Development and Evaluation of Chainmail Solids for Shock Mitigation in Aerospace

Milad Mesbahi
University of California, Los Angeles
Mentor: Ali Kolaini
Co Mentor: Sean Pham

Table of Contents

Abstract

Vibration management is paramount for the sustainability and functionality of engineering systems. Traditional damping methods, although effective to a degree, exhibit limitations that can compromise mission success The recent exploration into chainmail as a potential damping material stands as a testament to this imperative. This research, with a focus on the chainmail's performance both individually and in conjunction with a solid block, carries paramount significance to industries grappling with vibrational challenges. A meticulous vibrational analysis showcased a staggering 98% reduction (-20dB) in transmissibility at certain decisive frequencies and near -30dB at frequencies over 800hz. Our observations also revealed the unique flexibility and compliance of chainmail, with both translational and rotational characteristics apparent at its primary modes. These results, complemented by Finite Element Method (FEM) simulations, affirm the promise of chainmail as a versatile damping solution in aerospace applications. As the chainmail's tunable structure allows movement of its natural mode, future work will explore further tuning for specific aerospace applications and delve deeper into its thermal properties.

Challenges of Dynamics in Aerospace Applications

In the aerospace domain, the management and mitigation of vibrations stand as pivotal aspects to guaranteeing the success of a mission. From the moment a spacecraft begins its launch process, it is subjected to intense vibratory loads. These vibrations can compromise the integrity of onboard instruments, impairing their ability to function accurately or even causing permanent damage. This is especially concerning for sensitive scientific apparatuses, where even minute disturbances can skew results and hamper data acquisition.

Traditionally, the industry has relied upon elastomeric materials to serve as damping solutions. While these materials have been effective to a certain degree, they come with inherent challenges. Over extended periods, elastomers are prone to degrade, diminishing their damping effectiveness. Moreover, their performance can be adversely affected by temperature variations, an unavoidable factor in the vast temperature swings of space. Another significant limitation lies in their capacity to dissipate vibratory energy. In situations where high levels of energy attenuation are necessary, these materials may fall short.

To counteract these inadequacies, one might consider employing more substantial, bulkier damping mechanisms. However, this alternative introduces its own set of problems. In the weight-sensitive realm of aerospace engineering, every added kilogram can have a cascading impact on fuel requirements, structural design, and overall mission costs.

Given these complexities, there's an urgent need to develop innovative damping strategies. These solutions should not only effectively mitigate vibrations but also be durable, weight-efficient, and resilient against the harsh conditions of space. As the industry pushes the boundaries of exploration, the importance of such advanced damping technologies becomes increasingly paramount.

Chainmail Solids: A Dynamic Solution

Enter the Chainmail Solids (CMS), a novel material class currently being advanced at Caltech. These innovative materials stand out due to their low density and adaptable stiffness. Their structure, a culmination of interconnected trusses forming hollow three-dimensional particles, offers a dual advantage - it reduces overall density while promoting efficient contact between elements. A key feature of CMS is their adaptability; they can bend, fold, and drape, seamlessly conforming to complex shapes. Yet, when needed, an applied boundary compression can induce a jamming transition. This mechanism, effectively stiffening the material, renders CMS load bearing. Recent studies, including those referenced from my mentor, reveal that a modest external pressure (around 93 kilopascals) can amplify the material's stiffness by over 25 times its original measure. This transformative quality, achieved without significant temperature shifts or intense electrical/magnetic fields, holds immense potential for space exploration missions.

Experimental Procedure

The focus of our experimental setup revolved around a meticulously designed Data Acquisition System that underwent an upgrade to a 20-channel capacity. Integral to our data collection efforts were 8 accelerometers, composed of 6 triaxial and 2 uniaxial sensors. Vibrational disturbances introduced into the system followed a random vibration profile, with a pre-random signature ranging from 20Hz to 2000Hz. The accelerometer placements were strategic, aiming for optimal data acquisition. On the chainmail's upper surface, four triaxial accelerometers were positioned at its corners. This placement was vital for understanding the mode shapes the Chainmail Structure (CMS) assumed during vibration. Furthermore, we employed two uniaxial accelerometers at the beam's extreme ends. Their primary function was to discern the modal responses stemming from the test article in contrast to the responses from the CMS. For a robust baseline that would aid in subsequent data analysis comparisons, two triaxial accelerometers were anchored to the base plate.

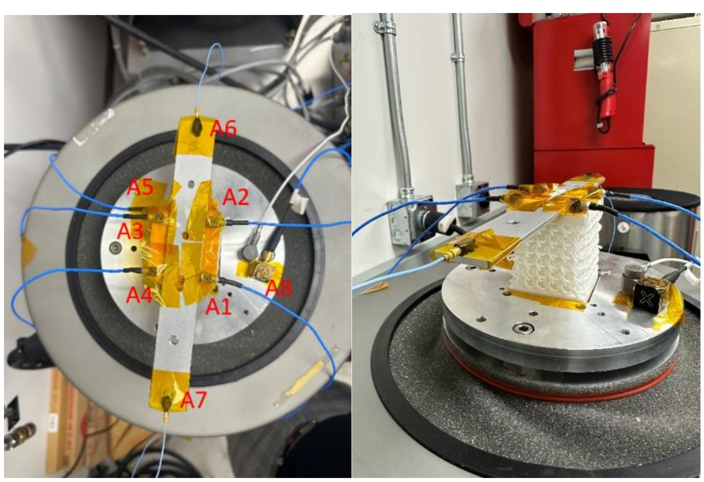

Figure 1: Chainmail Vibrational setup on Electric Shaker

Our initial setup employed a cubic chainmail structure fastened to an aluminum baseplate, with a chainmail-specific recess, using ¼-20 fasteners. An additional plate was added, forming a sandwich structure around the chainmail, secured with four ¼-20 fasteners. This setup, however, presented a challenge. The bolts inadvertently created a direct load path from the shaker to the test article, sidelining the chainmail's damping effects. To address this, we adopted an adhesive assembly. The chainmail was glued into the base plate's recess, and the aluminum beam was adhered atop the chainmail. This ensured the shaker's vibrations primarily channeled through the CMS, providing a truer reflection of its damping properties.

Methods

Solid Block – Chainmail PSD Comparison

To evaluate the damping properties of both the chainmail and the solid block, we subjected both to a series of random signature tests. By comparing Power Spectral Density (PSD) at attenuations of -12, -9, and -6dB, we could glean a clear depiction of their vibrational responses. Our plots distinctly illustrated the responses of the solid block beam accelerometer, the chainmail beam accelerometer, and the control which can be seen below (-6dB example).

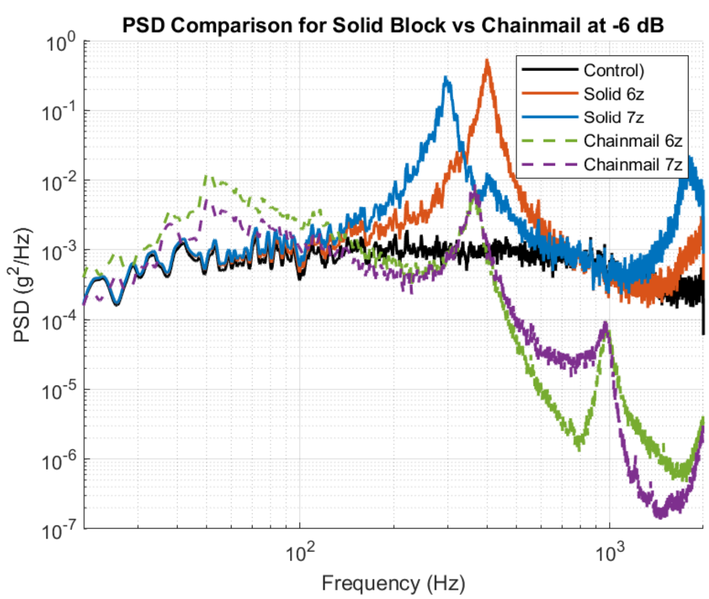

Figure 2: PSD comparison between solid block and chainmail at 6dB

This comparison was imperative to discern the difference in magnitude amplification between the two materials. For the solid block, notable peaks in responses occurred at 294Hz and 400Hz, which roughly matched the modes and behavior of our FEM, which can be seen below.

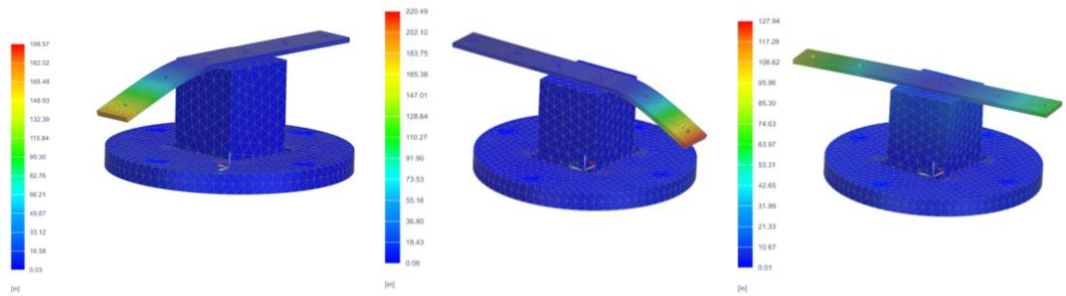

Figure 3: FEM Random Vibration analysis highlighting modes at i) 300hz ii) 415hz iii) 950hz.

Conversely, the chainmail predominantly showcased a singular beam peak at 370Hz. During our initial tests for chainmail, two modes were detected at 365Hz and 400Hz. The consolidation of these into a single peak at 370Hz in our later tests might hint at changes in boundary conditions or an adaptation in the structural integrity of the chainmail after repeated testing. This peculiar behavior however needs to investigate further in order to confirm these suspicions. The chainmail response for both cases exhibited sharp attenuation past 400Hz, showing promise for its damping properties.

In order to evaluate the percent vibrational reduction of the beam peaks between the solid block and chainmail, I ratioed the two PSDs of these signals, which quantifies the efficiency with which vibrations traverse through our system. This can be denoted as

$$T(f) = \frac{Solid\ Block\ PSD}{Chainmail\ PSD}$$

Our findings were compelling. We observed staggering percent reductions of 97.27% and 98.44% from the original vibrations when transitioning from the solid block to the chainmail. At the primary peaks, the chainmail demonstrated a reduction of approximately 20dB compared to the solid block. This attenuation is particularly noteworthy, as a reduction of this magnitude indicates that the chainmail effectively dampens the vibrational energy to 1% of the solid block's response, a substantial diminution. More intriguingly, as the frequency spectrum extends beyond 1000Hz, the chainmail's damping capacity amplifies. Here, we observed a drop surpassing 30dB relative to the solid block. Such significant attenuation at higher frequencies is emblematic of the chainmail's exceptional performance in shock applications.

Chainmail PSD Comparison at Varying Input Levels

To comprehensively understand the chainmail's vibrational response, we subjected it to a series of tests across varying input levels: -12, -9, -6, -3, and 0 dB. By scrutinizing the Power Spectral Density (PSD) across this amplitude spectrum, our intent was to ascertain the consistency and linearity of the chainmail's behavior under different excitations. This plot can be seen below:

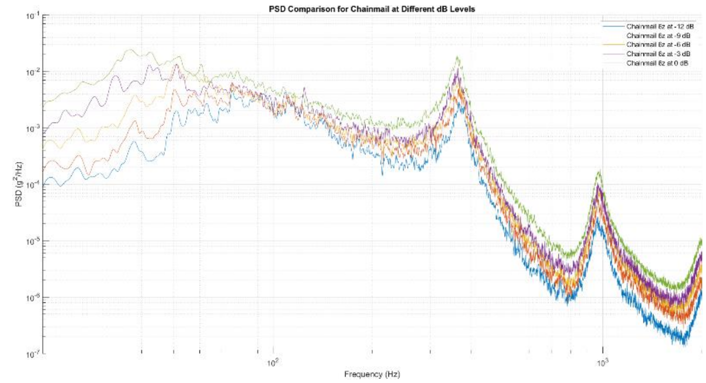

Figure 4: PSD comparison between -12dB and 0dB for chainmail

The chainmail's response exhibited remarkable consistency, presenting a behavior that scaled uniformly in magnitude directly correlating with the input levels. Most notably, when comparing the extreme ends of our test spectrum, namely the -12 dB and 0 dB tests, the frequency peaks showcased minimal deviations, less than 5Hz.

The significance of such a consistent and linear suggests that the chainmail's damping properties are inherently robust, displaying minimal variability regardless of the excitation magnitude. This not only underscores its reliability as a damping medium but also offers predictive capabilities for system designers. Such behavior is indicative of a stable material, resilient to dynamic forces and changes in external stimuli, making it an ideal candidate for applications where consistent vibrational performance is crucial.

Chainmail Modal Analysis

In a bid to understand the intrinsic behavior of chainmail in vibration isolation applications, our investigation encompassed subjecting the chainmail to a comprehensive random vibration test, spanning frequencies from 20Hz to 2000Hz and consisting of a similar setup to our comparison study.

One notable observation was the identification of distinct PSD peaks at 364Hz and 405Hz by the uniaxial accelerometers positioned on the beam. These frequencies coincide with beam modes pre-identified through a Finite Element Method (FEM) simulation, reinforcing the reliability of our simulations and suggesting a strong correlation between our predictive models and the physical manifestations. The PSD trended toward attenuation post 100Hz, underscoring the pronounced damping attributes of the chainmail, especially at escalated frequencies.

However, the appearance of multiple, albeit smaller, peaks within the 100-170Hz spectrum piqued our interest. A dominant mode at 95Hz was accompanied by peaks at 101Hz, 130Hz, 150Hz, and 170Hz, patterns consistently registered by all four accelerometers stationed atop the chainmail. Intriguingly, peaks at 39hzand 70hz manifested in the X and Y PSDs, but did so with reduced vigor, predominantly subsiding beneath the noise threshold as they were not the primary axis of excitation. These preliminary insights, initially presented to Caltech, instigated a deeper dive into our data through the computation of transmissibility, Cross Spectral Densities (CSDs), and coherence across accelerometer pairings. With values nearing 1, the strong coherence emphasized the genuine modes inherent to the system, distinguishing them from potential noise-induced artifacts. The PSD plots hinted at the potential vibrational modes at 95Hz, 101Hz, 130Hz, 150Hz, and 170Hz. These were further corroborated by CSDs, supporting their credibility as genuine vibrational modes of our chainmail structure. This assertion was solidified by the near-unity coherence values observed across all axes.

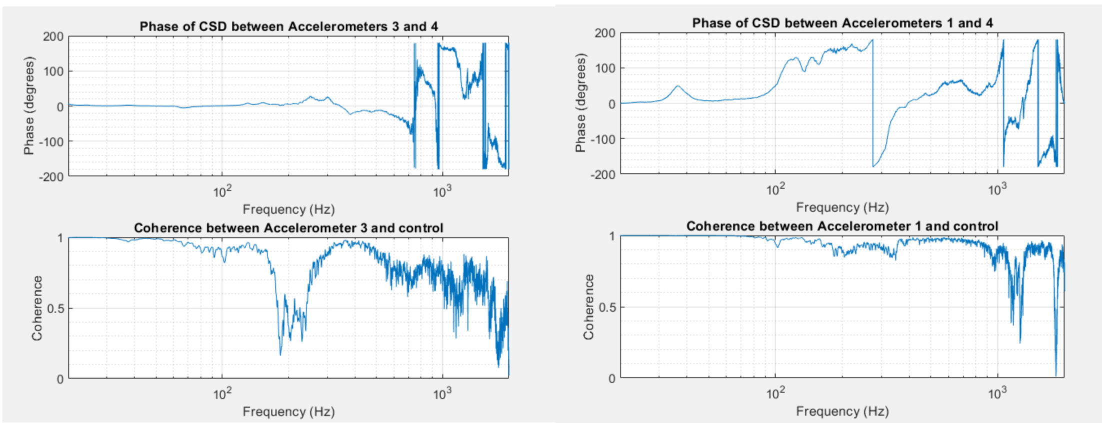

Figure 5: Coherence and phase plots for accelerometers on the same side(3 & 4) of the chainmail face and opposite sides (1 & 4)

It's also pertinent to remark on the disparity in beam peaks for the chainmail between these runs and our prior comparisons. Such variations could be attributed to the tunable state of the chainmail, as there testing occurred weeks after one another and the chainmail may have loosened from its original jammed state. As the chainmail's state can influence its inherent stiffness, it bears the potential to shift the natural isolated frequency. This adaptive nature presents a dual-fold avenue: firstly, the chainmail's stiffness can be modulated to resonate with specific applications; secondly, understanding and modeling the state of the chainmail becomes paramount to predicting and aligning its natural mode. This capability not only underscores the chainmail's versatility but also foregrounds it as a promising candidate for bespoke vibration isolation applications.

Although the phase plots gave us intuition on the modal behavior of these modes, we proceeded to create MATLAB animations to better understand how the chainmail behaves. Screenshots of these gifs are shown here

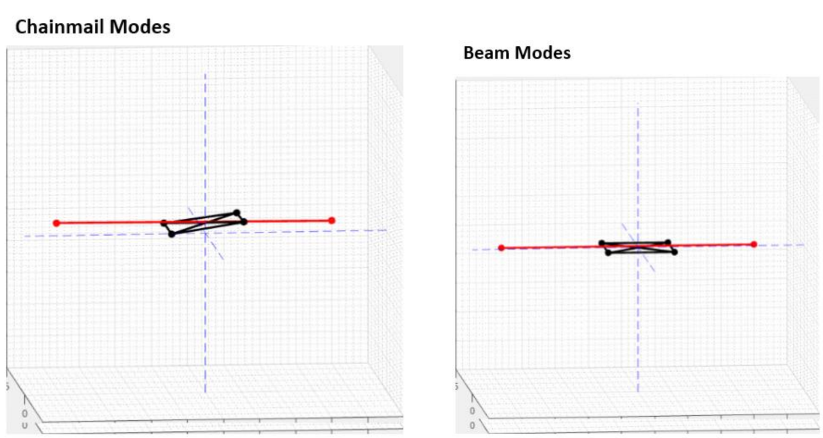

Figure 6: Screenshots of animations depicting modes for the test article and chainmail and their behavior

The animations unravel the dynamic response of the chainmail under varying conditions. Notably, they reveal a pronounced translation of the chainmail along the z-axis, complemented by rotation about the x-axis. This dual movement is emblematic of the chainmail's inherent flexibility. The capability of the chainmail to exhibit such multi-dimensional shifts, especially in rotational terms, showcases its compliance and adaptability. In contrast, for the beam modes, there was marked absence of any x or y-axis movement. Instead, the beam seemed to be the vanguard of change, reacting dominantly to the imposed vibrations. This confirmed the nature of these identified modes being solely attributed to the beam.

Conclusion & Moving Forward

Our research underscored the profound vibration attenuation capabilities of the chainmail structure. Across our experimental evaluations, the chainmail consistently reduced the modes of our test article, exhibiting a remarkable -20dB attenuation. More intriguingly, this reduction amplifies, reaching -30dB, as we traverse into higher frequencies. The chainmail's dynamic structure offers an intriguing facet of tunability, allowing for modifiable natural modes. Throughout our rigorous testing phases, this attenuation behavior remained unwavering and consistent, irrespective of the variations in input levels. Furthermore, our analyses illuminated the chainmail's unique vibrational behavior. At its primary modes, it predominantly showcased a blend of translational and rotational responses, marking its adaptability to a diverse array of vibrational forces.

As we chart our future trajectory in this exploration, several avenues beckon deeper investigation. We aim to evaluate the efficacy of a washer configuration to discern if it augments the damping capabilities further. In our bid to glean a holistic understanding of the chainmail's modal behavior, we'll strive to uncover any latent axial or torsional modes, achieved by exciting the structure on multiple axes. Additionally, a comprehensive grasp of the chainmail's thermal properties remains paramount, given its potential aerospace applications. Lastly, our ultimate objective lies in tailoring the chainmail structure for specific aerospace applications, integrating it and assessing its real-world performance in those challenging environments.

References

1. Cutolo A, Engelen B, Desmet W, Van Hooreweder B (2020). Mechanical properties of diamond lattice Ti-6Al-4V structures produced by laser powder bed fusion: On the effect of the load direction. J Mech Behav Biomed Mater. doi:10.1016/j.jmbbm.2020.103656. Epub 2020 Feb 4. PMID: 32174413.
2. Keysight Technologies. (2008). *The Fundamentals of Signal Analysis - Keysight*. The Fundamentals of Signal Analysis. https://www.keysight.com/us/en/assets/7018-06760/application-notes/5952-8898.pdf
3. Kolaini, Ali R.; Nayeri, Reza; Kern, Dennis L., 2009, "Pyroshock simulation systems: are we correctly qualifying flight hardware for pyroshock environments?", https://hdl.handle.net/2014/44680, JPL Open Repository, V1
4. Simmons, R. (2009). *FEMCI Book - Random Vibration Analysis Information*. NASA. https://femci.gsfc.nasa.gov/random/index.html

5. Wang, Y., Li, L., Hofmann, D., Andrade, J. E., & Daraio, C. (2021). Structured fabrics with tunable mechanical properties. Nature, 596(7871), 238–243. https://doi.org/10.1038/s41586-021-03698-7

Acknowledgements

I'd like to extend my heartfelt gratitude to the following individuals who played an indispensable role in the success of this project:

- Ali Kolaini: His mentorship was invaluable, and I'm deeply thankful for his extensive knowledge in dynamics that significantly steered our research in the right direction.
- Lindsey Berger: Lindsey's commitment to the project and her willingness to invest time to help troubleshoot and refine our FEM approach was unparalleled. Her expertise became a cornerstone for the significant strides we achieved this summer.
- Sean Pham: His consistent support and direction in testing and analysis were paramount in ensuring our experiments were both precise and enlightening.
- Vachik Gargarian and Carlos Esproles: A special note of thanks to Vachik and Carlos for their generosity. Their consultation and expertise in machine fabrication substantially elevated the quality and accuracy of our hardware.
- Colton Crosby: Colton's adeptness in data visualization and his invaluable contribution in signal processing streamlined our data analysis, making it both effective and insightful.
- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the JPL Summer Internship Program and the National Aeronautics and Space Administration (80NM0018D0004).