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Electronic Damping in Multifunctional Material Systems

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This grant investigated the use of active and passive repeated lattice structures to provide vibration suppression in the context of mechanical metamaterials. The major accomplishments are: providing vibrations suppression without increasing mass, discovering that linear varying of absorber frequencies results in broadband suppression, created an experimentally validated model of mechanical metamaterials, characterized the damping properties of 3D printed metamaterial systems, determined the dividing line between using a single attached absorber versus a mechanical metamaterial, and developed an active mechanical metamaterial to mitigate temperature effects.

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Electronic Damping in Multifunctional Material Systems

Final Report AFOSR Grant Number FA9550-14-1-0264

This grant investigated the use of active and passive repeated lattice structures to provide vibration suppression in the context of mechanical metamaterials. The major accomplishments are: providing vibrations suppression without increasing mass, discovering that linear varying of absorber frequencies results in broadband suppression, created an experimentally validated model of mechanical metamaterials, characterized the damping properties of 3D printed metamaterial systems, determined the dividing line between using a single attached absorber versus a mechanical metamaterial, and developed an active mechanical metamaterial to mitigate temperature effects. When passive methods fail an active control concept is introduced to mitigate vibration as temperature increases that is keyed to turn on when the passive systems fail.

Summary of Accomplishments

The main accomplishments under this research are listed here:

1. Showed that the concept of using distributed vibration absorbers can effectively reduce vibrations without adding additional mass to the structure.
2. Using vibration absorbers with linearly varying natural frequency leads to more broadband suppression.
3. Created a physical one-dimensional metastructure model that experimentally exhibits the predicted metastructure behavior.
4. Characterized the frequency and temperature dependence of the Objet Connex 3D printed materials.
5. Implemented the GHM model to predict the amount of damping in a metastructure from measured material properties.
6. Used the GHM model to accurately predict the fundamental natural frequencies of cantilevered beams at various temperatures.
7. Showed that the concept of adding a single active vibration absorber to a metastructure can control the response of a single mode of a metastructure with linearly varying natural frequencies.
8. Developed an active vibration absorber design that is effective at reducing the vibrations in a metastructure
9. Showed that in 3D printed metastructures from polymers that the damping can overshadow the absorption.
10. Developed a mechanical metamaterial capable of vibration suppression in three orthogonal directions.

These results are all detailed in a series of journal and conference papers. These are listed below:

1. Hobeck, J.D., and Inman, D.J., " Magnetoelastic metastructures for passive broadband vibration suppression ," *Proceedings of SPIE - The International Society for Optical Engineering* **9431**, 943119–9 (2015).
2. Hobeck, J.D., Laurent, C.M.V. and Inman, D.J."3D Printing of Metastructures for Passive Broadband Vibration Suppression" , 20th International Conference on Composite Materials Copenhagen, 19-24th July 2015.
3. Reichl, K. K. and Inman, D. J., "Modeling of Low-frequency Broadband Vibration Mitigation for a Bar Experiencing Longitudinal Vibrations Using Distributed Vibration Absorbers", 20th International Conference on Composite Materials Copenhagen, 19-24th July 2015.
4. Reichl, K. K., and Inman, D. J., 2016. "Active Vibration Control of Metastructures", ICAST 2016: 27th International Conference on Adaptive Structures and Technologies, October 3-5, 2016, Lake George, New York, USA.
5. Abdeljaber, O, Avici O. and Inman, D. J., 2016, "Optimization of Chiral Lattice Based Metastructures for Broadband Vibration Suppression Using Genetic Algorithms" *Journal of Sound and Vibration*, Vol. 369, 12 May 2016, Pages 50–62.
6. Essink, B.C., and Inman, D. J., 2016, "Optimized 3D Printed Chiral Lattice for Broadband Vibration Suppression", IMAC-XXXIV, Society of Experimental Mechanics, Orlando, Florida, January 25-28, 2016, Paper No.204.
7. Abdeljaber, O., Avci, O. and Inman, D. J., 2016, "Genetic Algorithm Use for Internally Resonating Lattice Optimization: Case for a Beam-like Metastructure", IMAC-XXXIV, Society of Experimental Mechanics, Orlando, Florida, January 25-28, 2016, Paper No. 124.
8. Essink, B. and Inman, D., 2016, "A Comparison of Damping and Vibration Absorption in Metastructures," 2016 Proceedings *International Conference on Noise and Vibration Engineering* (ISMA), Leuven, Belgium October 17-20, 2016
9. Reichl, K. K., and Inman, D. J., 2016, "Dynamic Modulus Properties of Objet Connex 3D Printer Digital Materials", IMAC-XXXIV, Society of Experimental Mechanics, Orlando, Florida, January 25-28, 2016, Paper No.149.
10. Reichl, K. K. and Inman, D. J., 2016, "Finite Element Modelling of Longitudinal Metastructures for Passive Vibration Suppression", Proceedings AIAA SciTech 2016, Jan 4-8, San Diego, CA, Paper No. AIAA-2016-1477.Essink, B.C., and Inman, D. J., 2016, "Optimized 3D Printed Chiral Lattice for Broadband Vibration Suppression", IMAC-XXXIV, Society of Experimental Mechanics, Orlando, Florida, January 25-28, 2016, Paper No.204.
11. Essink, B.C., and Inman, D. J., 2016, "Optimized 3D Printed Chiral Lattice for Broadband Vibration Suppression", IMAC-XXXIV, Society of Experimental Mechanics, Orlando, Florida, January 25-28, 2016, Paper No.204.
12. Reichl, K.K. and Inman, D.J., 2017, "Constant Mass Metastructure with Vibration Absorbers with Linearly Varying Natural Frequencies", IMAC XXXV, Conference and Exposition on Structural Dynamics, January 30-February 2, 2017, Garden Grove, CA, USA.

13. Reichl, K. and Inman, D. J., 2017, "Longitudinal Metastructure Bar with an Active Vibration Absorber", Proceedings SPIE Smart Structures and NDE, Portland, Oregon, 25-29 March 2017, paper number [10164-34]
14. Reichl, K.K. and Inman, D.J., 2017 "Lumped Mass Model of a 1D Metastructure for Vibration Suppression with no Additional Mass" *Journal of Sound and Vibration,* Vol. 403, pp. 75–89
15. Liu, M. L., Reichl, K. K., and Inman, D. J. (2017). Complex Modulus Variation by Manipulation of Mechanical Test Method and Print Direction. Proceedings of the *Society of Engineering Mechanics Annual Conference.* Indianapolis, IN, June 2017.
16. Inman, D. J., Reichl, K. K. and Essink, B. C., "A Metastructure Approach to Damping and Vibration Absorption," APVC2017: the 17th Asian Pacific Vibration Conference , Keynote Address, November 13-15, 2017, Nanjing, P. R. China, Paper number 001.
17. K. K. Reichl and D. J. Inman, "Dynamic mechanical and thermal analysis of Objet Connex 3D printed materials," *Experimental Techniques*, vol. 42, pp. 19-25, 2018>

Further details are given in the PhD dissertation of Katie Reichl: Reichl, K. K., PhD., **Active Metastructures for Lightweight Vibration Suppression**, March 2018

This is available without charge from the University of Michigan Library.

Brittany Essink, also supported under this grant will finish her PhD on this topice in May of 2019 and her dissertation should also be available from the University of Michigan library post May 2019.

All papers are posted on Research Gate or available by emailing the PI at daninman@umich.edu

In addition the PI gave 4 Keynote addresses based on this research:

1. Inman, D.J, 2017, "A Metastructure Approach to Damping and Vibration Absorption", APVC2017: the 17th Asian Pacific Vibration Conference , Keynote Address, November 13-15, 2017, Nanjing, P. R. China.
2. Inman, D. J., 2014, "Smart Structures and Metastructures in Vibration Problems", Keynote Address, 4th International Conference on Dynamics, Vibration, and Control, Shanghai, China, August 22-25, 2014.
3. Inman, D. J., 2014, "Adaptive Structures, Multifunctional Structures and Metastructures for Improved Performance", keynote Address**,** Sixth World Conference on Structural Control and Monitoring, 15-17 JULY 2014, Barcelona, Spain.
4. Inman, D. J., 2014, "Adaptive Structures Applications: Smart Materials to Metastructures", Keynote Address, 2014 Canadian Society of Mechanical Engineers Congress, Toronto, Ontario, Canada, 3-7 June, 2014.