



AFRL-RW-EG-TR-2015-091

A REVIEW OF SHOCK MITIGATION TECHNIQUES

Dr. Kyle K. G. Smith
Dr. Jason R. Foley

AFRL/RWMF
306 W. Eglin Blvd., Bldg. 432
Eglin AFB, FL 32542-5430

April 2015

INTERIM TECHNICAL REPORT

DISTRIBUTION A. Approved for public release; distribution unlimited. (PA# 96TW-2014-0154).

**AIR FORCE RESEARCH LABORATORY
MUNITIONS DIRECTORATE**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this 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 this 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 Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 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 any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE 04-06-2015		2. REPORT TYPE INTERIM		3. DATES COVERED (From - To) 1 Oct 2012 – 1 Oct 2014	
4. TITLE AND SUBTITLE A REVIEW OF SHOCK MITIGATION TECHNIQUES				5a. CONTRACT NUMBER In-House	
				5b. GRANT NUMBER N/A	
				5c. PROGRAM ELEMENT NUMBER 62602F	
6. AUTHOR(S) Kyle K.G. Smith Jason R. Foley				5d. PROJECT NUMBER 2502	
				5e. TASK NUMBER 0900	
				5f. WORK UNIT NUMBER W0JU	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Munitions Directorate AFRL/RWMF; 306 W. Eglin Blvd.; Bldg 432 Eglin AFB, FL 32542-5430				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RW-EG-TR-2015-091	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory, Munitions Directorate AFRL/RW 101 W. Eglin Blvd. Eglin AFB, FL 32542				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL-RW-EG	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RW-EG-TR-2015-091	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION A. Approved for public release; distribution unlimited. (PA# 96TW-2014-0154).					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Shock mitigation methods (i.e., techniques for attenuating high amplitude stresses with high frequency content) are of great importance in defense applications. This presentation focuses on classifying and critically evaluating these techniques using categories based on the physical mechanism responsible for the mitigation. For example, crushable structures such as automotive "crumple zones" effectively attenuate single shock loads via irreversible deformation (plasticity), but they can also amplify subsequent shock loads. Other mitigation mechanisms include phase transformations, viscous dissipation, wave mode conversion, and stress wave redirection. A "bottom-up" approach is used to define shock mitigation performance, beginning with simple 1-D models of stress wave transport through a multiple component system. Transmission and reflection performance of the mitigating material(s) are defined, calculated, and verified using simple experiments. Finally, approaches for improving the overall mitigation performance using topological optimization will be discussed.					
15. SUBJECT TERMS Hard target fuzes, intelligent fuzes, hard target penetration, shock, instrumentation, shock sensors, recorders, accelerometers, pressure sensors, strain gages					
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 17
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	19a. NAME OF RESPONSIBLE PERSON Dr. Jason Foley		
				19b. TELEPHONE NUMBER (include area code) (850) 883-0584	

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

Qualified requestors may obtain copies of this report from the Defense Technical Information Center (DTIC) <<http://www.dtic.mil/dtic/index.html>>.

AFRL-RW-EG-TR-2015-091 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

FOR THE DIRECTOR:

//SIGNED//

GEORGE S. JOLLY
Fuze Technology CTC Lead

//SIGNED//

JASON R. FOLEY, Ph.D.
Program Manager

//SIGNED//

HOWARD G. WHITE, Ph.D.
Chief Engineer, Ordnance Division

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.



Integrity • Service • Excellence

A Review of Shock Mitigation Techniques

85th Shock & Vibration Symposium

Reston, VA

27 October 2014

Kyle K. G. Smith, Ph.D.

Jason R. Foley, Ph.D.

Fuzes Branch

Munitions Directorate

Air Force Research Laboratory

DISTRIBUTION A; Approved for Public Release; Distribution Unlimited (PA# 96TW- 2014-0154).



Outline

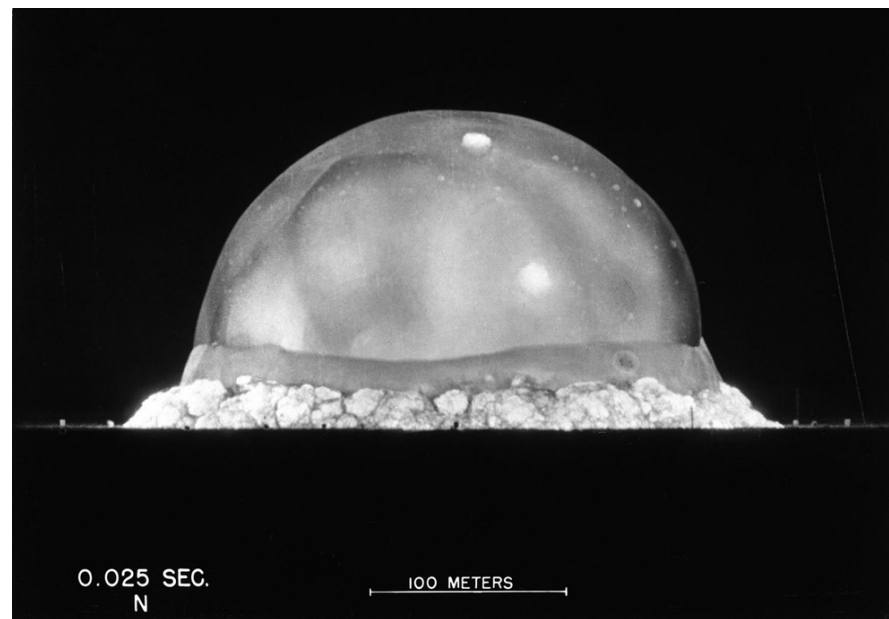


- **Introduction**
 - Motivation of Shock Mitigation Technology
- **Review of Shock Mitigation Techniques**
 - Current approaches
- **Shock Mitigating Metamaterials**
 - Characteristics of Mechanical Metamaterials
 - Computational framework
 - Optimization
- **Summary**



Introduction

- *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
 - High amplitude
 - Wide range of damage
 - Sensor resonance
 - Material failure
 - Fatigue, etc.





Motivation and Approach



Motivation:

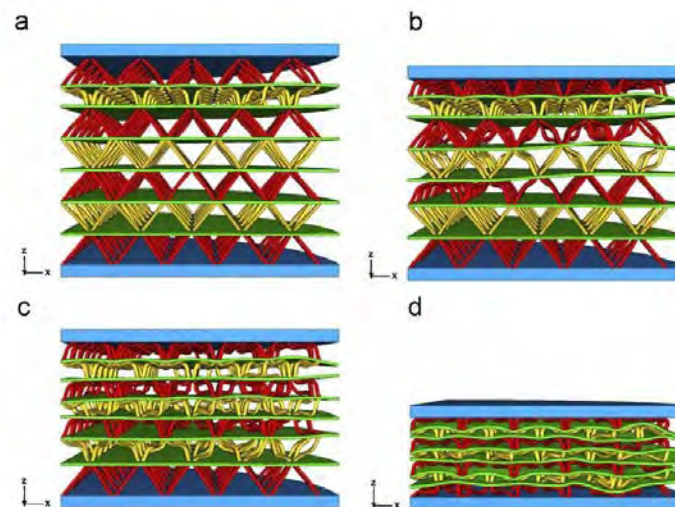
- Improve the survivability of fuzes and electronic subsystems in high shock environments

Approach:

- Design, Develop, and Demonstrate shock mitigation technology



Mechanical Deformation

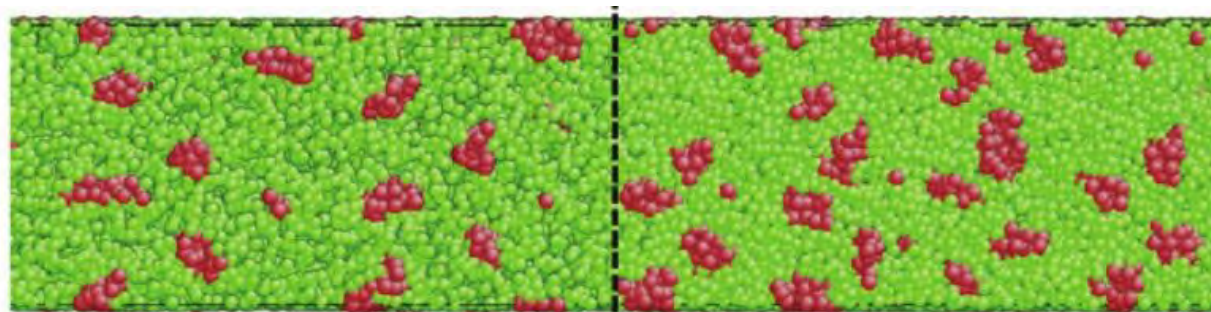




- Crumple Zones
 - e.g., Crushable Cellular Material [1]
 - Low and Intermediate Velocity Impact
 - Mainly Inelastic → One Shot

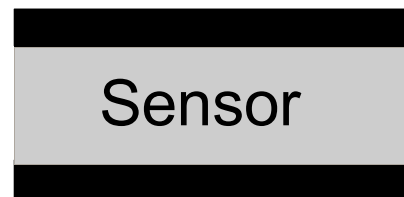
[1] H. Wadley, K. Dharmasena, Y. Chen, P. Dudt, D. Knight, R. Charette, and K. Kiddy, "Compressive response of multilayered pyramidal lattices during underwater shock loading", International Journal of Impact Engineering 35 (2008) 1102–1114



Viscoelastic



- Polyurea 
 - energy dissipation from hard and soft domains [2]
- Polysulfide 
 - mechanical isolator [3]

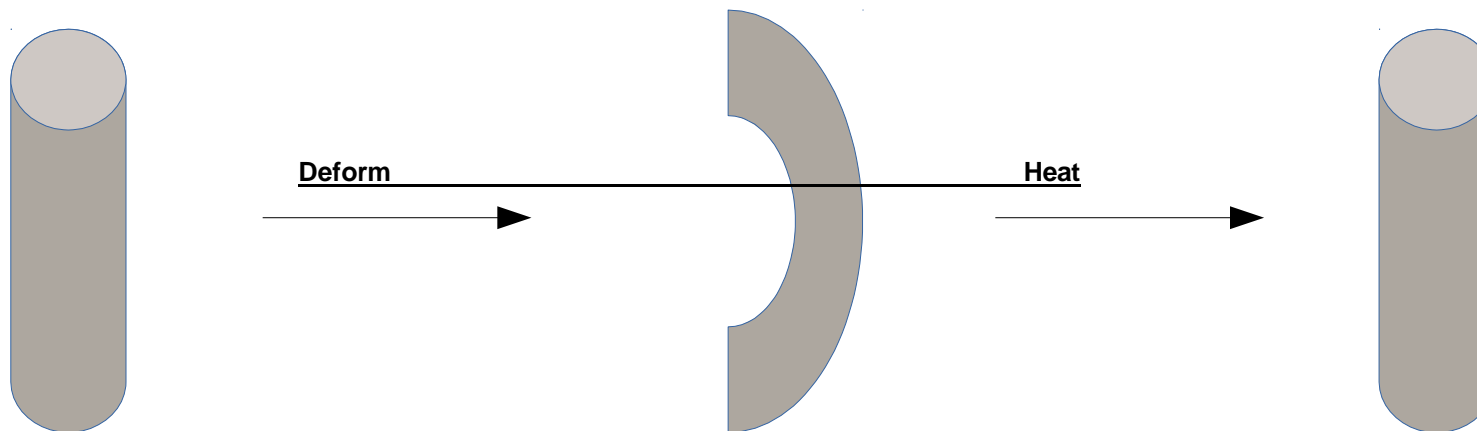


[2] Bedri Arman, A. Srinivas Reddy, and Gaurav Arya, "Viscoelastic Properties and Shock Response of Coarse-Grained Models of Multiblock versus Diblock Copolymers: Insights into Dissipative Properties of Polyurea", *Macromolecules*, 2012, 45 (7), pp 3247–3255

[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



Superelastic

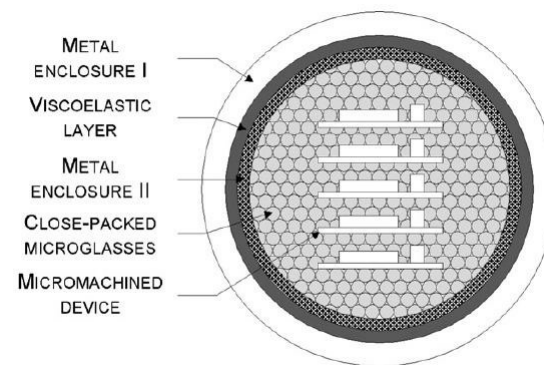
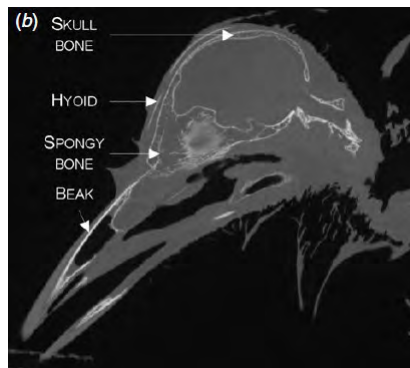
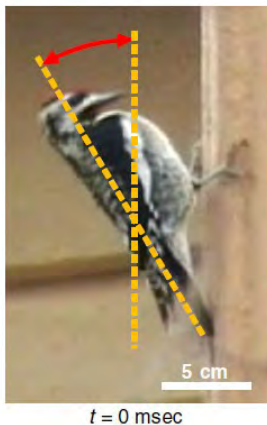


- NiTi → Shape Memory Alloy (SMA)
- Strength of metal and flexibility of plastic
- Dissipated energy from phase transformations
- Kink and crush Resistant
- Large amount of recoverable deformation

[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.



Constrained Layer Damping

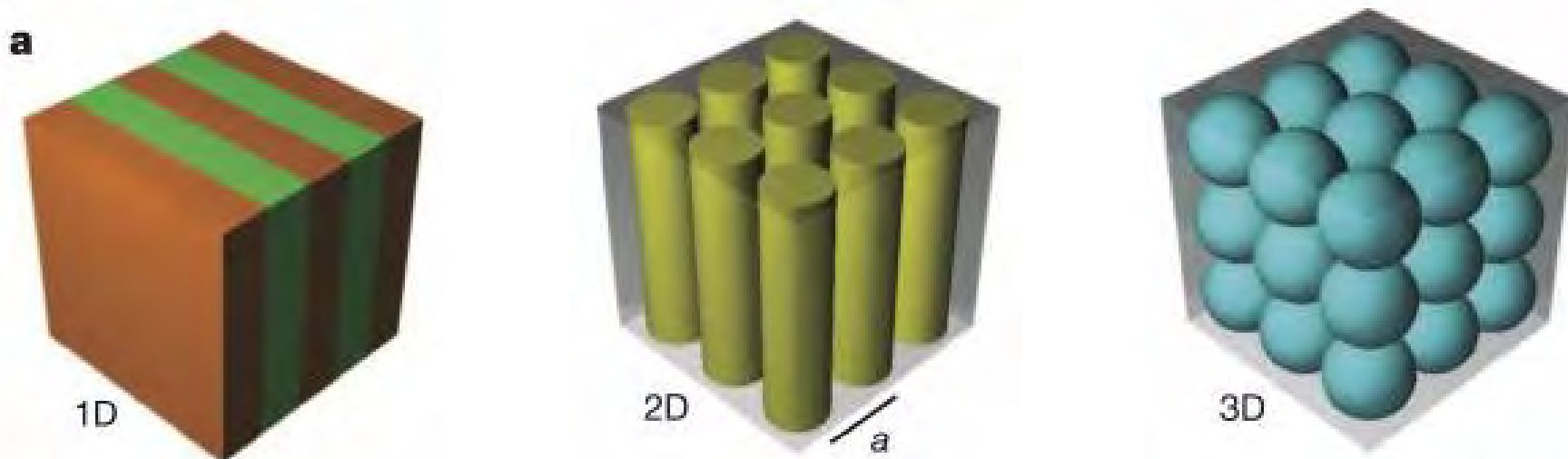


- Biomimetic – Biologically inspired
- Mimics constrained layer damping mechanism found in the woodpecker skull

[6] 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.



Mechanical Metamaterials

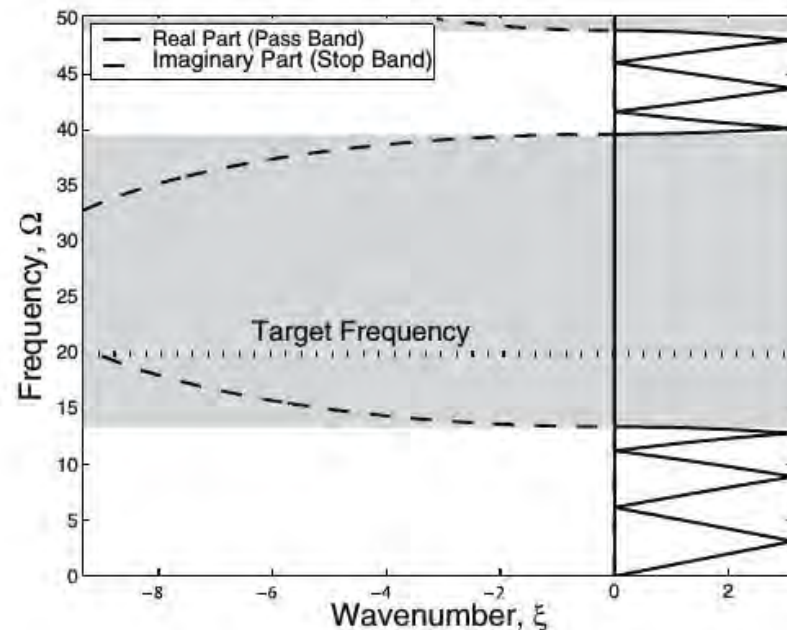
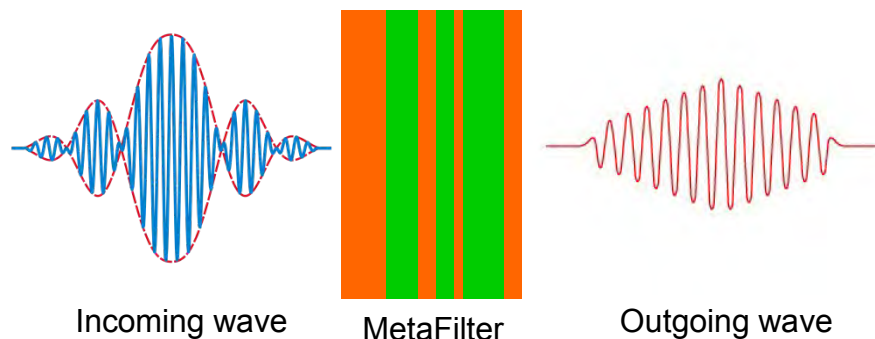


- Allows one to tailor the physical properties of composite systems at the continuum scale, even to the point in which unphysical properties emerge
- Mechanical properties are determined by the shape, interfaces, and sizes of the composing materials

[6] M. Maldovan, "Sound and Heat Revolutions in Phononics," *Nature*, 503, p. 209-217 (2013).



1-D Mechanical MetaFilter



- Given a material, determine layer size which filters mechanical waves in a desired frequency range

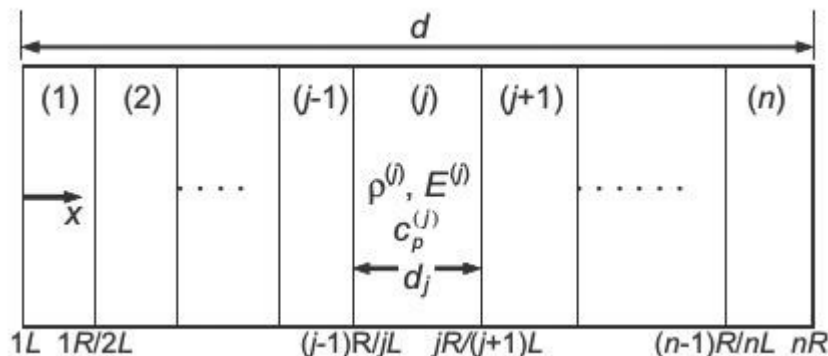
[7] N.A. Winfree et al, 2010, "Mechanical filter for sensors", US Patent 7706213

[8] 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

Unit Cell



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

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

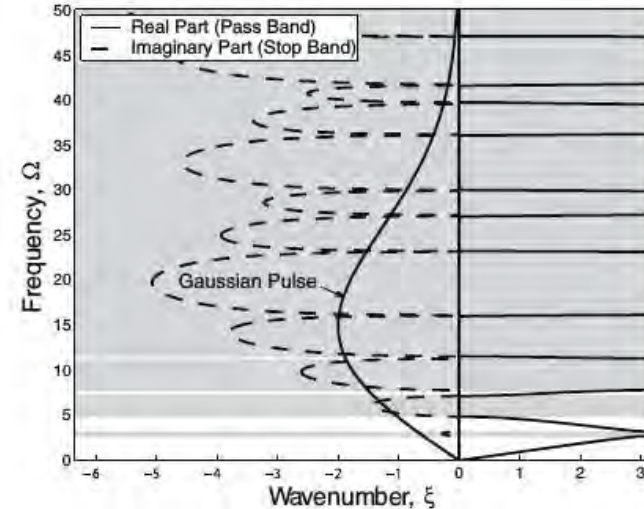
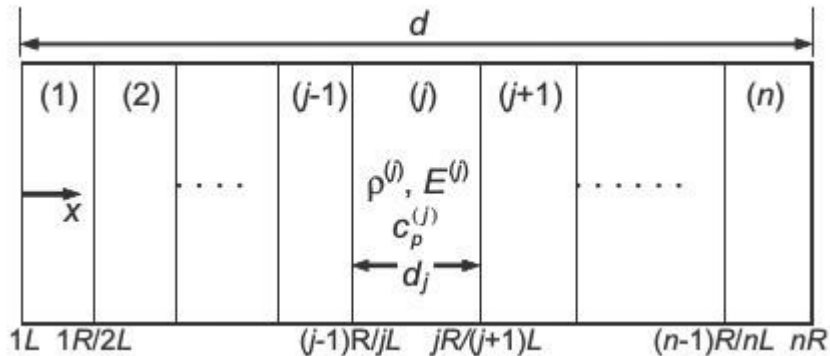
• Transfer matrix method

- 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

[9] 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



Computational Design

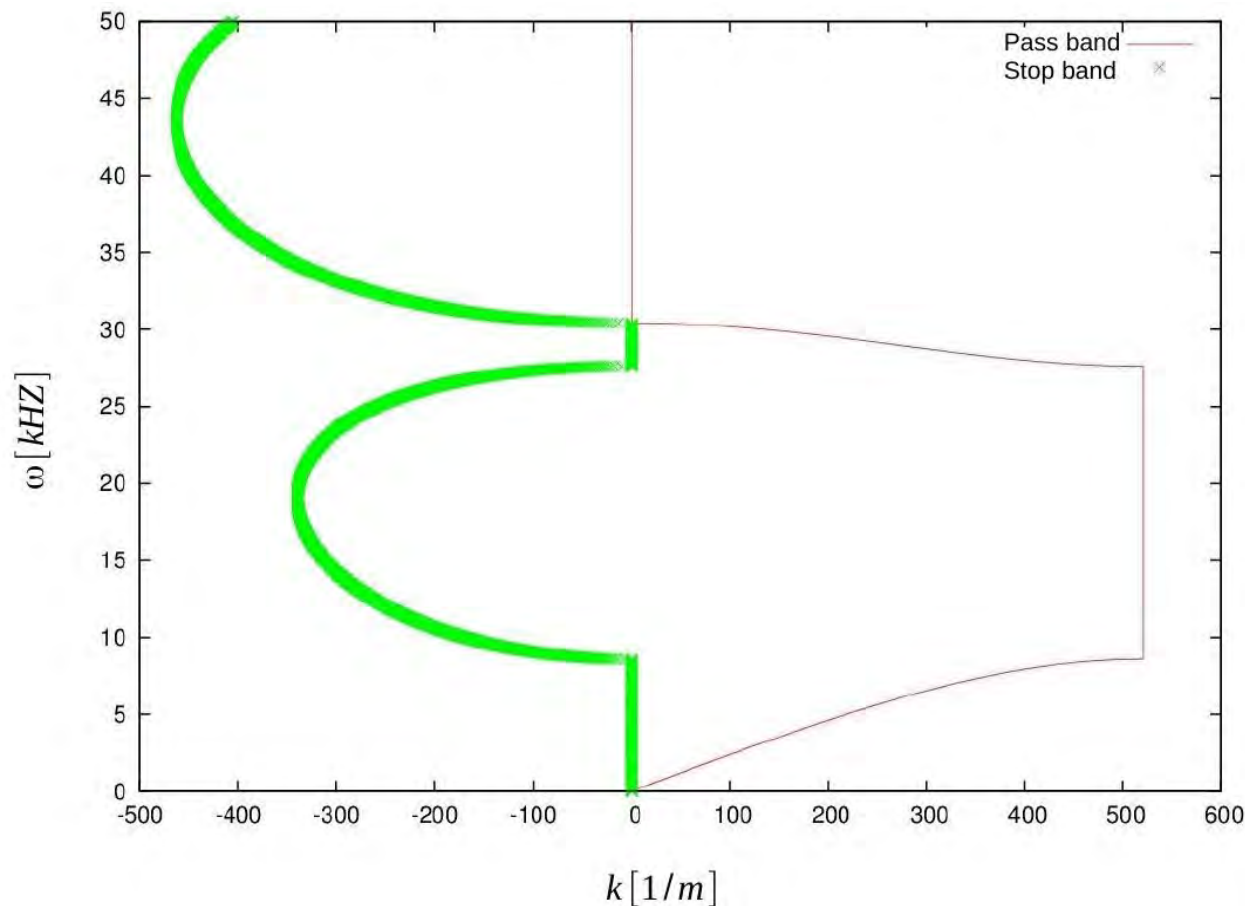
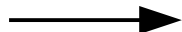


- Couple continuum level simulation with optimization algorithms to obtain the optimum design parameters.
- Shock Filter Design: fitness function involves a weighted penalty for a passband in a specified frequency range.
- Design parameters: layer thickness, number of layers, density, elastic modulus.

[10] 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).



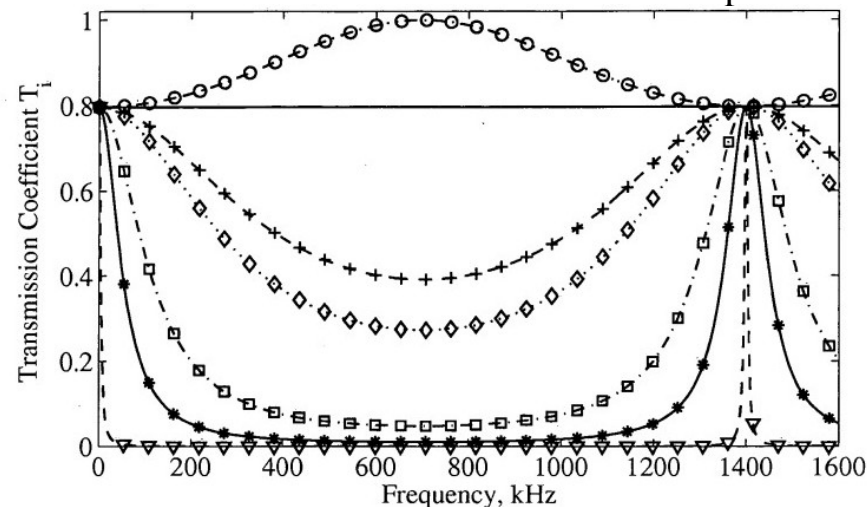
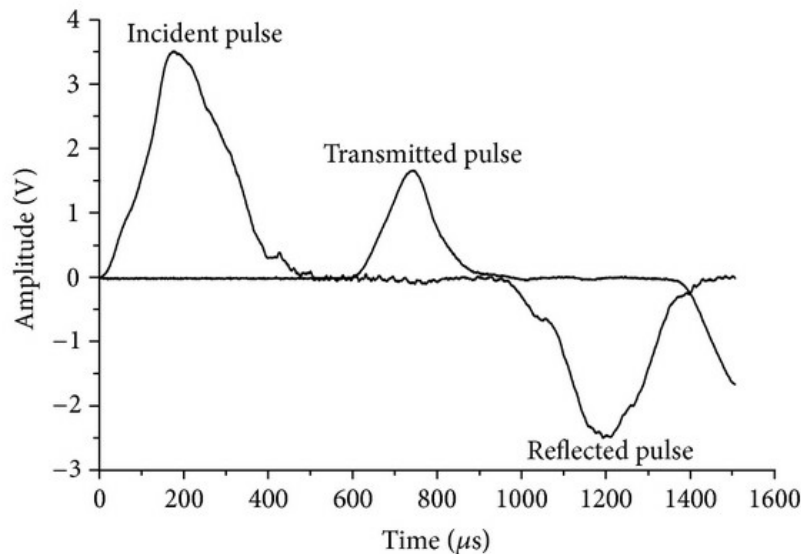
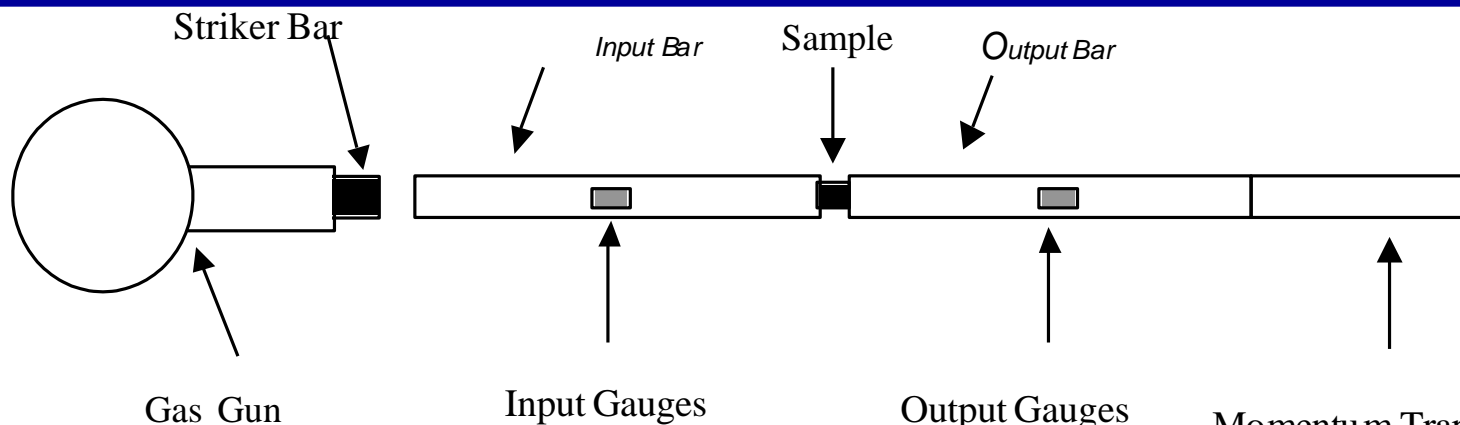
Potential MetaFilter



- 10 layer unit cell of Polyethylene (HDPE) and Aluminum layers on the order of mm- μ m



Next Step: Experimental Validation



[10] N.A. Winfree et al, 2010, "Mechanical filter for sensors", US Patent 7706213

[11] Jordan, J.L., C.R. Siviour, J.R. Foley, and E.N. Brown, "Compressive Properties of extruded polytetrafluoroethylene," *Polymer*, 48 [14], p. 4184-4195 (2007).

DISTRIBUTION A; Approved for Public Release; Distribution Unlimited (PA# 96TW- 2014-0154).



Summary



- Shock mitigation is a difficult task
 - High Frequency, High Amplitude Stress Waves
 - Wide range of shock induced systems failure
- Many current technologies and techniques exist
 - Mechanical Deformation
 - Viscoelastic
 - Superelastic
 - Constrained Layer Damping
 - Biomimetic
 - ...
- Mechanical metamaterials provides a robust framework to develop shock mitigating technology
 - Properties are determined by the shape, interfaces, and sizes of the composing materials
 - Computational design for specific application



Acknowledgements



NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES



“Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Air Force or the National Research Council.”



Acknowledgements



Contact Information:

Kyle K. G. Smith

NRC Postdoctoral Research Associate
Air Force Research Laboratory
Fuzes Branch, Munitions Directorate

Temporary Contact Info:

Phone: 1-850-883-0584

Email: jason.foley.1@us.af.mil

DISTRIBUTION LIST
AFRL-RW-EG-TR-2015-091

Defense Technical Information Center
Attn: Acquisition (OCA)
8725 John J. Kingman Road, Ste 0944
Ft Belvoir, VA 22060-6218

1 Electronic Copy (1 File & 1 Format)

EGLIN AFB OFFICES:

AFRL/RWOC (STINFO Office)
AFRL/RW CA-N
AFRL/RWME
AFRL/RWMF
AFRL/RWMW

1 Electronic Copy (1 File & 1 Format)
1 Electronic Copy (1 File & 1 Format)
1 Electronic Copy (1 File & 1 Format)
1 Electronic Copy (1 File & 1 Format)
1 Electronic Copy (1 File & 1 Format)