Metamaterial-enhanced Elastic Wave Energy Harvesting Concepts

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We explore dramatic enhancement of structure-borne wave energy harvesting through wave focusing by tailoring refraction and reflection properties of elastic plates. The two particular approaches of interest for wave focusing in this work are the use of elastic wave lens and elastic wave mirror designs. In the first lens scenario, we discuss our computational and experimental results on the focusing of plane waves by means of a Gradient-Index Phononic Crystal Lens (GRIN-PCL) design for enhanced piezoelectric energy harvesting. The proposed lens consists of a 3D printed layer bonded to an aluminum plate host structure. The 3D printed layer contains an array of nylon stubs with different heights. The orientation and height of the stubs are determined according to the hyperbolic secant gradient distribution of refractive index for the lowest asymmetric mode Lamb waves in the aluminum plate. Under plane wave excitation from a line source, experimentally measured wave field successfully validates the numerical simulation of wave focusing. Energy harvesting performance enhancement associated with the 3D printed GRIN-PCL is evaluated by comparing the piezoelectric energy harvester integrated with the lens at its focus to the baseline case of energy harvesting without the lens on the uniform plate counterpart. While the GRIN-PCL is an extremely effective design for elastic wave focusing, its performance is very sensitive and susceptible to orientation of the incident plane wave. The second lens concept we explore, the so-called Luneburg lens, aims to alleviate the directivity issue due to its omnidirectional focusing characteristics. The proposed lens is formed by radially distributed blind holes with different diameters resulting in the Luneburg refractive index distribution. The numerical simulation of wave focusing is validated by experimentally measured wave fields under plane wave excitation. Furthermore, omnidirectionality is verified by testing the lens under plane wave excitation from different directions. With piezoelectric energy harvesters located at the boundary of the Luneburg lens, substantially larger power output can be obtained as compared to the baseline harvester. Finally, we present a detailed investigation of structurally-embedded mirror (SEM) design, analysis, and experimental validation for enhanced elastic wave energy harvesting. The SEM configuration proposed in this effort is enabled by inserting metallic beads (e.g. tungsten, lead, steel) into blind holes that form the mirror geometry in the flat aluminum plate domain. Specifically, the relationship between SEM geometry and wavelength is unveiled in order to minimize the energy in the side lobes near the focus. The frequency dependence of the reflection coefficient of embedded spherical inclusions is also investigated to understand the limitations of the approach due to local resonances of the inclusions. The basic concepts demonstrated through finite-element simulations of the elastic wave field are validated experimentally over a range of frequencies. Dramatic enhancement of the harvested power (by an order of magnitude) is also demonstrated using an elliptical SEM made from spherical tungsten inclusions in an aluminum plate.