Proof of concept for an ultrasensitive meta-device to detect and localize nonlinear elastic sources

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(Dated: January 3, 2017)

In recent years, elastic metamaterials have attracted great attention due to their unconventional dynamic behaviour, with effects such as negative refraction, frequency band gaps, wave filtering/focusing, acoustic cloaking, subwavelength sensing, etc. Their periodic structure, rather than single material constituents, is responsible for their behaviour, which exploits Bragg scattering or the presence of localized resonances. The attractive property of metamaterials is their capability to manipulate elastic waves. The scattered signal is recorded, applies it to a defect acting as a source of nonlinear elastic waves and can be detected only using cumbersome digital signal processing techniques. Here, we propose and experimentally validate an alternative approach, using the filtering and focusing properties of elastic metamaterials to naturally select the higher harmonics generated by nonlinear effects and to increase their signal-to-noise ratios, enabling the realization of time-reversal procedures for nonlinear elastic source detection. The proposed device demonstrates its potential as an efficient, compact, portable, passive apparatus for nonlinear elastic wave sensing and damage detection.

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consists of a 1D array of 8 cross-like cavities cut in a narrow rectangular waveguide and MM2 of a C-shaped array of smaller unit cells. The cavities are fabricated using waterjet cutting, with different lattice parameters, depending on the filtering (Fig.1b) or reflecting (Fig.1c) function they are designed for. Specifically, the lattice parameters are \( L_1 = 8 \) mm, \( L_2 = 0.8 \cdot L_1 \), \( L_3 = 2R = 0.4 \cdot L_1 \) for the MM1 region and \( l_1 = 4 \) mm, \( l_2 = 0.8 \cdot l_1 \), \( l_3 = 2r = 0.4 \cdot l_1 \) for the MM2 region, respectively. A cross-like geometry is chosen because it allows large Band Gap (BG) nucleation.

In order to investigate the BG structure of the MM1 region, its transmission spectrum is first investigated in a pitch-catch experiment \(^{39}\) according to the schematic representation of Fig. 1h (see \(^{41}\) for details). An ultrasonic pulse with a frequency content between 50 and 450 kHz is launched by a transducer attached to the top surface of the plate (point E in Fig.1h) and received at points A and B by means of 5 mm-diameter piezoelectric disk sensors. Fig.2a shows the Fast Fourier Transform (FFT) of the input signal in E (green line) and those recorded in A and B (blue and red lines, respectively). A large BG appears between 172 kHz and 244 kHz, highlighted by a considerable frequency drop at the corresponding frequencies (up to 100 dB). Two smaller BGs are visible around 285 kHz and 380 kHz. On the contrary, the spectral content of the signal recorded in the plate (blue line in Fig.2a), which is not subject to any filtering, shows the same frequency content as the excitation. These results are confirmed by numerically computed dispersion diagrams using Bloch-Floquet theory \(^{12}\) in full 3D FEM simulations, shown in Fig.2b. Here, the band structures are shown in terms of the reduced wave vector \( k^* = \left[ k_x \cdot L_1 / \pi; k_y \cdot L_3 / \pi \right] \) varying along the first irreducible Brillouin zone boundary \( \Gamma - X \). Three BGs are predicted (highlighted in grey) in the considered frequency range, in excellent agreement with experimental results, thus validating the numerical approach.

Further information of the dynamical properties of the MM1 region is provided by injecting a short pulse at point E and using a Scanning Laser Doppler Vibrometer (SLDV) to measure the out-of-plane component of the velocity at the surface of the plate along the dotted path highlighted in Fig. 1h (details are provided in \(^{41}\)). Results for the space/time evolution of the measured amplitudes are shown in Figure 3a. Due to the antisymmetric excitation, mainly antisymmetric A0 Lamb waves are generated. However, Fig.3b also clearly shows the presence of the reflected symmetric S0 mode (i.e. the faster waves visible in the \( t = 40 \mu s \) region). Strong reflections of the incident waves are clearly visible at a distance \( d = 50 \) mm from the source (corresponding to the first cavity in the MM1 waveguide) due to the impedance mismatch. Weaker reflected waves traveling through MM1 are also present at each cavity (white areas in the figure). Finally, the time vs. space representation shows a slight variation of the slope for the modes crossing the MM1 region, corresponding to a gradual decrease of the wave speed with the distance travelled in the MM1 for the different modes.

The signals detected at various positions along the path are processed by applying a two-dimensional Fourier transform (2D FFT) and determining the energy values for each processed point. This enables to obtain a frequency-wavenumber representation (Fig. 3b). Data is shown for the \( d1 \) acquisition region of the plate (i.e. from \( d = 0 \) up to the first cavity), with negative and positive values of the wavenumber \( k_x \), providing information about reflected and incident waves, respectively. This representation clearly identifies the energy distribution among the excited modes. The energy maxima of the reflected waves (left panel) occur near the predicted BG frequency range, i.e. around 200 kHz and 380 kHz, associated with the incident antisymmetric fundamental mode A0 (right.
FIG. 3. (a) Out-of-plane displacement as a function of time \( t \) and position \( d \) along the dotted line in Fig. 1a. White areas correspond to the cavities of the MM1 region. \( (t1, t2, t3, t4) \) are the time intervals used for signal processing of Fig. 3b. (b) Frequency \( f \) vs. wavenumber \( k \) representation of the measured signals. Theoretical dispersion curves (in white) are superimposed.

The role of the MM1 region is thus to act as a natural filter for the frequencies contained in the 172 - 244 kHz range. The excitation of a nonlinear material with a monochromatic wave of frequency contained in the BG of MM1 (e.g. 200 kHz) produces higher harmonics in the plate, which are able to cross the MM1 barrier and to enter the circular “chaotic cavity” [40]. Due to its ergodic properties and negligible absorption, the latter is widely used in TR experiments to generate multiple reflections and a reverberant acoustic field, making a single transducer sufficient for signal acquisition [40, 43, 44]. The additional C-shaped metamaterial structure is designed to reflect the higher harmonics of the signal falling within a BG and to concentrate them in the geometric centre of the mirror, thus enhancing their signal-to-noise ratio. Analysis of SLDV-measured signals filtered at the frequencies of interest shows that there is good energy concentration at the centre of the mirror structure compared to peripheral regions in the chaotic cavity [41].

Additional FEM transmission simulations using the ABAQUS software are performed. The incoming wave is the superposition of two quasi-monochromatic waves centred around \( f_1 = 200 \) kHz and \( f_2 = 400 \) kHz, respectively, with an imposed out-of-plane displacement of \( 1 \times 10^{-6} \) mm at point E. Two models are compared: one comprising both the filtering and the focusing regions and another consisting of only the filtering region (i.e. with a homogeneous aluminium chaotic cavity).

Figs. 4a and 4b provide snapshots of the Von Mises stress maps at \( t = 16 \cdot 10^{-5} \) s for the two configurations. In the case of a chaotic cavity with the C-shape metastructure, the formation of stationary waves occurs between the vertical portion of the mirror and the beginning of the waveguide. This allows the energy corresponding to the second harmonic (i.e. the signature of the nonlinearity) to be enhanced.

The possibility of combining both the filtering and focusing functionalities of the meta-device for NEWS-TR is now demonstrated. As discussed, the MM1 region provides a natural and selective filter that is transparent only to the higher harmonics generated by the nonlinear source and does not require any post-processing proce-
measurements are performed on a spatial grid covering the signal detected by PZT 2 (blue signal in Fig. 5a) is moved in the back propagation experiment) consisting of 200 equally spaced grid points. The laser vibrometer is positioned perpendicularly at 50 cm from the surface to record the out-of-plane velocities of the points over the target area. Multiple (128) measurements are performed and averaged for each node, to filter out part of the noise.

After the backward propagation, time compression of the signal and spatial focusing of the wave field are observed at the nonlinear scatterer location. Fig. 5d reports an example of a time re-compressed signal detected with the SLDV. Also, at the focal time, the spatial map of the recorded velocities reveals focusing at the location of the defect, with a considerable concentration of energy, as shown in Fig. 5d. Notice that multiple scattering due to backward propagation of the wavefield through the metamaterial region increases the efficiency of TR and provides a high degree of focusing. Wavefield focalization on the nonlinear scatterer position occurs for amplitude ratios as small as 3% between the generated nonlinear signal and the input.

In conclusion, we have presented combined experimental and numerical results to demonstrate the feasibility of a novel passive sensor for signals generated by nonlinear elastic scatterers, such as cracks or delaminations. To do this, we have exploited the advanced frequency filtering and spatial focusing properties of elastic metamaterial structures, and proved the applicability of the sensor to time reversal experiments that allow to determine the spatial location of damage. The chosen metamaterial configurations, providing wide band gaps in the desired frequency ranges, were first characterized experimentally in pitch-catch experiments, demonstrating good agreement with numerical predictions based on FEM simulations. The dispersion properties of the metamaterial were also verified through scanning laser doppler vibrometer measurements. The same full-field non-contact technique was further adopted to confirm numerical predictions for wave filtering of the fundamental frequency by the first metamaterial region of the device. Higher harmonics were then generated by introducing a nonlinear source and focusing of the first harmonic in a chaotic cavity was demonstrated by means of a mirror-like meta-

$$Y(t) = Y_1 = A_1 \sin(2\pi f_1 t) \ast H(t_0)$$

where $A_1$ is the amplitude of the sine function and $H(t_0)$ is the Hanning window centered in $t_0$ with a width corresponding to 21 cycles of the sine wave of the fundamental frequency, $f_1$. The time and frequency domain representations of the signal received by PZT 2 are shown in Figs. 5b and 5a, respectively. In the case without the nonlinear scatterer, only noise is recorded inside the cavity (red line), whereas, in the presence of the artificial nonlinearity, a resonance peak appears (blue line) localized around the first harmonic of the fundamental frequency, (i.e. $f_2 = 2f_1 = 400$ kHz).

The NEWS-TR experiment is thus performed as follows: PZT 1 transducer emits a signal $Y = Y_1$ (Eq. 1); the signal detected by PZT 2 (blue signal in Fig. 5b) is time reversed and transmitted back in the sample; SLDV measurements are performed on a spatial grid covering a $30 \times 30 \text{mm}^2$ region around the nonlinear source (removed in the back propagation experiment) consisting of $200 \times 200$ equally spaced grid points. The laser vibrometer is positioned perpendicularly at 50 cm from the surface to record the out-of-plane velocities of the points over the target area. Multiple (128) measurements are performed and averaged for each node, to filter out part of the noise.

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terial structure, confirming the possibility of extracting the signal above the noise level with no need for digital signal filtering. Finally, a time reversal experiment was carried out, showing good refocusing in time and space onto the nonlinear source, demonstrating the feasibility of the proposed meta-device for damage localization in structures.

In future, we aim to improve the design of this metamaterial-based sensor addressing issues such as optimized filter or focusing mirror designs, exploitation of multiple band gaps or frequency tunability using piezoelectric patches, and its effective application to external tested structures with reduced signal losses. Nevertheless, the results presented in this paper already provide the proof of concept for an efficient, portable, damage sensor with applications for passive continuous structural health and acoustic emission monitoring e.g. in civil engineering and the aerospace industry.

Acknowledgments
M.M. has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement N. 658483. A.K. has received funding from the European Union’s Seventh Framework programme for research and innovation under the Marie Sklodowska-Curie grant agreement N. 609402-2020 researchers: Train to Move (T2M). N.M.P. is supported by the European Research Council (ERC StG Ideas 2011 BIHSNAM no. 279985 on ”Bio-inspired hierarchical supernanomaterials” and ERC PoC 2015 SILKENE No. 693670), and by the European Commission under the Graphene FET Flagship (WP14 ”Polymer Nanocomposites” No. 604391). FB is supported by BIHSNAM.

[1] B. Morvan, A. Tinel, A.-C. Hladky-Hennion, J. Vasseur, and B. Dubus, Applied Physics Letters 96, 101905 (2010).
[2] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, Physical Review Letters 71, 2022 (1993).
[3] R. Martinez-Sala, J. Sancho, J. V. Sanchez, V. Gomez, J. Linares, and F. Meseguer, Nature 375, 241 (1995).
[4] S. Yang, J. H. Page, Z. Liu, M. L. Cowan, C. T. Chan, and P. Sheng, Physical Review Letters 93, 024301 (2004).
[5] M. Brun, S. Guenneau, A. B. Movchan, and D. Bigoni, Journal of the Mechanics and Physics of Solids 58, 1212 (2010).
[6] A. S. Gliozzi, M. Miniaci, F. Bosia, N. M. Pugno, and M. Scalerandi, Applied Physics Letters 107, 161902 (2015).
[7] S. Zhang, C. Xia, and N. Fang, Physical Review Letters 106, 024301 (2011).
[8] D. I. Souma, R. Fleury, and A. Alù, Physical Review Applied 4, 014005 (2015).
[9] W. Kan, V. M. García-Chocano, F. Cervera, B. Liang, X.-y. Zou, L.-l. Yin, J. Cheng, and J. Sánchez-Dehesa, Physical Review Applied 3, 064019 (2015).
[10] S. Zhang, Y. Zhang, Y. Guo, Y. Leng, W. Feng, and W. Cao, Physical Review Applied 5, 034006 (2016).
[11] X. Zhu, B. Liang, W. Kan, Y. Peng, and J. Cheng, Physical Review Applied 5, 054015 (2016).
[12] P. Deymier, Acoustic Metamaterials and Phononic Crystals, Springer Series in Solid-State Sciences (Springer Berlin Heidelberg, 2013).
[13] Y. Pennec, J. O. Vasseur, B. Djafari-Rouhani, L. Dobrzynski, and P. A. Deymier, Surface Science Reports 65, 229 (2010).
[14] R. Craster and S. Guenneau, Acoustic Metamaterials: Negative Refraction, Imaging, Lensing and Cloaking, Springer Series in Materials Science (Springer London, Limited, 2012).
[15] A. Krushynska, V. Kouznetsova, and M. Geers, Journal of the Mechanics and Physics of Solids 71, 179 (2014).
[16] M. Carrara, M. Cacan, J. Toussaint, M. Leamy, M. Ruzzene, and A. Erturk, Smart Materials and Structures 22, 065004 (2013).
[17] K.-A. Van Den Abeele, P. A. Johnson, and A. Sutin, Research in nondestructive evaluation 12, 17 (2000).
[18] V. Y. Zaitsev, V. E. Gusev, V. Tournat, and P. Richard, Physical Review Letters 112, 108302 (2014).
[19] C. Payan, V. Garnier, and J. Moysan, Journal of Acoustical Society of America 121, EL125 (2007).
[20] I. Solodov, J. Wackerl, and K. P. et al., Applied Physics Letters 84, 5386 (2004).
[21] Y. Ohara, T. Mihara, T. Sasaki, T. Ogata, S. Yamamoto, Y. Kishimoto, and K. Yamanaka, Applied Physics Letters 90, 011902 (2007).
[22] G. Renaud, S. Call, and M. Defontaine, Applied Physics Letters 94, 011905 (2009).
[23] P. Finkel, A. G. Zhou, S. Basu, O. Yeheskel, and M. W. Barsoum, Applied Physics Letters 94, 241904 (2009).
[24] C. Trarieux, S. Callé, H. Moreschi, G. Renaud, and M. Defontaine, Applied Physics Letters 105, 264103 (2014).
[25] M. Scalerandi, A. S. Gliozzi, M. A. Ouarabi, and F. Boubenider, Applied Physics Letters 108, 214103 (2016).
[26] J. Chen, J. Kim, K. Kurtis, and L. Jacobs, Journal of Acoustical Society of America 130, 2728 (2011).
[27] M. Scalerandi, A. Gliozzi, C. L. E. Bruno, D. Masera, and P. Bocca, Applied Physics Letters 92, 101912 (2008).
[28] M. Scalerandi, M. Griffa, P. Antonaci, M. Wyrzykowski, and P. Lura, Journal of Applied Physics 112, 054312 (2013).
[29] M. A. Ouarabi, F. Boubenider, A. S. Gliozzi, and M. Scalerandi, Physical Review B 94, 134103 (2016).
[30] N. Krohn, K. Pfleiderer, R. Stoessel, I. Solodov, and G. Busse, Acoustical Imaging 27, 91 (2004).
[31] Z. Ficek and P. D. Drummond, Physics Today 50, 34 (1997).
[32] T. Ulrich, P. A. Johnson, and A. M. Sutin, Journal of Acoustical Society of America 119, 1514 (2006).
[33] A. S. Gliozzi, M. Griffa, and M. Scalerandi, Journal of Acoustical Society of America 120, 2506 (2006).
[34] T. Ulrich, A. Sutin, R. Guyer, and P. Johnson, International Journal of Non-Linear Mechanics 43, 209 (2008).
[35] C. Prada, E. Kerbrat, D. Cassereau, and M. Fink, Inverse Problems 18, 1761 (2002).
[36] T. Goursolle, S. D. Santos, O. B. Matar, and S. Callé, International Journal of Non-Linear Mechanics 43, 170 (2008), 11th International Workshop on Nonlinear Elasticity in Materials.
[37] T. Ulrich, P. A. Johnson, and R. Guyer, Physical Review Letters 98, 104301 (2007).
[38] G. Zumpano and M. Meo, International Journal of Solids and Structures 44, 3666 (2007).
[39] M. Miniaci, A. Marzani, N. Testoni, and L. De Marchi, Ultrasonics 56, 251 (2015).
[40] O. Bou Matar, Y. F. Li, and K. Van Den Abeele, Applied Physics Letters 95 (2009).
[41] See Supplemental Material.
[42] M. Collet, M. Ouisse, M. Ruzzene, and M. Ichchou, International Journal of Solids and Structures 48, 2837 (2011).
[43] M. Draeger, Carsten; Fink, Physical Review Letters 79 (1997).
[44] A. M. Sutin, J. A. TenCate, and P. A. Johnson, The Journal of the Acoustical Society of America 116, 2779 (2004).
[45] I. Solodov, D. Döring, and G. Busse, J. Mech. Eng. 57, 169 (2011).
[46] C. Pecorari and M. Poznic, Proceedings of The Royal Society A 462, 769 (2006).