Metamaterials-based sensor to detect and locate nonlinear elastic sources

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In recent years, acoustic metamaterials have attracted increasing scientific interest for very diverse technological applications ranging from sound abatement to ultrasonic imaging, mainly due to their ability to act as band-stop filters. At the same time, the concept of chaotic cavities has been recently proposed as an efficient tool to enhance the quality of nonlinear signal analysis, particularly in the ultrasonic/acoustic case. The goal of the present paper is to merge the two concepts in order to propose a metamaterial-based device that can be used as a natural and selective linear filter for the detection of signals resulting from the propagation of elastic waves in nonlinear materials, e.g., in the presence of damage, and as a detector for the damage itself in time reversal experiments. Numerical simulations demonstrate the feasibility of the approach and the potential of the device in providing improved signal-to-noise ratios and enhanced focusing on the defect locations. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4934493]

Acoustic metamaterials (AMMs) are artificially structured composite materials that enable manipulation of the dispersive properties of vibrational waves. Generally, they are periodic distributions of cavities or inclusions (scatterers) embedded in a matrix.[1] Among their unique vibrational characteristics, the attractive property of such structures to act as stop-band filters can be exploited to attenuate mechanical waves over entire frequency bands, commonly known as band gaps (BGs). As a consequence, appropriate configurations of the metamaterial structure allow focusing of energy in selected frequency ranges.[2]

These two main properties make the AMMs potentially interesting for applications in nonlinear acoustics and structural health monitoring.[3,4] A mechanical wave that travels through a damaged structure generally interacts with interfaces, crack tips, delaminations, etc., acquiring and conveying information about the specimen integrity or type of damage. Nonlinear phenomena emerging from these interactions are by far the most interesting features, both from the theoretical and the applicative point of view.[5–8] In the presence of large stress or strain values, the linear approximation in the stress-strain relation (Hooke's law) is no longer valid due to the anomalous local dynamics of material portions (typically defects).[9] This gives rise to a spectral modification in the output response, generating multiple harmonics of the input solicitation frequency, nonlinear attenuation effects, and changes in the wave velocity or in the resonance frequency. The nonlinear techniques that have been developed for damage detection are in general designated as Nonlinear Elastic Wave Spectroscopy (NEWS).[10–12]

One important application of the NEWS techniques is damage locating through nonlinear Time Reversal (TR) experiments.[13–15] The TR procedure consists of re-injecting a time-reversed signal into the sample: due to the invariance of the equation of motion under a time inversion ($t \rightarrow -t$), the re-injected wave back-propagates through the medium retracing the incoming multiple scattering paths and ultimately refocuses at the original source location. The basic idea of nonlinear TR is that the defects, by scattering incident elastic waves, act as active sources of higher order harmonics. It is then possible to filter the recorded signal and time-reverse only the part of the signal generated by the defect.

Despite the considerable interest attracted by the NEWS and nonlinear TR techniques and the resulting advances in recent years,[16,17] several aspects remain to be addressed. Since the information is carried by higher order harmonics and their spectral weight is very low compared to that of the fundamental (at most of the order of a few percent), an increase of the signal to noise ratio is of primary importance[18–20] and it is necessary to amplify signals due to the nonlinear effects that are often submerged below the noise level.[21]

In this work, we propose to integrate standard piezoelectric sensors with the AMM-based structures, exploiting their capability of naturally filtering out or reflecting incident mechanical waves in the prescribed frequency ranges, thus enhancing the efficiency in sensing higher harmonics and focusing on the nonlinear TR. The advantages with respect to traditional digital (post-processing) filtering performed with standard piezoelectric sensors are discussed and an application to NEWS-TR is presented.

An example of such a meta-device is shown schematically in Fig. 1(a). The device includes a chaotic cavity,[22,23]

