Spider web-inspired acoustic metamaterials

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(Received 17 June 2016; accepted 5 August 2016; published online 19 August 2016)

Spider silk is a remarkable example of bio-material with superior mechanical characteristics. Its multilevel structural organization of dragline and viscid silk leads to unusual and tunable properties, extensively studied from a quasi-static point of view. In this study, inspired by the Nephila spider orb web architecture, we propose a design for mechanical metamaterials based on its periodic repetition. We demonstrate that spider-web metamaterial structure plays an important role in the dynamic response and wave attenuation mechanisms. The capability of the resulting structure to inhibit elastic wave propagation in sub-wavelength frequency ranges is assessed, and parametric studies are performed to derive optimal configurations and constituent mechanical properties. The results show promise for the design of innovative lightweight structures for tunable vibration damping and impact protection, or the protection of large scale infrastructure such as suspended bridges. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4961307]

Many natural materials display outstanding properties that can be attributed to their complex structural design, developed in the course of millions of years of evolution.[1–3] Particularly fascinating are spider silks, which exhibit unrivalled strength and toughness when compared to most materials.[4–7] Previous studies have revealed that mechanical performance of spider webs is not only due to the remarkable properties of the silk material, but also to an optimized architecture that is adapted to different functions.[8,9]

Structural behaviour of orb spider webs has been extensively analyzed under quasi-static[6,8,10] and dynamic[11,12] loading conditions. However, the spider-web structure has yet to be exploited for the design of phononic structures. These are usually periodic composites capable of inhibiting the propagation of elastic waves in specific frequency ranges called band gaps. This unique ability opens a wide range of application opportunities, such as seismic wave insulation,[13] noise reduction,[14] sub-wavelength imaging and focusing,[15] phonon transport,[16] strain-dependent thermal conductivity,[17] acoustic cloaking,[18] and thermal control.[19] In phononic structures, band gaps are induced by either Bragg scattering from periodic inhomogeneities[20] or by local resonances.[21] The latter are commonly achieved by employing heavy constituents.[21–24] Recently, it has been found that hierarchically organized continuous[25] or lattice-type[26,27] structures exhibit band gaps due to the two mentioned mechanisms. From this perspective, a spider web-inspired, lattice-based elastic metamaterial seems to be another promising alternative to simultaneously control wave propagation at multi-scale frequencies. In this letter, we design a metamaterial inspired by the Nephila orb web architecture and analyze the dynamics of elastic waves propagating therein, with the aim of obtaining improved structures compared to simple lattices.[28]

We consider a spider web-inspired metamaterial in the form of an infinite in-plane lattice modeled by periodically repeating representative unit cells in a square array. The primary structure of the unit cell is a square frame with supporting radial ligaments (Fig. 1(a)). The ligaments intersect the frame at right-angle junctions acting as "hinge" joints (square junctions in Fig. 1(a)). The secondary frame is defined by a set of equidistant circular ligaments (or ring resonators) attached to the radial ligaments by hinge joints, in the following called "connectors" to distinguish them from the joints in the first frame (Fig. 1(b)). The geometry of the metamaterial is completely defined by 5 parameters: unit cell pitch a, size of square joints b, thickness of radial and circular ligaments c, number of ring resonators N, and radius of a ring resonator R_N. We initially consider $a = 1\text{m}$, $b = 0.04 \cdot a$, $c = 0.01 \cdot a$, $N = 7$, and $R_N = 0.1 \cdot a \cdot (N + 1)/2$. The material properties

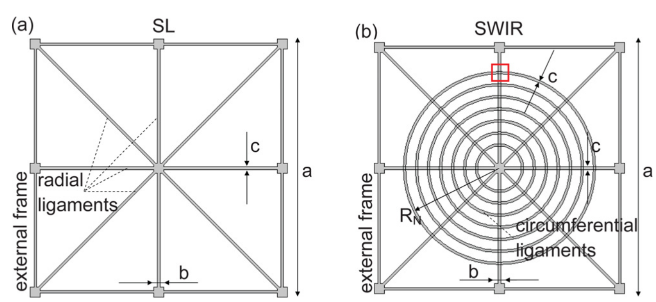

FIG. 1. (a) Bearing frame and (b) spider web-inspired unit cells for lattice-type metamaterials.

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