Design Optimization of Vibration Energy Harvesting Microstructures

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The development of sustainable energy harvesting technology is critical to reduce environmentally destructive practices. The miniaturization of such technology could provide distributed power to the increasing number of portable electronic devices, medical implants, and autonomous sensors. One possible source for small-scale sustainable power is vibration energy harvesting microstructures. Readily available energy sources include traffic, electronic motors, and the human heartbeat, which are all primarily sub-100 Hz. However, current silicon-based harvesters are too large to integrate into portable electronic devices and too rigid to efficiently exploit low frequency environmental vibrations. As an alternative, polymer-based harvesters are more flexible, leading to lower resonant frequencies. Additionally, because polymer microstructures can be fabricated with 3D printing technology, there are wide possibilities for design, which particularly lends itself to topology optimization.

In this work, a set of design optimization techniques is exploited to evolve a polymer-based vibration energy harvester microstructure, and we investigate strategies for applying topology optimization to resonator design. Previously, an intuitive design consisting of polymer helical spring structures was demonstrated with a 65 Hz resonant frequency [1], but a lower resonant frequency is desirable for many applications. Building upon the helical spring concept, we achieve a significant reduction in the first natural frequency by performing a parametric optimization on the geometry of the springs while constraining the maximum shear stress. Taking advantage of the material manufacturing process, we then expand the design space to include curing time, a critical variable in polymer fabrication. To validate the material model and improve the optimization parameters, we develop an iterative optimization-fabrication-testing cycle that allows rapid exploration of material properties and concurrent material and structural design. This design-in-the-loop methodology is particularly applicable to small, 3D printed structures that can be manufactured quickly and inexpensively.

Secondly, we investigate strategies to employ topology optimization techniques to the design of resonators. Although topology optimization is well suited to developing novel structures, it has limitations for certain classes of problems. Specifically, when stress is not considered, maximizing a resonator displacement or minimizing the first natural frequency leads to unsuitable, degenerate structures [2]. Local stress constraints are also a challenge for topology optimization techniques. We examine methods for obtaining manufacturable results from a 2D SIMP-based approach to the above design problem, without applying local stress constraints. We succeed by setting the objective to be the ratio between dynamic displacement at the target frequency and compliance for a similar static load case. This modification prevents the degeneration of the structure, at the cost of some increased stiffness. The 2D topology optimization strategy can be extended to 3D for greater improvements.

[1] Baker, E. et al. Microstereolithography of Three-Dimensional Polymeric Springs for Vibration Energy Harvesting. Smart Materials Research, 2012. ID 741835, 9 pgs.
[2] Tcherniak, D. Topology optimization of resonating structures using SIMP method. Int. J. Numer. Meth. Engng., 2002. 54(11): 1605–1622.