



Integrity ★ Service ★ Excellence

Proposed FY13 LRIR:
**Shock-Mitigating
Multilayered Mechanical
Metamaterials
(SM⁵)**

**2012 Annual Grantees' Meeting
for AFOSR M⁴ Program**

Arlington, VA

2 August 2012

Jason R. Foley, Ph.D.

Fuzes Branch

Munitions Directorate

Air Force Research Laboratory

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 02 AUG 2012		2. REPORT TYPE		3. DATES COVERED 00-00-2012 to 00-00-2012	
4. TITLE AND SUBTITLE Proposed FY13 LRIR: Shock-Mitigating Multilayered Mechanical Metamaterials (SM5)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory,Munitions Directorate AFRL/RWME,306 W. Eglin Blvd., Bldg. 432,Eglin AFB,FL,32542-5430				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees'/Contractors' Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 29	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			



Outline



- **Research Team & Acknowledgements**
- **Introduction**
 - Harsh Mechanical Environments: Penetration & Impact
 - State of the Art in Shock Mitigation Schemes
 - Definitions: Metamaterials, band gap materials, etc.
- **Proposed Approach**
 - Overview
 - Analytic framework
 - Optimization
- **Future Work**
- **Summary**
- **Questions**



Research Team, Collaborators, & Up-Front Acknowledgements



Research Team

- **AFRL:** Dr. Jason Foley (PI), Dr. Brad Martin (co-PI), Dr. Amanda Schrand, Dr. Jacob Dodson, *et al.*
- **ARA:** Dr. Alain Beliveau, Dr. Vincent Luk

Collaborators

- **ARDEC:** Chris Mougeotte, Dr. Jennifer Cordes, Dave Geissler, *et al.*
 - **Sandia National Labs:** Dr. Scott McEntire *et al.*
 - **Univ. of Texas-San Antonio:** Prof. John Foster
 - **Univ. of South Carolina:** Prof. Jinkyu “JK” Yang
 - **CalTech:** Prof. Chiara Daraio
- and many others...

Support

- **Air Force Office of Scientific Research**
 - Dr. Byung-Lip “Les” Lee and Dr. David Stargel
- **DoD SMART Scholarship for Service Program**





DoD Harsh Environments



Stress/Pressure



Shock/Vibration

Weapon Thermomechanical Environment



Temperature



Erosion/Corrosion/Wear



Power and Fields

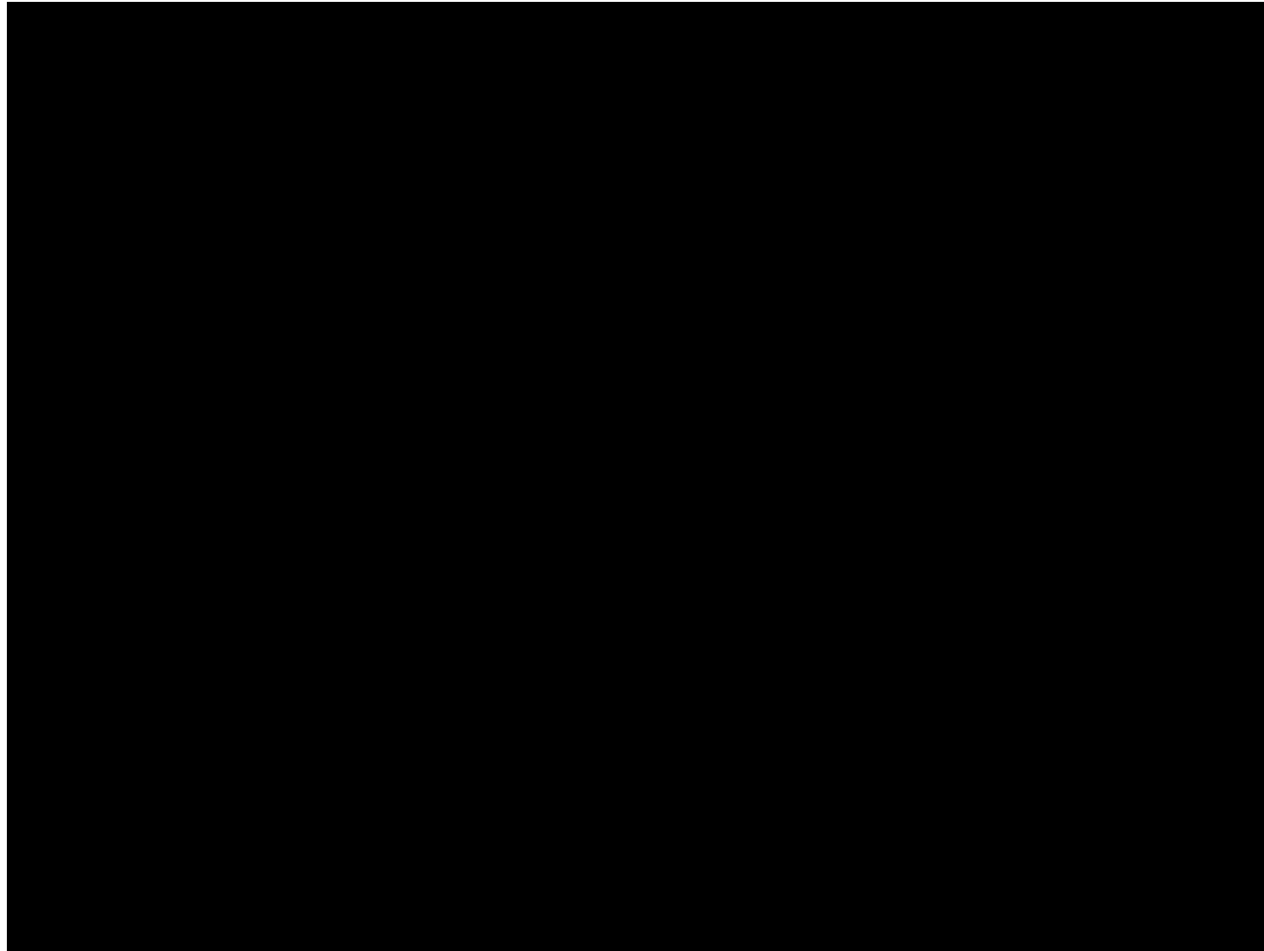


Radiation





Weapon Dynamic Environment



Sled Test Video (Dist A, 96ABW-2010-0139).wmv

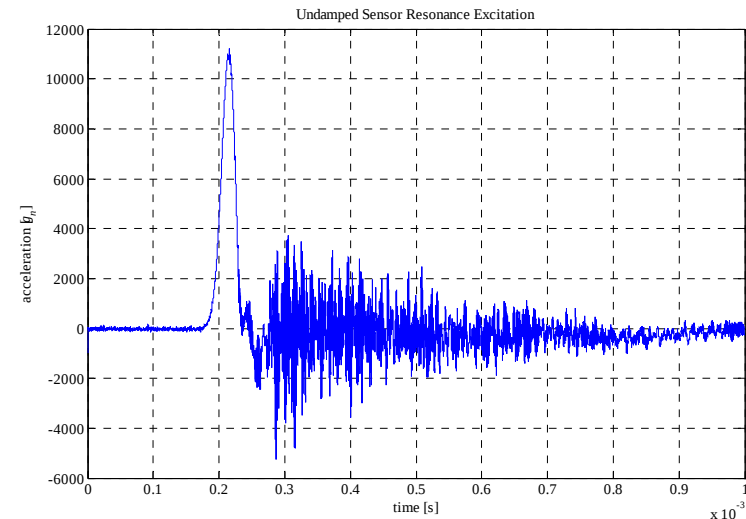




Weapon Dynamic Environment



- **Impact and shock is relevant to many fields**
 - Crash testing
 - Blast protection
 - Defense
 - Oil & Mining
- **Common features**
 - **Impulse stress waves**
 - Short rise time
 - High frequency waveforms
 - High amplitude
 - Multiaxial
 - **Wide range of damage**
 - Sensor resonance
 - Material failure
 - Fatigue, etc.



Sensor resonance from impact loads



Fractures Group, Cavendish Laboratory, Cambridge

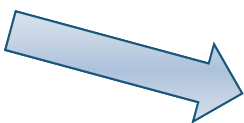
Blast-Induced High-Rate Material Fracture

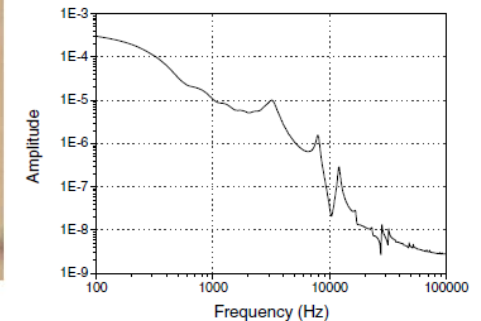
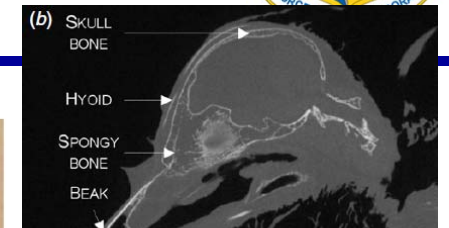


State of the Art in Shock Mitigation

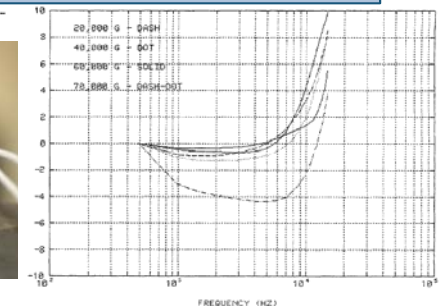


Classes (by dissipation mechanism)

- **Mechanical deformation**
 - Automotive “crumple zones”
- **Constrained layer damping** 
 - Woodpecker skull (biomimetic) [11]
- **Energy localization**
 - Functional polyurea nanoparticles [12]
- **Viscoelastic/viscoplastic** 
 - Polysulfide-isolated mount [13]
- **Superelastic**
 - NiTi shape memory alloy [14]
- **Multilayered mechanical filter**
 - Metal & polymer “bandstop” filter [15]



Woodpecker brain isolation [11]



Polysulfide filter [13]

- [11] 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.
- [12] 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.
- [13] 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
- [14] 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.
- [15] N.A. Winfree et al, 2010, "Mechanical filter for sensors", US Patent 7706213



Proposed Research Objectives



Technical Challenge

- **Improve survivability of complex systems in high shock environments (e.g., ballistic impact & explosive loading)**

Technical Objective

- **Identify and demonstrate concepts for broadband shock mitigation**
 - Attenuate impulsive uniaxial and multiaxial stress waves with simultaneous high amplitude stress and high frequency content

Proposed Approach: Multilayered Mechanical Metamaterials

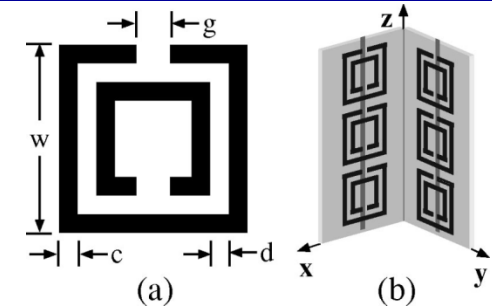
- **Develop theory/models in metamaterials framework**
 - “Bottom-up”, e.g., uniaxial elastic is initial focus
 - End state: Broadband spectral framework with rate-/temp-dependent materials
- **Identify best candidates using optimization**
 - Multiobjective, constrained
 - Also includes consideration of uncertainty
- **Demonstrate using state-of-the-art experiments**
 - Validate models and performance in shock-like loading regimes



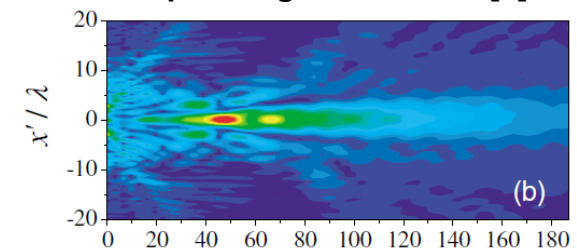
Metamaterials & Other Buzzwords



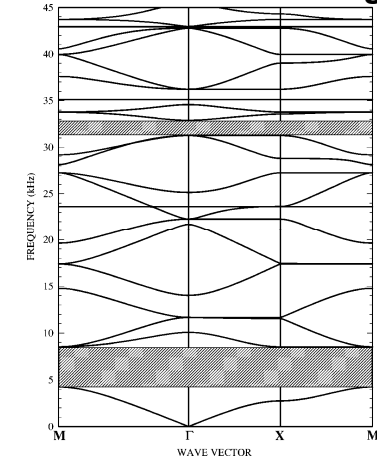
- **Metamaterials** [1]
 - Definition: Engineered materials designed w/properties not occurring naturally
 - “Effective” macroscopic properties strongly dependent on (nano-/micro-) structure & material (“unobtainium”)
- **Phononic Crystals (PC)/Band Gap (PBG) Materials**
 - Definition: Artificial periodic (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 gaps 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)	$\sim a/v$ (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.



Our Approach

- **Simultaneously consider the depth and breadth of the shock mitigation problem...**

Theoretical Mechanics

- Dispersion
- Wave modes/polarization
- Metamaterials

Materials Modeling

- Rate-dependent
- Temperature-dependent
- Complex properties

Optimization

- Topological Optimization
- Multi-objective

Experimental Mechanics

- Shock/vibration analysis: transmissibility, damping
- High rate test methods

Fabrication

- Reproducibility
- Characterization
- Distribution of properties

Analysis

- Uncertainty quantification
- Stochastic analysis
- Spectral element models

...beginning with simple 1-D geometries (multilayered films) and well-known materials (metals, polymers) in a metamaterials framework



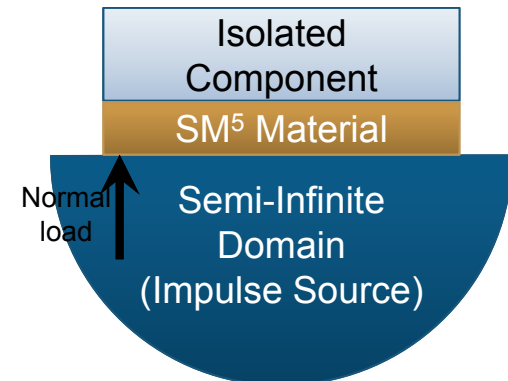
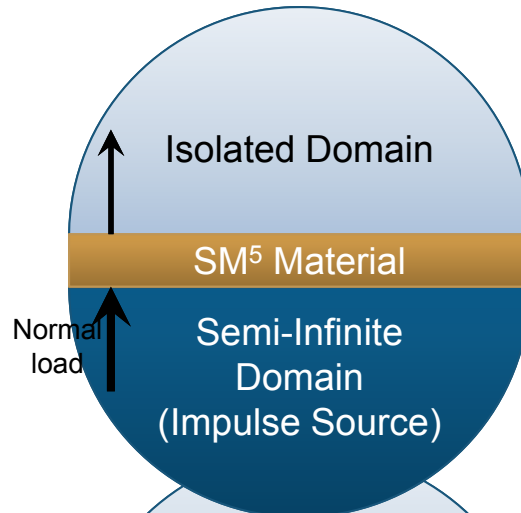
Geometry

Driven by system/subsystem isolation goal

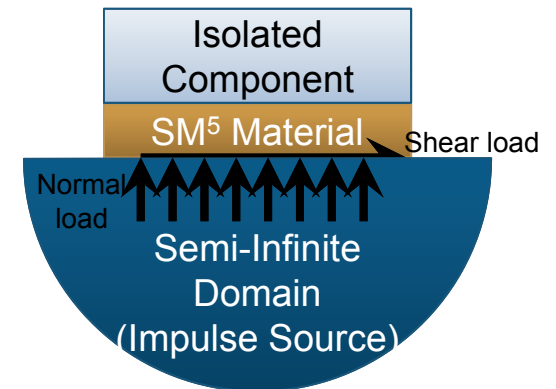
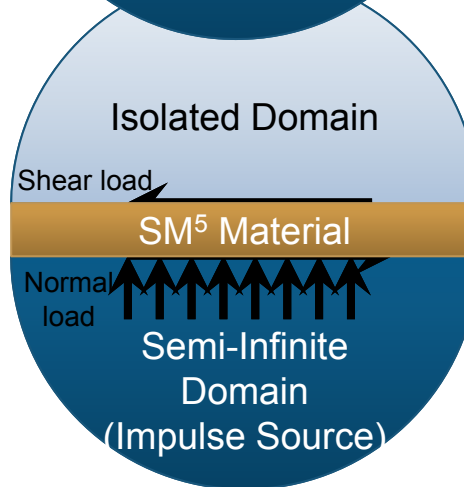
Planar Domain Isolation

Finite Component Isolation

Uniaxial wave propagation



Biaxial wave propagation





Materials



Material classes

- **Metals**
 - W, Ti, steel, Cu
- **Polymers**
 - Epoxy, polysulfide, PMMA, PTFE
- **Composites**
 - G10, syntactic foam, Ultem

Constitutive behavior

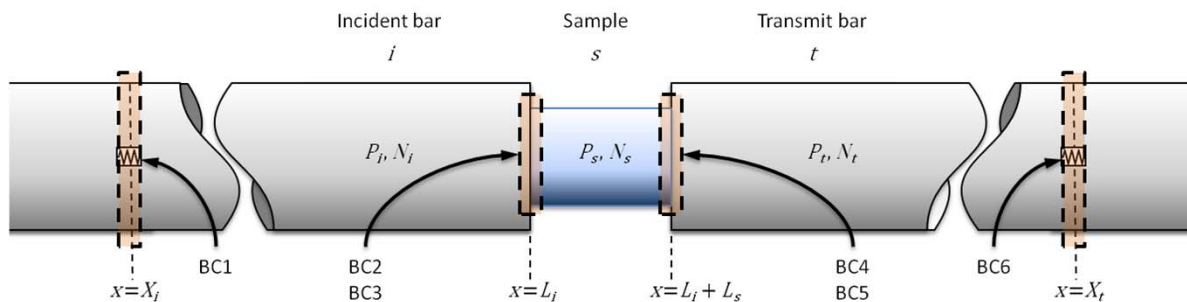
- **“Effective” properties**
 - Anisotropic response from isotropic films
 - Strongly dependent on interfaces and spacing
- **Time-Temperature Equivalency**
 - Applicable to polymers
- **Spectral properties**
 - Complex moduli as a function of frequency...



Material Spectral Constitutive Response (Frequency Domain)

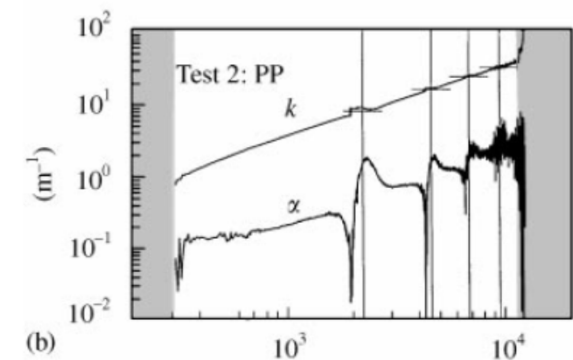
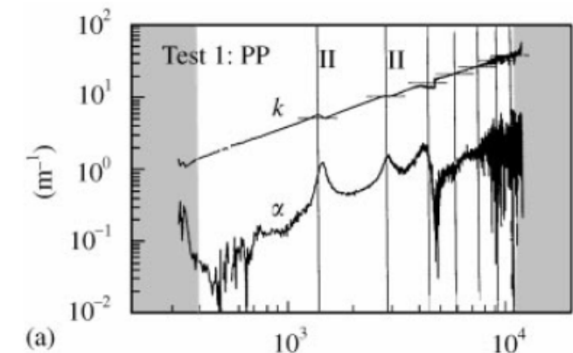


- **Materials can be modeled with frequency dependent (complex) properties**
 - Complex modulus $\tilde{E}(\omega) = E'(\omega) + iE''(\omega)$
 - γ : Re $\rightarrow$ attenuation (α), Im $\rightarrow$ propagation (κ)
- **Developed solution for 1-D and 2.5-D wave transport with complex media**
 - Working on application to SHPB data sets



$$\tilde{\epsilon}_j(x, \omega) = \tilde{P}_j(\omega)e^{-\gamma_j x} + \tilde{N}_j(\omega)e^{\gamma_j x}$$

$$\gamma = i\omega \sqrt{\frac{\rho}{\tilde{E}}}$$



Hillström, L., Mossberg, M., and Lundberg, B., 2000, "IDENTIFICATION OF COMPLEX MODULUS FROM MEASURED STRAINS ON AN AXIALLY IMPACTED BAR USING LEAST SQUARES," Journal of Sound and Vibration, 230(3), pp. 689-707.





Wave Properties in Various Media



		$Z = F/v = \rho A c$		$c = \sqrt{E/\rho} = f\lambda$	
	Material	Elastic Modulus E [GPa]	Density ρ [kg/m ³]	1-D Impedance $Z'' = Z/A$ [x 10 ⁶ kg/m ² s]	1-D Wave Speed c [m/s]
Metals	6/4 Titanium	104	4420	21.4	4840
	Maraging Steel	188	8080	39.1	4835
	Tungsten	329	16920	75.3	4406
	Copper	115	8960	32.1	3583
Polymers	Polycarbonate	2.3	1200	1.86	1550
	Epoxy	2.3	1140	1.62	1420
	PVC	1.6	1380	1.48	1077
Composites	PBX ⁽¹⁾	~0.5 (0.1-2.9+)	~1800	1.89	527
	G10 ⁽²⁾	~18.8 (x) ~7.8 (z)	~1700	5.64 (x) 3.64 (z)	3320 (x) 2140 (z)
	CFRP	~1.5	~1500	1.50	1000

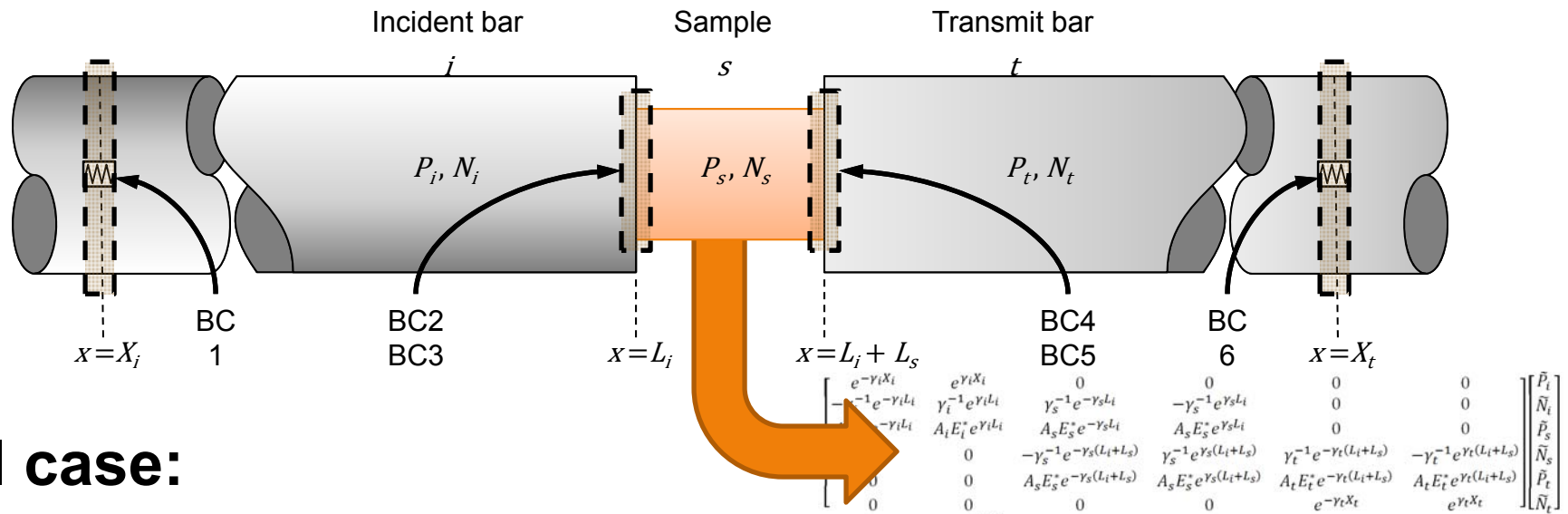
Frequency f [Hz]	Wavelength λ [m]
1	4800
100	48
10k	0.48
1M	4.8m
100M	48μ

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

(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

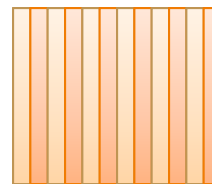


Analysis Solution

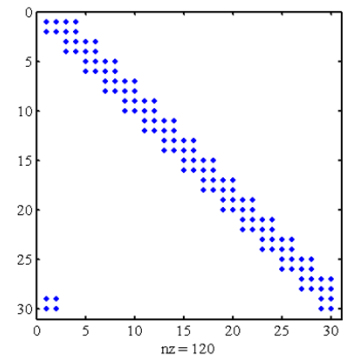


Initial case:

- **Simple 1-D geometry**
 - Limit: Kolsky bar behavior
- **Simultaneous coupled problem for wave terms**
 - Arbitrary N -layer solution
 - Banded coupling equation



$$\begin{bmatrix}
 a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} & & \\
 a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} & & \\
 & a_{3,3} & a_{3,4} & & & \\
 & a_{4,3} & a_{4,4} & & & \\
 & & & & a_{N-3,N-3} & a_{N-3,N-2} & a_{N-3,N-1} & a_{N-3,N} \\
 & & & & a_{N-2,N-3} & a_{N-2,N-2} & a_{N-2,N-1} & a_{N-2,N} \\
 & & & & & & a_{N-1,N-1} & a_{N-1,N} \\
 a_{N-1,1} & a_{N-1,2} & & & & & & \\
 a_{N,1} & a_{N,2} & & & & & &
 \end{bmatrix}$$



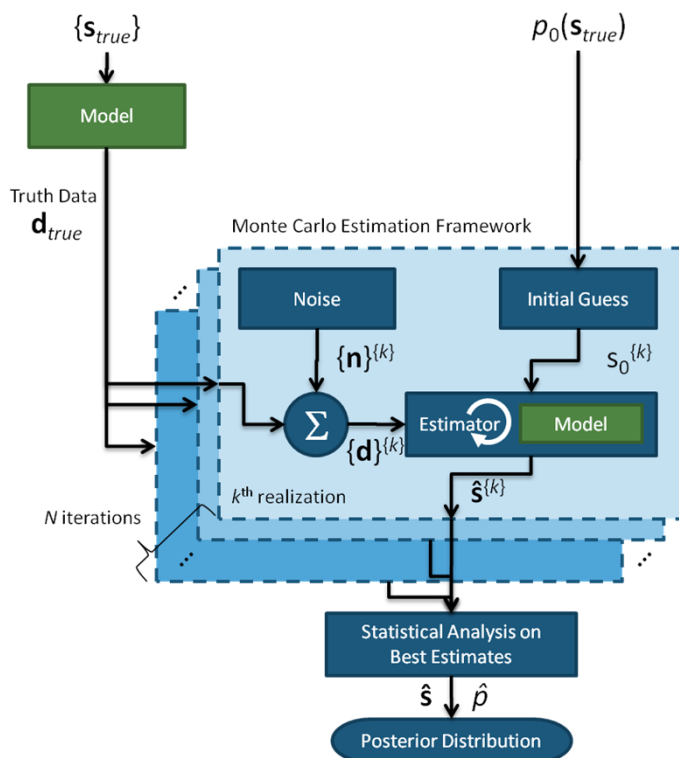


Optimization



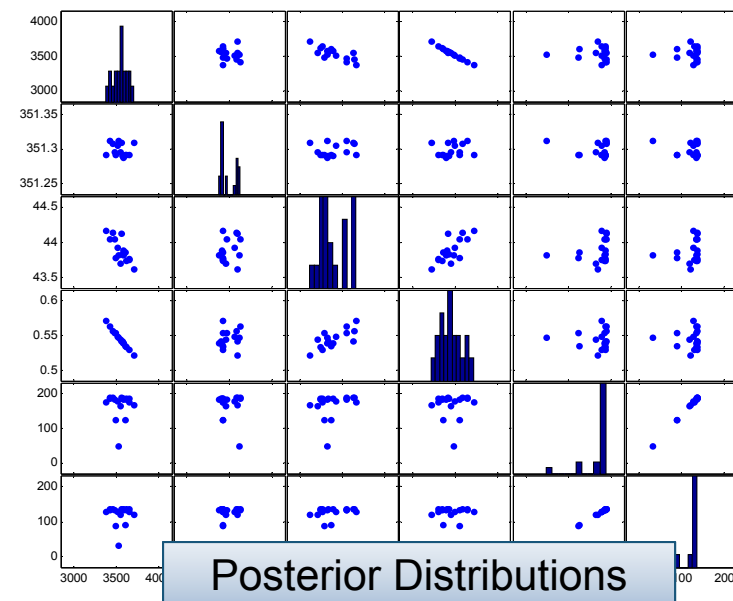
- **Topological Optimization**

- Initial optimization criteria:
Spectral transmissibility



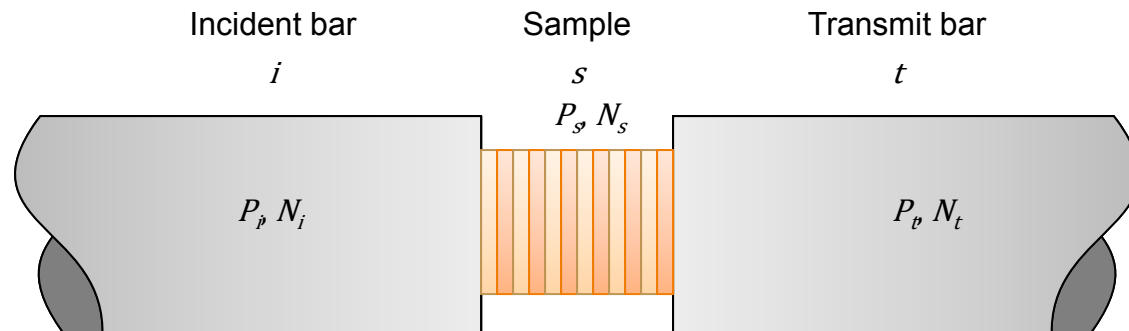
- **Uncertainty Quantification**

- Bayesian framework for estimating parameters
- Prior information, observation and process uncertainty
- Monte Carlo truth modeling





Initial Shock Filter Design Optimization Problem



- **Design goals/objectives:**

- Spectral energy isolation (transmission rejection ratio)
- Minimum complexity (N_{layers} , L_{system})

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

- **Constraints:**

- Discrete material set (non-continuous property variables)
- Defined layer pattern
- Constant layer sizing (L_A , L_B)

- **Initial guess:**

- Polysulfide/steel stack

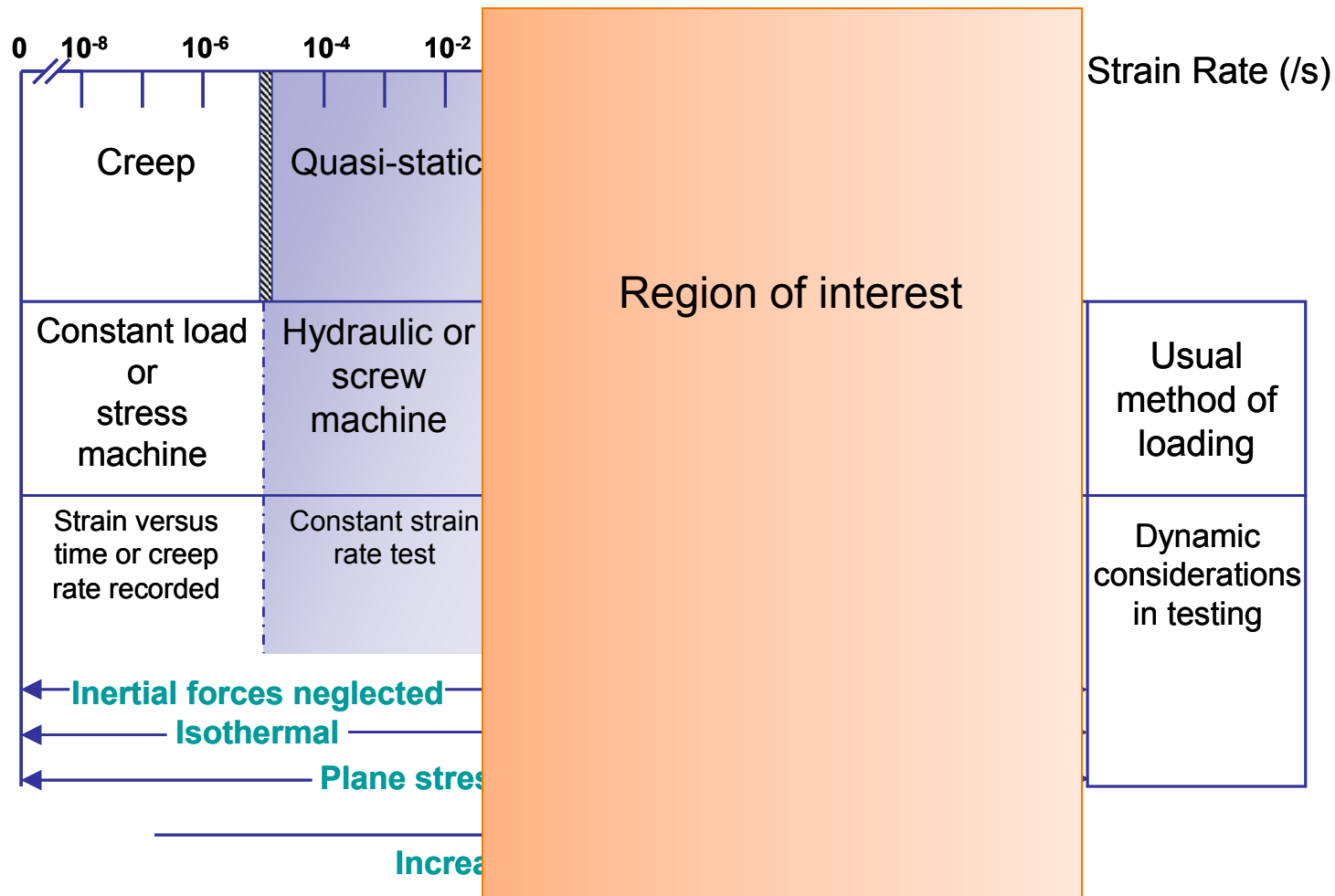
- **Method:**

- Discrete genetic algorithm w/local gradient-based improvement

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



Experimentation



Nemat-Nasser, S. "High Strain Rate Tension and Compression Tests," *ASM Handbook Vol 8: Mechanical Testing and Evaluation*, Materials Park: ASM International, p. 429 (2000).

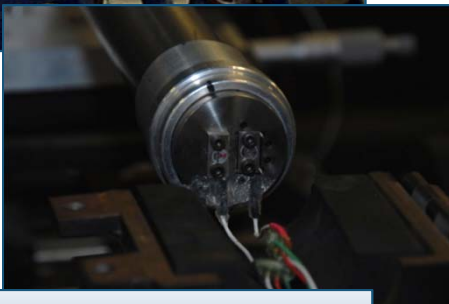
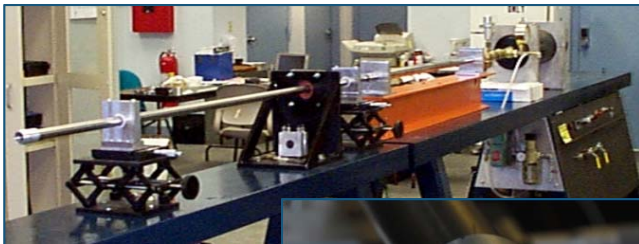




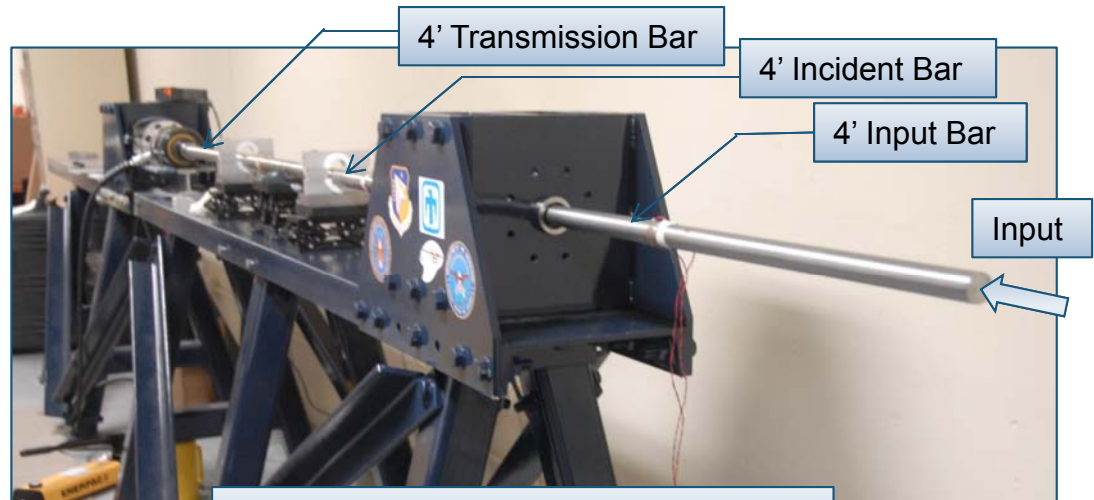
Experimentation



- **Hopkinson/Kolsky Bar**
 - Approximate uniaxial behavior
 - **Ideal SHPB-like case**
 - Simple Analysis
 - SOTA instrumentation
- **Preload Interface Bar**
 - Unique capability
 - Dynamic impulse with static quasi-uniaxial confinement
 - **Design to 50,000 lbf**



Hopkinson Bar @ AFRL



Preload Interface Bar @ AFRL



Way Ahead



- **Get started!**
 - Initial focus on optimization problem definition and figures of merit, theoretical framework, and “art of the possible”
- **Coordinate w/relevant efforts AFOSR tasks...**

- Interested? Let's chat!

Examples:

- Spectral Element Modeling (SEM)
 - **Nonlinear SEM, PI: Andrew Dick (Rice)**
 - **Wavelet SEM in Plates, PI: Ratan Jha (Clarkson)**
 - Soliton-Based Artificial Nervous System
 - **PI's: “JK” Yang (USC), Amanda Schrand (AFRL)...**



Bio-inspired Artificial Nervous System Using Soliton-supporting Granular Phononic Crystals

Jinkyu “JK” Yang, Ph.D., Assistant Professor in Mechanical Engineering, University of South Carolina

Amanda Schrand, Ph.D., Materials Research Engineer, Air Force Research Laboratory, Munitions Directorate (AFRL/RWME)

DESCRIPTION & IMPACT

Solitons, self-reinforcing nonlinear wave pulses, are integral parts of biomembranes and nerves for the efficient transmission of electrochemical signals. Inspired by complex organ systems such as skin [Fig1A], we propose a novel artificial nervous system (ANS) composed of granular phononic crystals (GPCs) [Fig1B], which support highly nonlinear solitons. Analogous to the mechanism of neurons embedded within skin, the ANS will be designed to discern vibrations, temperature, impacts and other aspects of the environment. The anticipated impact: **Micro-scale** touch-sensitive transduction components (e.g., *tactile sensors*) and **Macro-scale** self-sensing mechanoreceptive structures that monitor and mitigate impact to the host structure in real time.

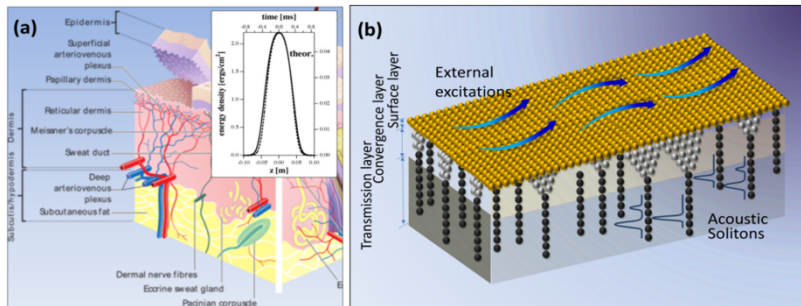


Fig. 1. Schematic depictions of (a) Mammalian skin displaying dermal nerve fibers and associated sensory mechanoreceptors such as Pacinian corpuscles (Inset: soliton packet). (b) Soliton-supporting ANS based on bio-inspired layering of granular phononic crystals.

APPROACH & OBJECTIVES

The ANS will be composed of multi-layered composite granular networks that convert surface stimuli into groups of compact-supported solitons in the underlying layer [Fig2A]. By analyzing the solitons transmitted by the granular chain networks, magnitudes and locations of external excitations will be identified. The main objectives are to: 1) Examine the *fundamental nonlinear wave dynamics* of granular phononic crystals and 2) Construct *proof-of-concept prototypes* [Fig2B] and experimentally verify external conditions and material properties (e.g., impact location and amplitudes).

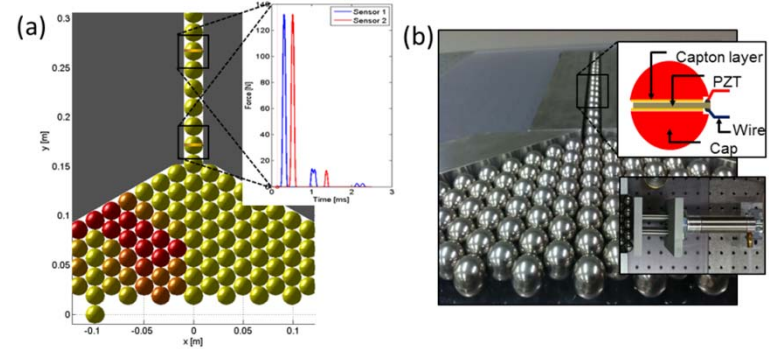


Fig. 2. 2D Granular phononic crystals configured in: (a) An elastic medium for detecting external impacts. (b) the experimental design and setup with a pneumatic actuator.

DELIVERABLES

Software: Discrete element model (DEM) for granular particle dynamics

Spectral element model (SEM) for interfacial wave propagation

Hardware: Soliton-supporting 2D/3D architecture of granular crystals

SCHEDULE

Tasks	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Analytical Study												
Soliton disintegration												
Soliton redirecting												
Soliton splitting												
Soliton superposing												
Numerical Study												
Discrete Particle Modeling												
Spectral Element Modeling												
Pattern Recognition												
Experimental Study												
Sensor Design/Fabrication												
2D Prototype Fabrication												
3D Prototype Fabrication												
Verification Tests												

References

- A. Schrand. Direct current regulates process formation in human dermal fibroblasts in a collagen matrix. *Masters Thesis*, Department of Biological Sciences, Wright State University, Dayton, OH, 2001.
- J. Yang, et al. Interaction of highly nonlinear solitary waves with elastic linear media, *Physical Review E*, 83: 046606, 2011.
- N. Boechler, J. Yang, et al., Tunable vibration band gaps in one-dimensional diatomic granular crystals with three-particle unit cells, *Journal of Applied Physics*, 109: 074906, 2011.
- J. Yang, et al., Amplitude-dependent attenuation of compressive waves in curved granular crystals constrained by elastic guides, *Acta Mechanica*, 223(3): 549–562, 2012.



Summary



- **Impact and penetration loads are extremely harsh thermomechanical environments**
 - Broadband & stochastic environment, nonlinear, etc.
- **Several methods have been proposed to mitigate this environment (i.e., shock isolation)**
 - TBD
- **Our research effort proposes harnessing metamaterials framework with extension...**
 - Extended multilayer spectral analytic method
 - Topological multiobjective optimization with uncertainty
 - Validation using high rate experiments
- **Open and willing to collaborate on research...**





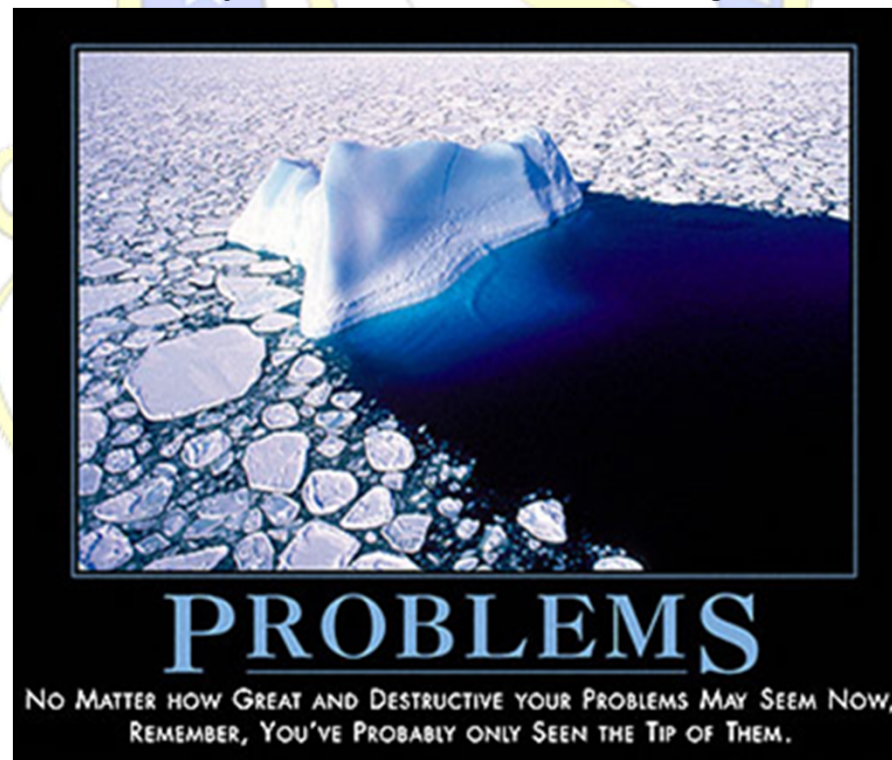
Questions?



Contact Information

Jason R. Foley, Ph.D.
Tech Area Lead, Hard Target Fuzing
Fuzes Branch
Munitions Directorate
Air Force Research Laboratory

Phone: 850-883-0573
Email: jason.foley@eglin.af.mil
Mail: AFRL/RWMF
306 W. Eglin Blvd., Bldg. 432
Eglin AFB, FL 32542-5430



www.despair.com







References

- [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.**



References

- [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.



Shock-Mitigating Multilayered Mechanical MetaMaterials (SM⁵)

LRIR Synopsis:

1. Fuzes CTC
2. Multifunc. Materials
3. PM: Dr. Les Lee
4. J. Foley/B. Martin

Technology Objective	Schedule/Cost (JON)				
- Discover/develop/demo methods for attenuating the severe mechanical environment in penetration: - High amplitude stresses/forces - High frequency content (broadband) waves - Multiaxial loading profiles - Stochastic environment - Proposed investigation uses mechanical metamaterials - Acoustic metamaterials have been demonstrated to have physically impossible transport properties: negative density, wave reversal/focusing, band mod - Conceptual foundations in superlattices, phononic crystals for wave interactions, effective properties	FY12	FY13	FY14	FY15	FY16
		▲			
	Program Initiation				
	1-D Mitigating MM				
	2-D/3-D Mitigating MM				
	Program completion				▲
	Civ. Salary (\$K)	0.0	125	100	100
	ARA (Onsite) Salary		75	80	90
	Travel		10	10	10
	Equipment, T&E		40	60	50
	Total (\$K)		250	250	250
Tech Challenges/Approach	Mission Alignment & Benefits; Partnerships				
- Challenge: Shock mitigation schemes are typically one-shot (i.e., use deformation); no description of dissipation - S&T Approach: "Bottom up": Develop 1-D analytic framework and solve wave eqns - Define, predict, & validate spectral coefficients, constitutive response, effective transport props - Define dissipation mechanisms and wave properties vs. structure, material, length scales - Challenge: Several candidate material classes - S&T Approach: Simulate mitigation; calculate effective properties; use topological optimization - Challenge: Real environments induce nonlinearities - S&T Approach: Add in frequency, structure nonlinear terms	RW Strategic Alignment: - Co-developed by hard target fuzing, warhead sub-CTC's - Supports S&T Vector 3, "Hold high value targets at risk" - Mitigation schemes are broadly applicable to penetrating warhead subsystems and critical fuze components: sensors, firesets, processors, batteries, etc. - Also enables directional inertial coupling for future "Brilliant Fuzing" concepts Industry/University/DoD Partners: - Leverage AFRL/RX, RY for fabrication - C.T. Sun (Purdue) and X. Zhang (Boston U.) via AFOSR O. Mondain-Monval, A. Aradian (CNRS, France) via EOARD				





Collaborations and Interactions

