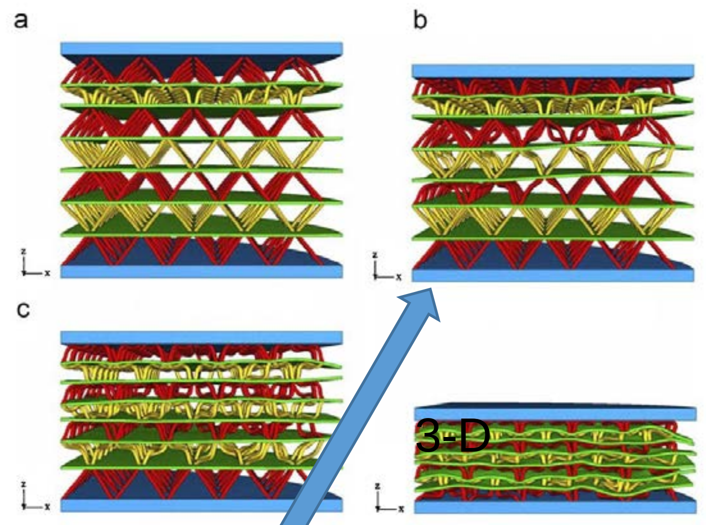
- Validate 1-D elastodynamic response
- Add more complex material response
  - Inelasticity
  - Constitutive parameters (rate, temp., pressure)
  - Frequency-dependence

$$\alpha(\omega) = -\frac{1}{\Delta x}\ln(R(\omega))$$

$$k(\omega) = \frac{\phi(\omega)}{\Delta x}$$

$$\begin{bmatrix} e^{-\gamma_1 X_1} & e^{\gamma_1 X_1} & 0 \\ -\gamma_2 e^{-\gamma_1 L_1} & \gamma_2 e^{\gamma_1 L_1} & \gamma_1 e^{-\gamma_2 L_1} \\ A_1 \tilde{E}_1^* e^{-\gamma_1 L_1} & A_1 \tilde{E}_1^* e^{\gamma_1 L_1} & A_2 \tilde{E}_2^* e^{-\gamma_2 L_1} \\ 0 & 0 & e^{-\gamma_2 X_2} \\ 0 & 0 & e^{-\gamma_2 X_3} \end{bmatrix} \begin{Bmatrix} \tilde{P}_1 \\ \tilde{N}_1 \\ \tilde{P}_2 \end{Bmatrix} = \begin{Bmatrix} \tilde{\varepsilon}_1 \\ 0 \\ 0 \\ \tilde{\varepsilon}_2 \\ \tilde{\varepsilon}_3 \end{Bmatrix}$$

- Include uncertainty (robust estimation)
- Exploit dimensionality & scale → "architextured" materials



N-D

2-D

1-D

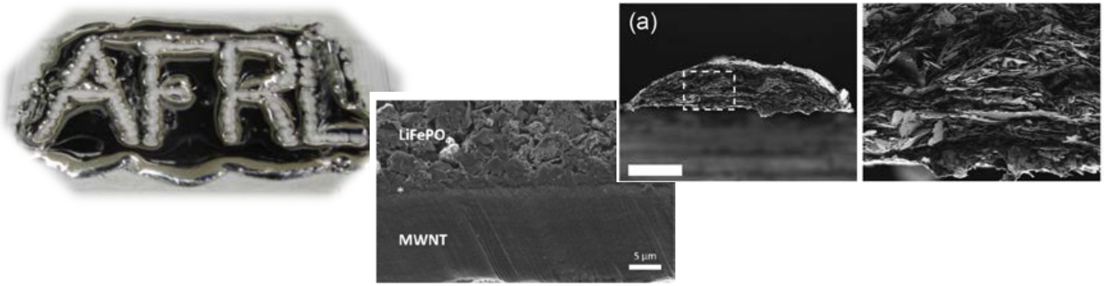
Linear Nonlinear Rate-Dependent

[1] H. Wadley, K. Dharmasena, Y. Chen, P. Dudt, D. Knight, R. Charette, and K. Kiddy, "Compressive response of multilayered pyramidal lattices during underwater shock loading", International Journal of Impact Engineering 35 (2008) 1102–1114

Other Novel Applications

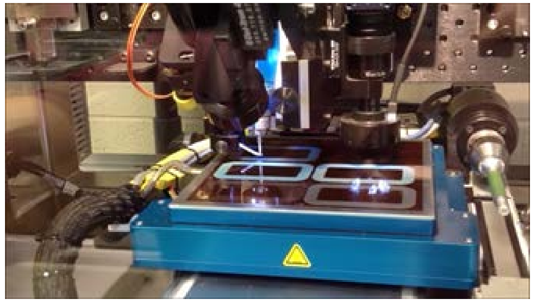
Flexible Materials and Processes at AFRL

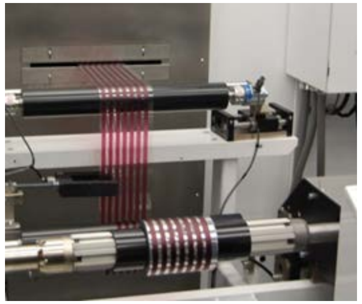
Next-Generation Materials



(Flexible ICs, Energy Storage, Stretchable Conductors)

Advanced Manufacturing

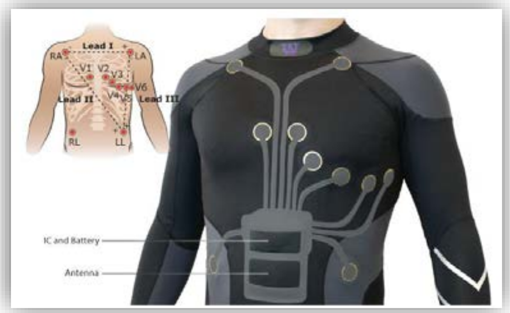




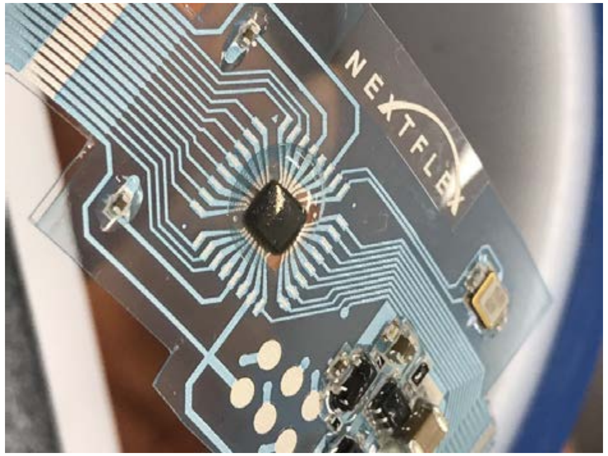
(Printed Electronics, Topology Optimization, AI/ML)

Printed Flexible Antennas

Human Performance Monitoring



Conformal Electromagnetics



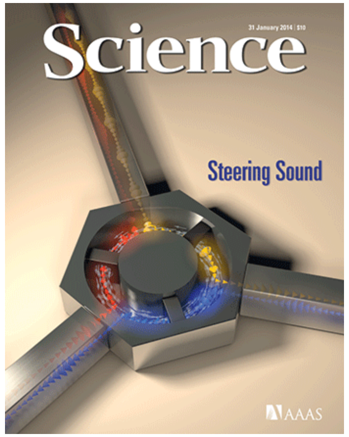
Flex hybrid Arduino

Distribution A: Approved for Public Release: 88ABW-2019-1497

Controlling Mechanical Wave Propagation Critical to Air Force

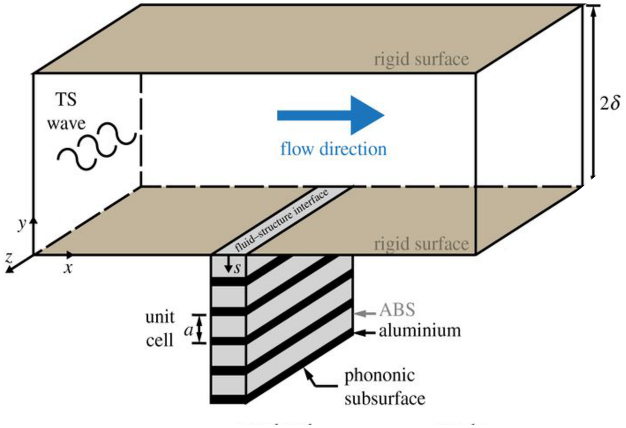
Battlefield Acoustics

Science, v 343, n 6170, p 516-19 (2014)



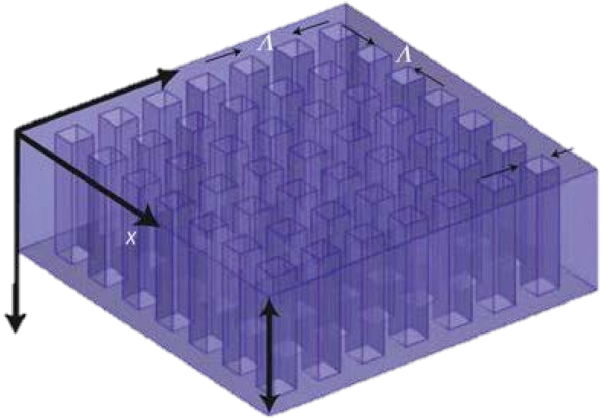
Aeroacoustics

Proc. of the Royal Society A, v 471, n 2177, (2015)



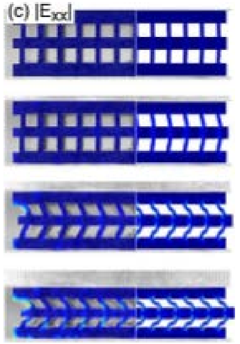
NDE/ Ultrasonic Imaging

Nature Physics, v 7, n 1, 52-5, (2011)



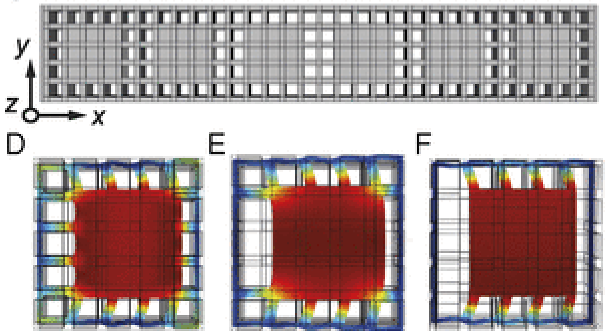
Munitions

Advanced Engineering Materials, v 20, n 5, (2018)



Vibration Control

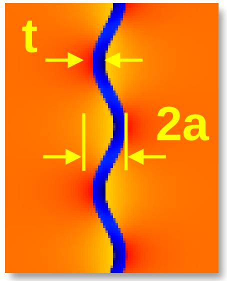
PNAS, vol. 113 (30), p. 8386-8390, (2016)

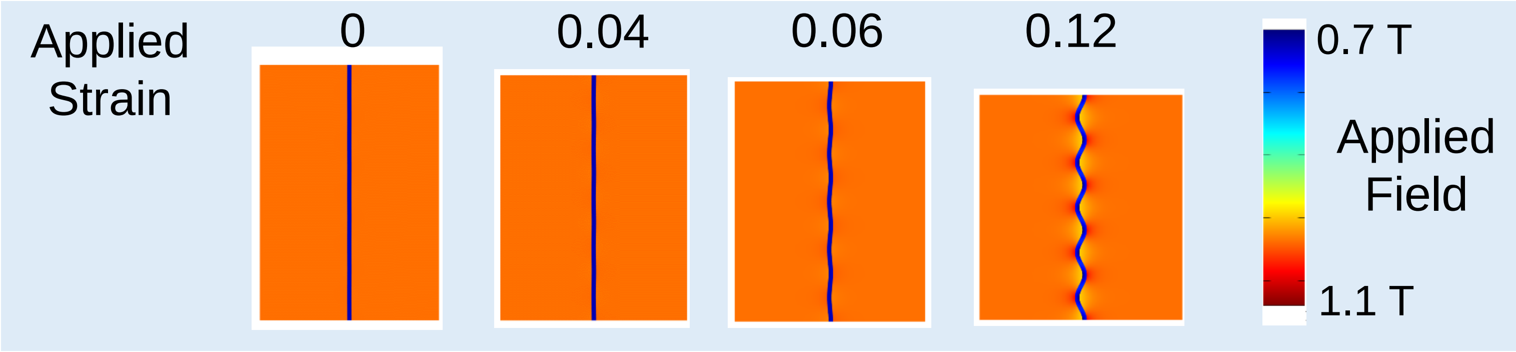


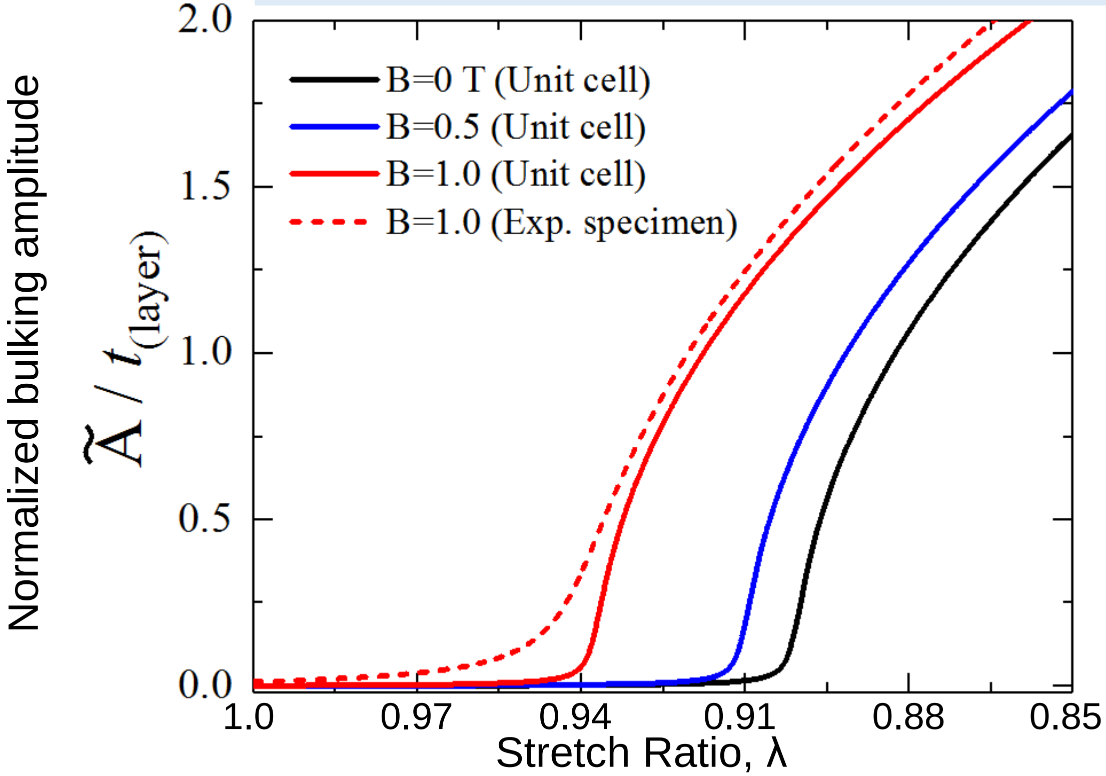
Current material solutions are diverse due to different environment/ frequencies.

But all current solutions are parasitic and add weight and volume!

Hyperelastic Magneto-responsive Material Model







<u>Two tuning mechanisms:</u>

Fixed Strain Tuning

Fixed Field Tuning

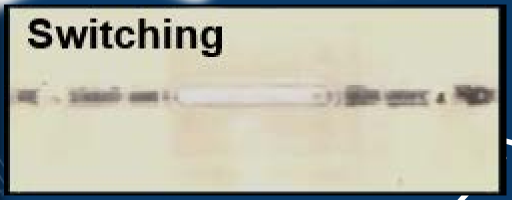
Stretch ratio = specimen height under strain/ original unconstrained height

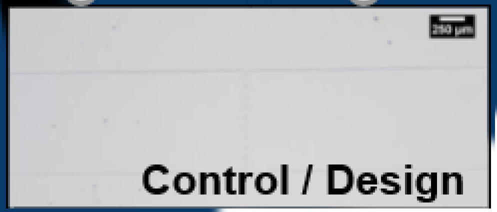
<u>Model Predictions:</u>

1. Applied field induces critical buckling at lower strains
2. Applied strain increases the amplitude of buckled pattern

Responsive Liquid Metal Electronics

Group Overview





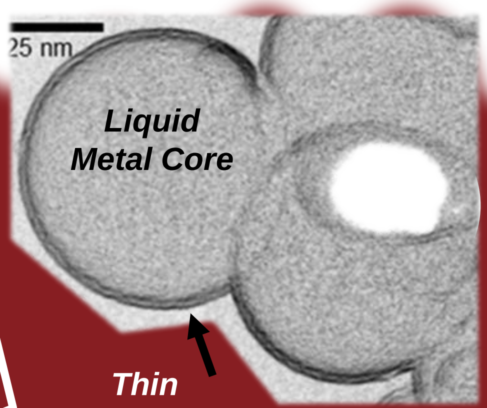
Adv. Mat. Inter, **2016**
JMM, **2016**
Langmuir, **2016**
IEEE-AP&S Proc,. **2017**
Adv. Ele. Mat, **2018**
IEEE-IMS, **2019**

Microfluidics

Reconfigurable Electronics

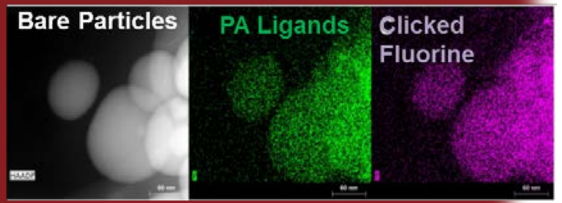
- DC – RF Devices
- Tunable Antennas, Switches

Core/Shell Nanoparticles



Self-healing Electronics

- Impact triggered conductivity
- Damage resistant circuits



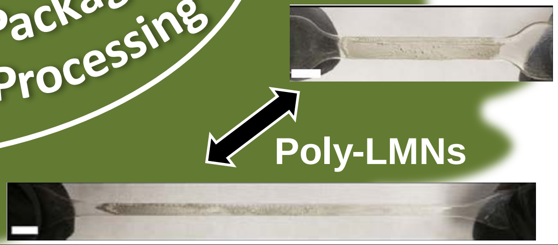
Adv. Mat. Inter, **2017**
Langmuir, **2018**
JPCC, **2018**
Nanoscale, **2019**

ACS Colloids and Interfaces, 2018
Adv. Eng. Mat, 2019
Adv. Eng. Mat, 2019
Adv. Mat, 2019

Ultra-stretchable Electronics

- Airman/machine interfaces
- Conductive hinges

Packaging & Processing



Polymerized Liquid Metal Networks (Poly-LMNs)

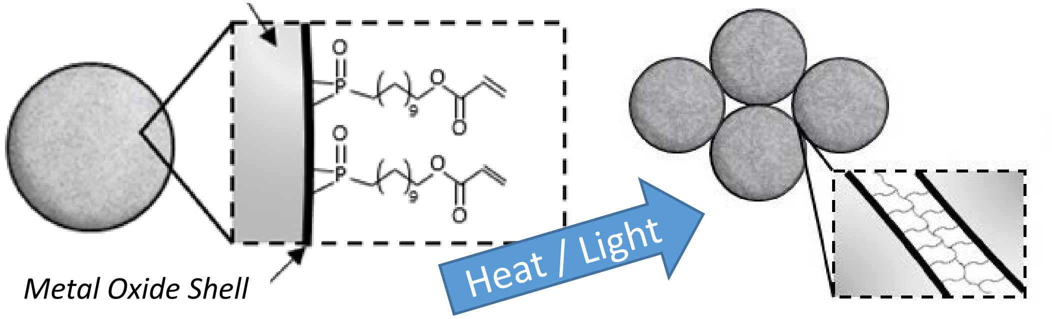
Stretchable Conductors

Patents Pending: 62754624; 62754635;
Thrasher et al, Adv. Mat, Vol 31 (40), 2019

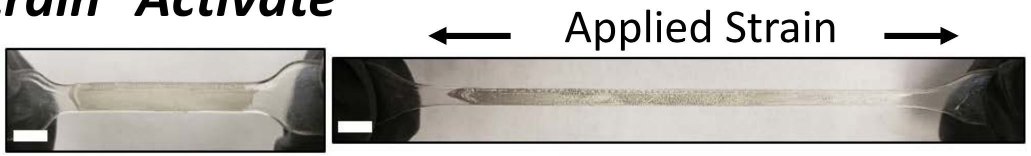
Step 1: Fabricate Ink

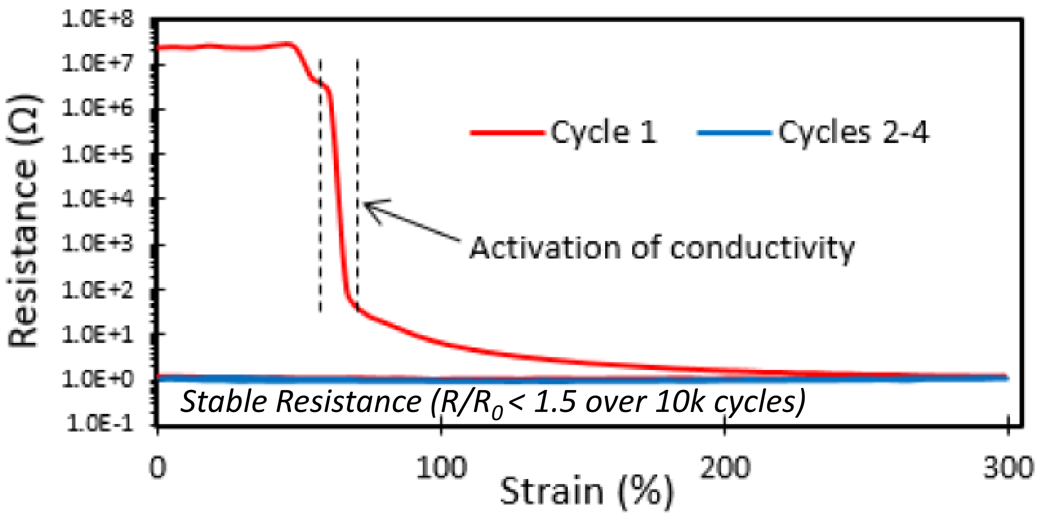
Step 2: Print Ink

Step 3: Cross-link Particles



Step 4: Strain "Activate"





Key Performance Parameters

- *Intrinsically high conductivity:* ***σ ~ 20,000 S/cm @ 700% strain***
- *Consistent resistance during strain:* ***R/R_0 < 1.8 @ 700% strain***
- *Facile processing:* ***photo-patterning, thermal curing, 3-D printing***
- *Stable performance:* ***10k cycles @ 300%***

Final Thoughts & Conclusion

Final Thoughts

Conclusion

- Defense applications are very demanding:
    - Complex systems
    - Extreme operating environments
    - Long operational lifetimes
- AFRL has many different research interests in elastomeric dynamics…
    - Energetic materials
    - Shock isolation systems
    - Architected materials
- Much work remains in all of these areas and more…

Future Research Trends

- Emphasis on adaptive, reconfigurable systems
- Also trend towards expendable/attritable "good enough" systems
    - Move away from "exquisite" solutions
- Flexible electronic materials, biomaterials
- 3D/4D-printed functional materials
- Tightly integrated lifecycle:
    - Co-design of materials & systems
    - Digital manufacturing (thread, tapestry)

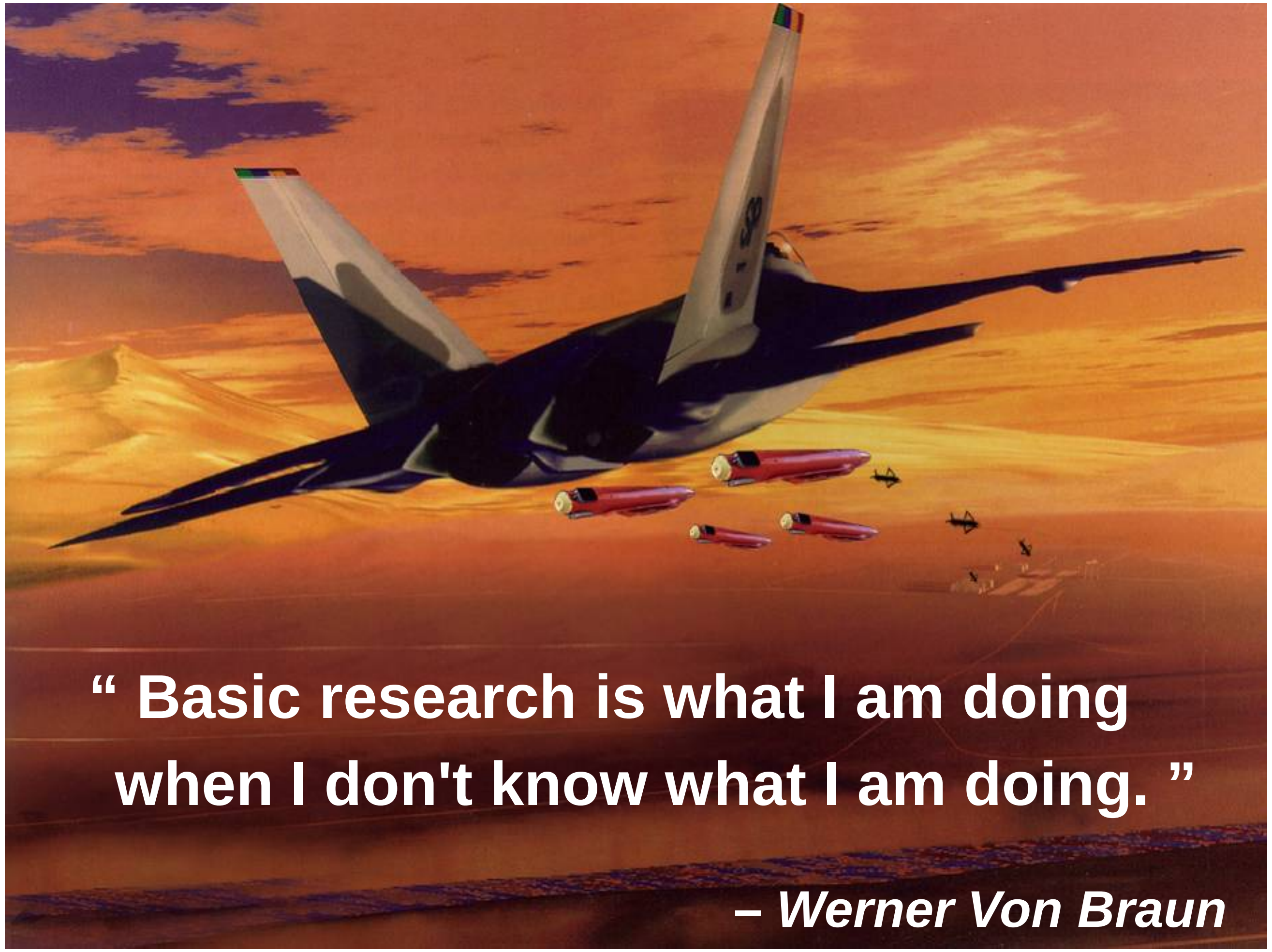
vs.

Acknowledgments

- RIEG
- Oxford/Pembroke/Clive Siviour
- AFRL & AFOSR
  - Teammates
  - Collaborations & funding
  - SFFP & NRC programs
- University partners (domestic & international)

- AFIT	- Auburn
- MTU	- UML
- Rice	- UWM
- VT	- Michigan
- Oxford	- Cambridge
- Southampton	

And many, many more!



“ Opinions, interpretations, conclusions, equipment selection, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force. ”

Questions?

Contact Information:

- **Jason R. Foley, Ph.D.**
  International Project Officer, Materials & Physics
  European Office of Aerospace Research & Development (EOARD)
  Air Force Office of Scientific Research
  U.S. Air Force Research Laboratory

- Phone: +44 (0)1895-616010 (DSN: 314-235-6010)
- Email: **jason.foley.1@us.af.mil**