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Reviewed Paper

Fabrication of Liquid-Filled Voronoi Foams for Impact Absorption Using Material Jetting Technology

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Abstract

An important consideration in the design of any mechanical system is its ability to isolate and dissipate vibrational and impact energy. Closed-cell foams utilize cell crumpling to absorb energy, relying solely on viscoelastic effects for damping. Liquids, however, can generate large amounts of damping from fluid channel friction and turbulence. We produced closed-cell foams that are liquid filled, resulting in tunable materials that absorb energy better than either component on their own, using a Voronoi generation model and a J750 printer that could jet curable and incurable liquids. We found that by changing the wall thickness and liquid percentage, we achieve a stiffness range of 4.1 N/mm to 80 N/mm. Our work introduces this new class of damping metamaterial that can absorb tunable amounts of energy per unit volume. These impact-absorbing structures may benefit applications such as protective equipment, healthcare, and automotive industries.

Introduction

Imbalances inherent to turning components in mechanical systems are often the origin of vibrations that can excite natural frequencies leading to long term performance reduction, reduced service life, and human discomfort. [1,2] Passive vibration mitigation employs dampers and isolators to attenuate a vibration source, preventing its propagation to the rest of the system and therefore protecting it from damages. Passive dampers are used to dissipate incoming kinetic energy and convert it to heat, usually involving viscous fluids, viscoelastic materials, piezoelectric elements, or electromagnetic devices. [3,4,5] Conversely, passive isolators such as closed-cell foam slabs, metal coil or wave springs, wire rope isolators, and rubber machine mounts are used to decouple a vibration source from a mechanical system, separating a system's natural frequency from the excitation frequency therefore avoiding resonance. [6,7]

Nonperiodic transient shock loads also commonly initiate vibration. Isolators store shock energy and gradually dissipate it via free vibration, requiring large displacements to be efficient. Dampers utilize friction to dissipate energy but limit displacement, reducing isolation efficiency. These competing mechanisms make it difficult to design a system where isolators and dampers work in tandem. [8] Furthermore, traditional elastomeric isolators can only operate within a predetermined narrow band width of harmonics. [9] Fluid viscous dampers can combat harmonics in a larger range of frequencies but are anisotropic and lack compliance. Additive manufacturing enables the creation of metamaterials capable of both damping and isolation on a tunable spectrum.

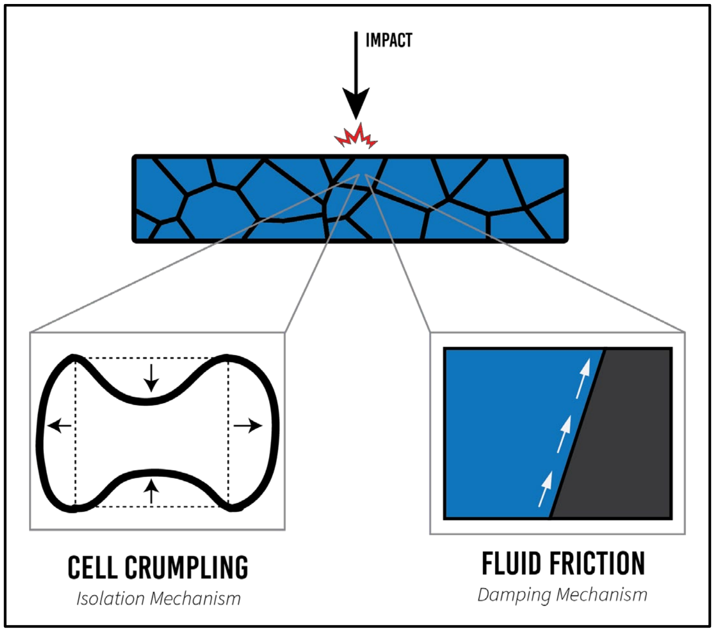

Figure 1. Visualization of vibration attenuation mechanisms

Using the Stratasys J750, we created a liquid filled closed-cell foam that can dissipate energy through fluid channel friction and isolate vibration via cell crumpling. This new metamaterial mitigates vibration while maintaining compliance and geometric freedom, utilizing the interface between the two phases and the inherent damping properties of liquid to achieve a higher attenuation density than traditional dampers or isolators on their own.

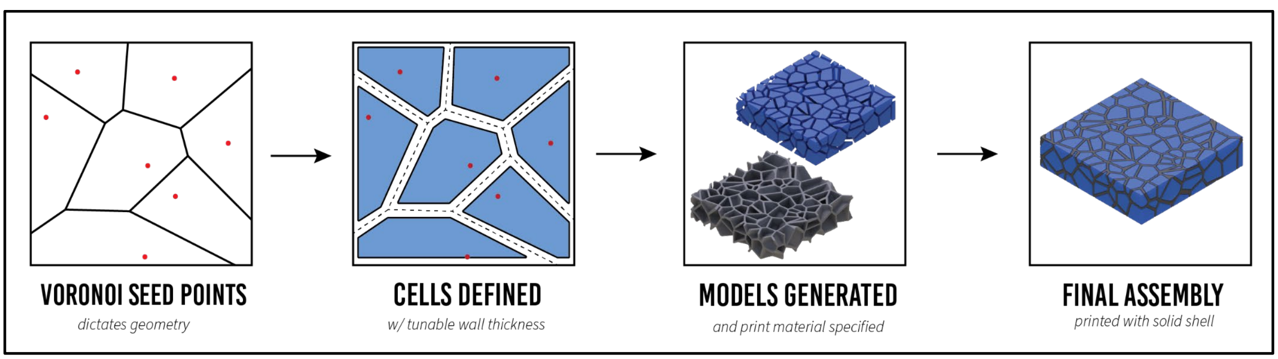

Figure 2. Schematic representation of metamaterial construction

To generate these Voronoi foams, a Voronoi-based infill-generating algorithm was used [10]. This algorithm functions by generating the seed points to fill the volume of a given 3D model, using the Parallel Jump Flood algorithm to indicate the volumes of the Voronoi cells, then running through several post-processing steps to find the cell walls and apply the desired wall thickness. [10,11] The properties of foams generated in this manner depend on seed-point distribution, seed-point density, shell thickness, shell shape, overall size, wall thickness, and liquid percentage relative to total volume. Seed point distribution and density were determined probabilistically, with each voxel in our discretized space as a probability of 5% of generating a seed point at its location. Shell thickness was kept at a constant 1.83mm, our tested minimum to prevent leakage during printing. With a rectangular prism shell shape, shell size was kept a constant 40 mm by 40 mm by 10 mm. Wall thickness was altered and tested in a range of 0.138mm to 0.975mm, including a baseline solid sample test with a technically infinite wall thickness. Likewise, liquid percentage relative to total volume was altered and tested in a range of 37% to 53%. Further studies may alter parameters we kept constant to obtain and explore a broader range of material properties.

It would be impossible to make a closed-cell liquid-filled foam with traditional manufacturing methods. The design freedom granted by additive manufacturing enables the creation of such a material that maintains the strengths of both traditional dampers and isolators in a tunable manner.

Results

Limit of Parameters

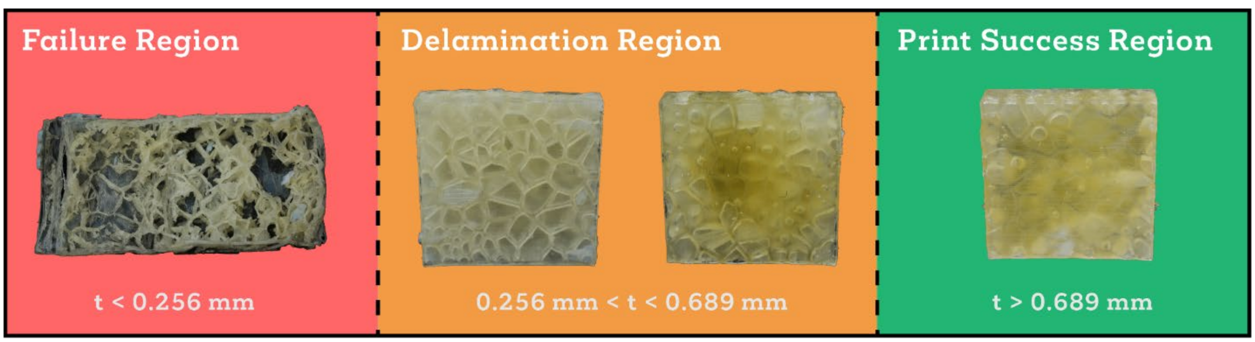

Figure 3. Effect of wall thickness on print success

The Stratasys J750 has a 7° vertical angle tolerance. This constraint can be somewhat bypassed when liquid is used as the pseudo-support material, but only up to a maximum cavity width of 10mm. [12] Print success is also dependent on the thickness of cell walls between seed points. Walls of insufficient thickness are not strong enough to hold the weight of liquid in higher layers, which can result in delamination or total failure. When layer delamination occurs, the bulk solid portion will partially or even completely remain intact but liquid leaks out of the foam depending on the severity of delamination. While not explored here, leakage could be purposefully employed to successfully print near closed-celled foams with air cavities that would be normally impossible with the 7° angle constraint.

Quasi Static Compression

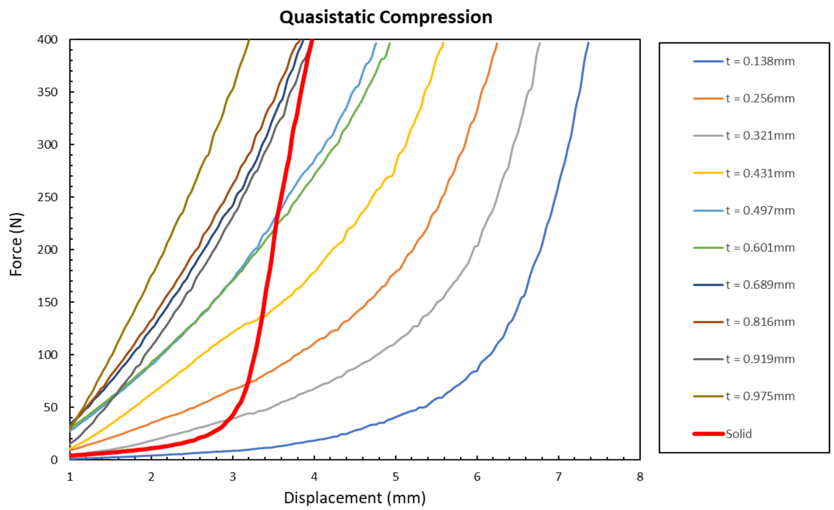

Figure 5. Load behavior for foam of varying wall thicknesses

Regardless of the perceived success of a print, all foam configurations were subject to a quasi-static compression test to gauge their fundamental failure behavior. As each foam was compressed to failure, liquid gradually leaked out of the sides. Lower wall thickness foams have a smoother trend at higher displacements because its behavior is dominated by the larger amounts of incompressible liquid present. The thinner walls are easily broken to allow liquid to flow. Higher wall thickness foams are less stiff at higher displacements because the dominating mechanism is compressive densification of the elastomer. Errors become more pronounced at higher wall thicknesses because it is more difficult for liquid to leak out of the more robust cells; once the forces from the liquid exceed the capacity of the thicker walls the leakage is much more violent causing more perturbations in the data.

Vibration

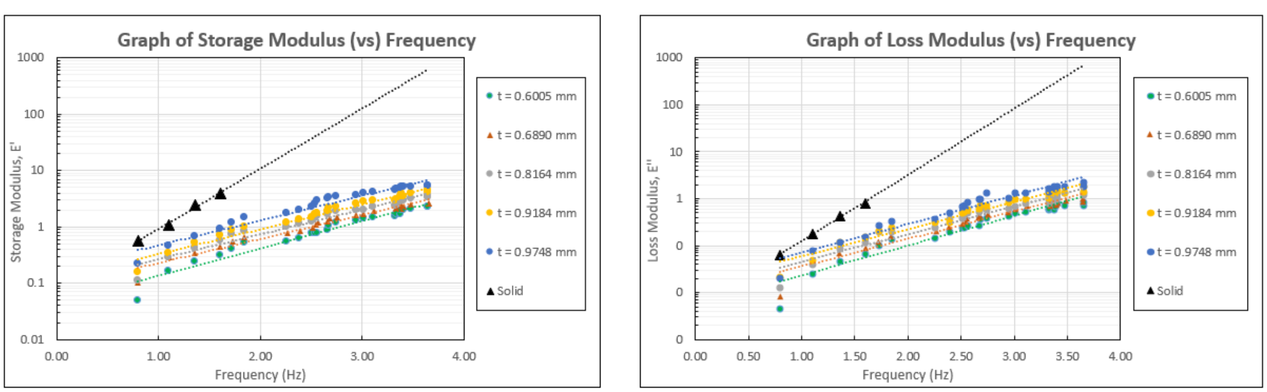

Figure 6. Foam behavior as a function of frequency

The stiffness of each foam configuration also changes as a function of excitation frequency. Lower wall thickness foams have a more gradual increase in stiffness, maintaining it over a broader range of frequencies, while larger wall thickness foams including the solid baseline have a very sudden increase in stiffness at higher frequencies. This supports the idea that viscous dampers operate in a wider frequency range than traditional elastomeric dampers. [13] Furthermore, if there is too much solid material, stiffness rises which inhibits the foams' ability to displace therefore decreasing its isolation efficiency. Cell crumpling and liquid friction surface area are both limited at higher thicknesses but don't leak as easily. This tradeoff would need to be optimized depending on the application and required specifications.

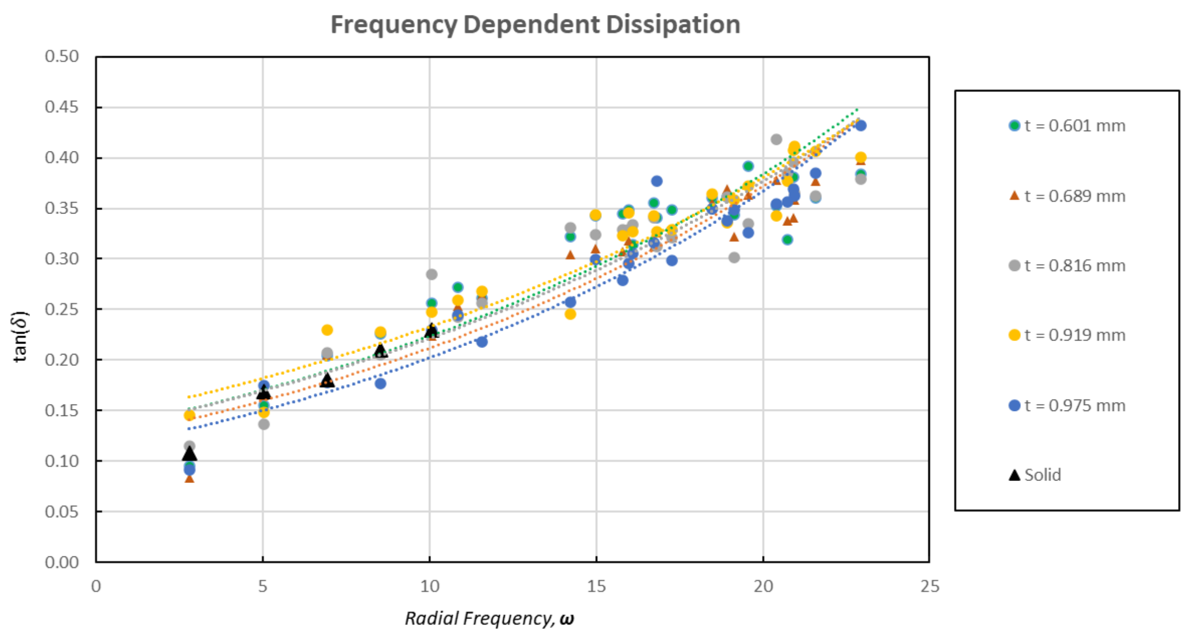

Figure 7. How dissipation potential changes with vibration frequency

In purely elastic materials, stress and strain are in phase. In purely viscous materials stress and strain are offset by a phase lag of $\delta = 90°$. By this logic, as the volume of liquid within the foam increases and the wall thickness decreases, phase lag should approach $\delta = 90°$ and $\tan(\delta)$ should tend upward toward infinity. As wall thickness increases, which in turn decreases the volume of fluid within the foam, phase lag should approach $\delta = 0$ and $\tan(\delta)$ should likewise approach zero. Foams of higher wall thickness should have a lower $\tan(\delta)$ because they have a higher density of elastic material. However, this is not always the case. At any given frequency, the phase lag order is not consistent with what would be intuitively expected. We attribute this behavior to the fact that liquid cells of different sizes resonate at different frequencies. $\tan(\delta)$ is the ratio of the loss modulus to the storage modulus and provides an indication of how well a material can dissipate energy. A higher $\tan(\delta)$, inherent to more viscous materials, suggests that a material is more well suited for energy dissipation rather than storage. Liquid cells of different sizes have different resonant frequencies, explaining the seemingly unintuitive ordering.

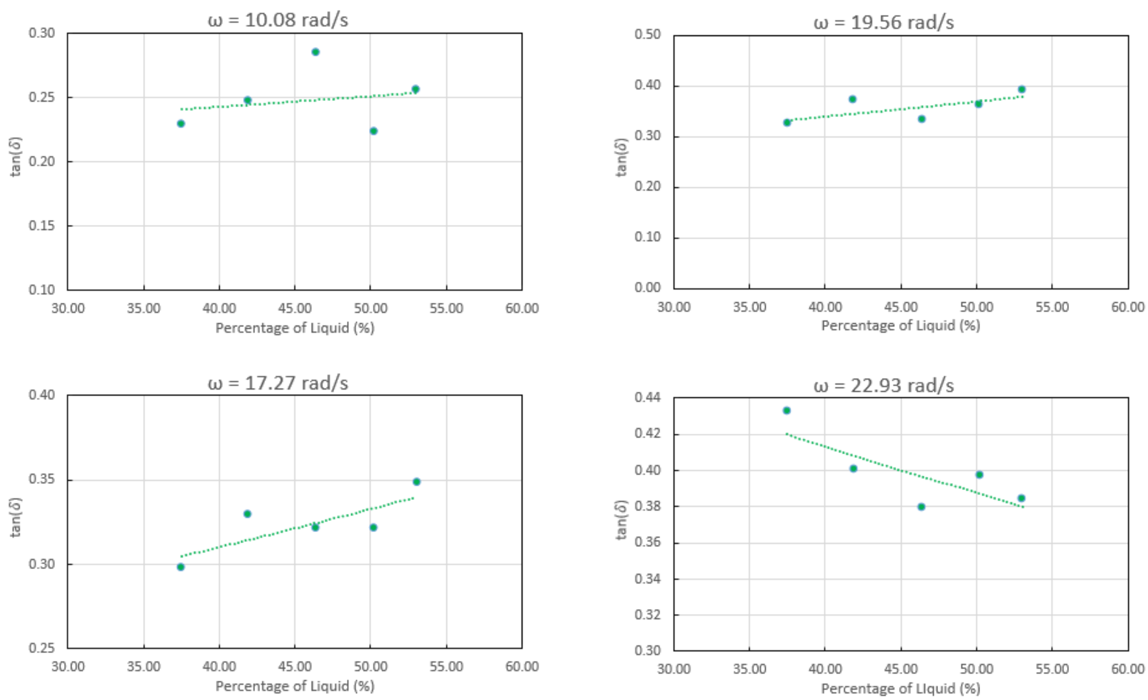

Figure 8. Alternative independent variable to wall thickness

The ability of a foam to efficiently dissipate energy, indicated by high tan(δ), generally increased as a function of liquid percentage. This is defined as the ratio of liquid volume to the total volume of foam. At higher frequencies such as $\omega = 22.93$ rad/s this isn't the case, attributed once again to the fact that different foam configurations have different resonant frequencies. The foam with a liquid percentage between 35-40% had a natural frequency that destructively interfered with the excitation source thus dissipating energy more efficiently. [14]

Conclusion

An important consideration in the design of any mechanical system is its ability to isolate and dissipate vibrational and impact energy. Additive manufacturing enables the creation of metamaterials that can isolate and damp vibration and shock in tunable amounts. Using a Voronoi generation model and a Stratasys J750 inkjet 3D printer, we created liquid filled closed-cell elastomeric foams with a stiffness range of 4.1 N/mm to 80 N/mm depending on the wall thickness of the printed specimen. This new class of damping metamaterials utilizes the interface between solid and liquid phases to dissipate energy and traditional cell crumpling as an isolation mechanism. Energy is attenuated while maintaining compliance and complete geometric freedom, opening the door to applications in the protective equipment, healthcare, and automotive industries. There are still many aspects of this new material that can be explored including seed point position, liquid channels, and varied liquid percentage that would further improve its damping and isolation capabilities.

Bibliography

1. H. Mahdisoozani et al., “Performance Enhancement of Internal Combustion Engines through Vibration Control: State of the Art and Challenges,” Applied Sciences, vol. 9, no. 3, Art. no. 3, Jan. 2019, doi: 10.3390/app9030406.
2. P. Jönsson and Ö. Johansson, “Prediction of vehicle discomfort from transient vibrations,” Journal of Sound and Vibration, vol. 282, no. 3, pp. 1043–1064, Apr. 2005, doi: 10.1016/j.jsv.2004.03.037.
3. Ge, Changfeng, Denis Cormier, and Brian Rice. "Damping and cushioning characteristics of Polyjet 3D printed photopolymer with Kelvin model." Journal of Cellular Plastics 57, no. 4 (2021): 517-534.
4. F. dell Isola, C. Maurini, and M. Porfiri, “Passive damping of beam vibrations through distributed electric networks and piezoelectric transducers: prototype design and experimental validation,” Smart Mater. Struct., vol. 13, no. 2, pp. 299–308, Apr. 2004, doi: 10.1088/0964-1726/13/2/008.
5. E. Diez-Jimenez, R. Rizzo, M.-J. Gómez-García, and E. Corral-Abad, “Review of Passive Electromagnetic Devices for Vibration Damping and Isolation,” Shock and Vibration, vol. 2019, p. e1250707, Aug. 2019, doi: 10.1155/2019/1250707.
6. H. Elderrat, H. Davies, and E. B. Brousseau, “Investigation of the foam filled fluid technology for anti-vibration devices,” International Journal of Structural Analysis & Design, vol. 1, pp. 182–187, Sep. 2014.
7. P. S. Balaji, M. E. Rahman, L. Moussa, and H. H. Lau, “Wire rope isolators for vibration isolation of equipment and structures – A review,” IOP Conf. Ser.: Mater. Sci. Eng., vol. 78, p. 012001, Apr. 2015, doi: 10.1088/1757-899X/78/1/012001.
8. D. F. Ledezma-Ramírez, P. E. Tapia-González, N. Ferguson, M. Brennan, and B. Tang, “Recent Advances in Shock Vibration Isolation: An Overview and Future Possibilities,” Applied Mechanics Reviews, vol. 71, no. 6, Sep. 2019, doi: 10.1115/1.4044190.
9. T. Komatsuzaki, Y. Iwata, H. Ringe, and K. Kawagoshi, “Adaptive Tuned Dynamic Vibration Absorber With Variable Stiffness Property Using Magneto-Rheological Elastomers,” in Volume 1: Development and Characterization of Multifunctional Materials; Modeling, Simulation and Control of Adaptive Systems; Integrated System Design and Implementation, Snowbird, Utah, USA, Sep. 2013, p. V001T03A021. doi: 10.1115/SMASIS2013-3106.
10. Williams, Tyler, Langehennig, Sarah, Ganter, Mark, & Storti, Duane, “Using Parallel Computing Techniques to Algorithmically Generate Voronoi Support and Infill Structures for 3DPrinted Objects.” Solid Freeform Fabrication Symposium Proceedings 30 (2019): pp.1830-52
11. Rong, Guodong and Tan, Tiow-Seng. “Jump Flooding in GPU with Applications to Voronoi Diagram and Distance Transform.” Symposium on Interactive 3D Graphics and Games. Pp109-116. Redwood City, CA, March 14-17, 2006. DOI 10.1145/1111411.1111431. https://dl.acm.org/citation.cfm?id=1111431
12. MacCurdy, Robert, Robert Katzschmann, Youbin Kim, and Daniela Rus. "Printable hydraulics: A method for fabricating robots by 3D co-printing solids and liquids." In 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 3878-3885. IEEE, 2016.

13. H. Akehashi and I. Takewaki, “Optimal Viscous Damper Placement for Elastic-Plastic MDOF Structures Under Critical Double Impulse,” Frontiers in Built Environment, vol. 5, 2019, Accessed: Aug. 26, 2022. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fbuil.2019.00020
14. Y. Andrienko, D. Siginer, and Y. Yanovsky, “Resonance behavior of viscoelastic fluids in Poiseuille flow and application to flow enhancement,” International Journal of Non-linear Mechanics - INT J NON-LINEAR MECH, vol. 35, pp. 95–102, Jan. 2000, doi: 10.1016/S0020-7462(98)00090-0.