PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Enhanced identifiability of nonlinear ultrasonic superharmonics for crack detection using an aluminum-lead composite bandgap meta-surface

Tian, Yiran, Shen, Yanfeng, Rao, Danyu, Xu, Wu

Yiran Tian, Yanfeng Shen, Danyu Rao, Wu Xu, "Enhanced identifiability of nonlinear ultrasonic superharmonics for crack detection using an aluminum-lead composite bandgap meta-surface," Proc. SPIE 10972, Health Monitoring of Structural and Biological Systems XIII, 109721Y (1 April 2019); doi: 10.1117/12.2514040

Event: SPIE Smart Structures + Nondestructive Evaluation, 2019, Denver, Colorado, United States

Enhanced identifiability of nonlinear ultrasonic superharmonics for crack detection using an aluminum-lead composite bandgap meta-surface

Yiran Tian [a], Yanfeng Shen *[a], Danyu Rao[b], Wu Xu[b]
[a] University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, 200240; [b] School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, 200240, China

ABSTRACT

In this paper, a bandgap meta-surface is carefully designed for enhancing the identifiability of nonlinear ultrasonic superharmonics for fatigue crack detection. In the unit cell design stage, modal analysis with Bloch-Floquet boundary condition is performed to obtain the dispersion features of guided waves in the meta-surface. Then, a finite element model (FEM) for a chain of unit cells is simulated to verify the bandgap effect. In practice, due to the inherent nonlinearity from the electronic instrument and bonding adhesive, the corresponding weak superharmonic components will adversely affect the identifiability of the nonlinear characteristics raised by wave crack interactions. In the current approach, the guided waves generated by the transmitter propagate into the structure, carrying the inherent nonlinearity with them. Immediately afterwards, they pass through the meta-surface with optimized transmission of the fundamental excitation frequency and complete mechanical filtration of the second harmonic component. In this way, the appearance and amplitude of the second harmonic in the sensing signal become evidently indicative of the presence and severity of the fatigue crack along the wave path between the meta-surface and the receiver. The proposed method possesses great potential in future SHM and NDE applications. Nonlinear ultrasonic experiments with the designed meta-surface are conducted to verify the theoretical and numerical investigations as well as to demonstrate the practical application of metamaterial in SHM and NDE. The paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: nonlinear ultrasonics, higher harmonic, metamaterial, structural health monitoring, nondestructive evaluation, fatigue crack, damage detection, guided waves

1. INTRODUCTION

In recent years, elastic metamaterials (EMMs) are drawing increasing attention among the structural health monitoring (SHM) and nondestructive evaluation (NDE) communities due to their capability of wave and vibration manipulation. Based on local resonance mechanism, the wave propagation can be manipulated at a subwavelength scale. Many novel EMMs designs have been investigated since the first localized resonant (LR) sonic structure was realized by Liu et al[1]. The designed EMMs can achieve some unique properties, such as bandgap[2-6], negative density[7, 8], negative modulus[9, 10], and so on. Wu et al.[11] demonstrated the existence of complete bandgaps in a plate with periodic stubbed surface. They analyzed the dispersion relation between Lamb waves and the stubbed surface to understand the effect of the heights of stubs on the band structure. Zhu et al.[12] designed a single-phase elastic hyperbolic metamaterial with anisotropic mass density to manipulate the wave propagation at a deep subwavelength scale base on LR mechanism. They also applied shunted piezoelectric elements to achieve the effective mass density in a broad frequency. Hsu et al.[13] studied the propagation of Lamb waves in two-dimensional lattices composed of soft rubber embedded in an epoxy host. They achieved complete bandgaps in relatively low frequency ranges. And they proved the resonant frequencies of flexural modes depend on both the radius of the rubber cylinders and the thickness of the composite plate. Oudich et al.[14] investigated the acoustic properties of a two-layer composite structure bounded on a thin homogeneous plate. They obtained extremely low frequency bandgaps based on LR mechanism and illustrated that the width of such bandgap strongly depends on the height and cross section area of the stubs.

*yanfeng.shen@sjtu.edu.cn; phone +86-21-34206765 Ext. 5021; fax +86-21-34206525;

Health Monitoring of Structural and Biological Systems XIII, edited by Paul Fromme, Zhongqing Su, Proc. of SPIE Vol. 10972, 109721Y · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2514040

On the other hand, guided waves have proved themselves a powerful tool for damage detection. The nonlinear ultrasonic technique has been investigated to be sensitive to detect incipient changes in structures because of the distinctive features such as higher harmonics and subharmonics[15, 16]. Shen et al.[17-19] conducted a research on the predictive modeling of nonlinear wave propagation for structural health monitoring with piezoelectric wafer active sensors. They put forward a Damage Index (DI) based on the amplitude ratio of the signal spectral harmonics to correlate the signal nonlinearity with damage severity. However, in practice, the identifiability of the contact acoustic nonlinearity (CAN) from the wave crack interaction is always adversely influenced by the inherent nonlinear sources in engineering practice. These sources can be categorized into two classes: (a) inherent nonlinearity of the electronic equipment and (b) material nonlinearity (the hysteretic behavior of the adhesive between sensors and the aluminum plate). Thus, the nonlinear characteristics will always be present in the sensing signal even for the pristine structures. To improve the accuracy of the diagnosis, the influence from the inherent nonlinear sources should be minimized.

This research investigates the design and application of a bandgap meta-surface to eliminate the inherent second harmonic for the purpose of improving the accuracy and reliability of nonlinear ultrasonic SHM and NDE for fatigue crack detection. After the introduction, the unit cell structure of the meta-surface will be presented, followed by the demonstration of its bandgap phenomenon. Finally, the nonlinear ultrasonic experiments with the designed meta-surface will be presented to verify the capability of the meta-surface nonlinear SHM system for fatigue crack detection and quantification.

2. DESIGN OF META-SURFACE UNIT CELLS

This section presents the design and performance analysis of the ultrasonic bandgap meta-surface for the mechanical filtration of the second higher harmonic component in the interrogating wave field.

2.1 Dispersion curve of the meta-surface structure

The standard finite element codes were utilized for computation of dispersion relations in materials with periodic microstructure through the methodology put forward by Aberg et al.[20]. The periodicity here means that the material is comprised of many finite-sized unit cells arranged in a regular pattern. By applying Bloch-Floquet constraints on the boundaries and corners of the unit cell, the dispersion relation representing the frequency-wavenumber domain can be calculated. Based on LR mechanism, when the excitation frequency approaches to the natural frequency of the resonators, the guided wave under this frequency cannot propagate through the structure, i.e., the corresponding frequency will not appear in the dispersion curve and bandgaps will develop.

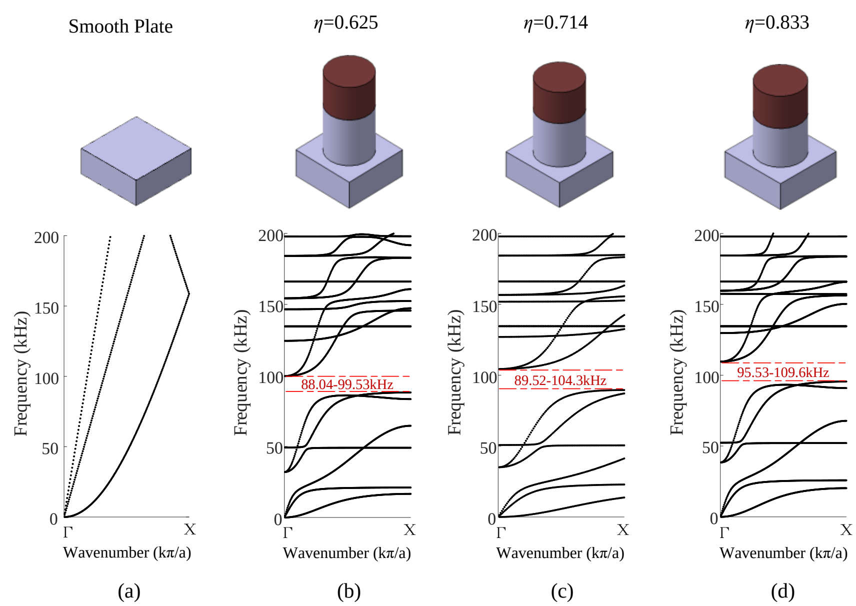


Figure 1. Unit cells with different aluminum and lead cylinder height ratios and the corresponding dispersion curves: (a) a smooth plate without stub; (b) meta-surface with a 0.625 height ratio; (c) meta-surface with a 0.714 height ratio; (d) meta-surface with a 0.833 height ratio.

By adjusting the height ratio between the aluminum and lead cylinders, the bandgaps over desired frequency ranges can be opened up. The height of aluminum cylinder (bottom part) is L and the height of the lead cylinder (top part) is l. The radius r of the stub is 1.75 mm and the lattice constant a of the unit cell is 5 mm. The total height of the stub is set to be 5.5 mm. The dispersion curves of the unit cells with different height ratios ($\eta = l / L$) are presented in Figure 1. From Figure 1a, it can be seen that there is no bandgap in the dispersion curve of a homogeneous host plate. By comparing the results shown in Figure 1b-d, as the height ratio increases, the bandgap shifts to a higher range gradually. Considering this research, the second harmonic component (100 kHz) needs to be filtered away; the designed unit cell in Figure 1d shows desirable bandgap coverage over the target frequency range. In this case, the height of aluminum cylinder L is 3 mm and the height of lead cylinder l is 2.5 mm, i.e., the height ratio is 0.833, a desired wide bandgap ranging from 95.53-109.6 kHz was achieved and it can be used to filter away the second superharmonic component.

2.2 Spectral response of the meta-surface

Harmonic analysis of a chain of unit cells was implemented to acquire the spectral response of the designed meta-surface and confirm the bandgap effect on eliminating the inherent nonlinearity. A chain model containing an array of 10×1 unit cells (Figure 1d) was constructed in ANSYS 15.0 package. Figure 2 shows the model layouts of the aluminum host plate and the meta-surface structure. A 50-N external force sweeping from 0 to 200 kHz was excited on the left side 20-mm away from the meta-surface unit cells. Two non-reflective boundaries (NRB) were added on both ends of each chain model to absorb the wave reflections[21].

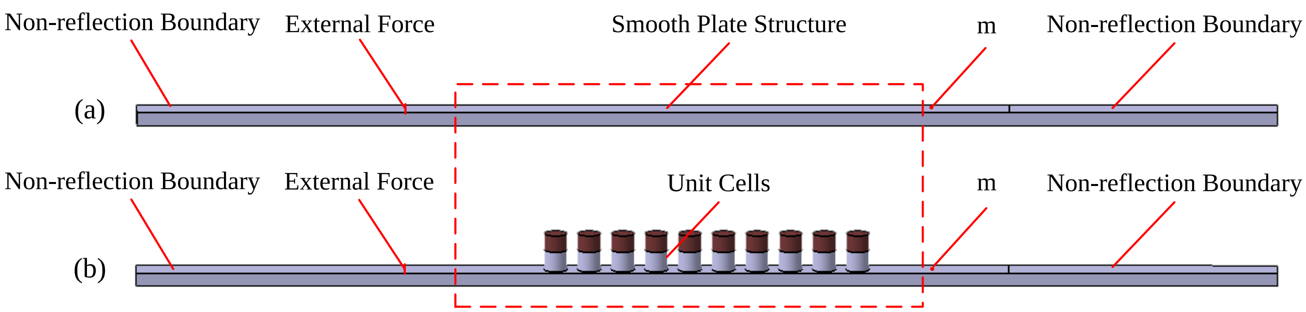


Figure 2. The model layouts: (a) a simple plate strip; (b) the meta-surface structure with an array of 10×1 unit cells.

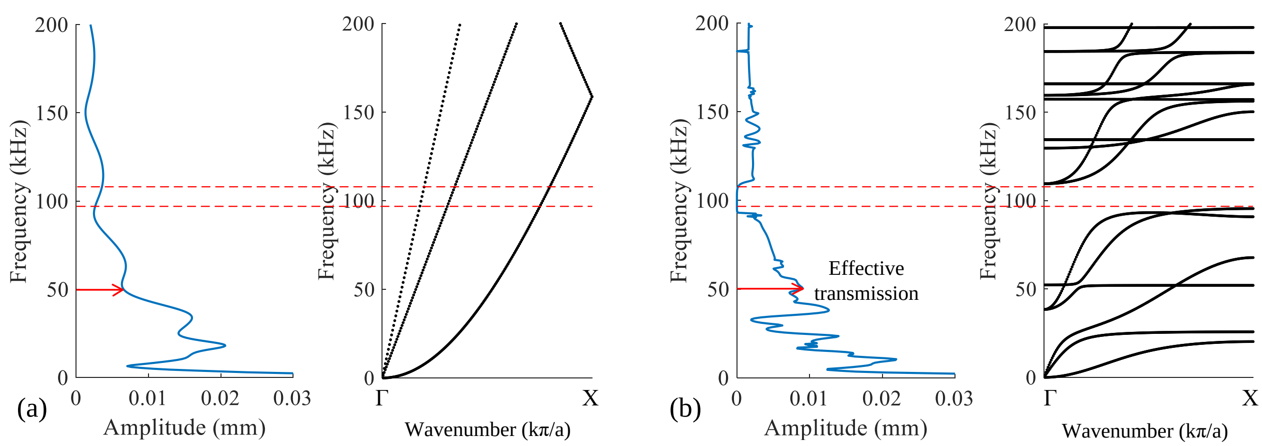


Figure 3. The results comparison between spectral response and band structure dispersion curve: (a) the smooth plate case; (b) meta-surface case. (Note the bandgap and effective transmission behaviors in the meta-surface).

Figure 3 shows the comparison between the in-plane displacement spectral responses and dispersion curves of the two structures. The results agree well with each other. It is can be concluded that for the meta-surface structure when the excitation frequency range is within the bandgap, the amplitude of the in-plane motion reaches the minimum amplitude, however, this phenomenon cannot be seen in the smooth plate case. It is worth mentioning that the improved nonlinear ultrasonic technique should not only require the elimination of the inherent second higher harmonic, but also maintain the effective transmission of the fundamental frequency. From Figure 3b, it is can be observed that the designed meta-surface structure has the capability of rendering the large response amplitude of the fundamental frequency around 50 kHz.

3. EXPERIMENTAL DEMONSTRATION

In order to validate the numerical results and demonstrate the prowess of our approach, nonlinear ultrasonic experiments with the designed meta-surface were carried out on a fatigue specimen. This section presents our major experimental findings.

3.1 Experimental Setup

A 2-mm thick aluminum plate with a 4-mm diameter rivet hole was manufactured to prepare for the pitch-catch active sensing tests. Before the implementation of the meta-surface, the plate was tested to demonstrate the existence of inherent nonlinearity from the electronic device and the bonding layer. Thereafter, the meta-surface with an array of 10 ×5 unit cells was implemented on the plate. Active sensing experiments on the specimen would validate the filtering efficacy of the designed meta-surface. Subsequently, fatigue loading was applied on the specimen to nucleate and grow fatigue cracks from the rivet hole. After the filtration, the guided waves without the inherent second harmonic would continue to interact with the fatigue crack of a growing size along with the fatigue procedure. A rectangular 5-mm×25-mm piezoelectric wafer active sensor (PWAS) was bounded on the plate to generate ultrasonic waves, and a 7-mm diameter circular PWAS was bounded on the other side to receive the signals. Damping clay was implemented surrounding the active sensing region to absorb the boundary reflections.

Figure 4 presents the experimental setup for the fatigue experiment as well as the nonlinear ultrasonic active sensing tests. The fatigue experiment was carried on the MTS Machine. When the loading cycle reached respective 10000 (initial crack generation), 14219 (1 mm crack length), 20777 (2 mm crack length), 26760 (3 mm crack length), and 30886 (4 mm crack length), the fatigue test was temporarily suspended. The nonlinear ultrasonic active sensing tests were carried out to measure the magnitude of the second higher harmonic in the sensing signals. When conducting the nonlinear ultrasonic active sensing tests, a Keysight 33500B function generator was utilized to generate the excitation waveform of a 60-count Hanning window modulated tone burst signal. After amplified by a Krohn-hite 7602M wideband power amplifier, the signal approaching to 100 vpp was applied on the transmitter PWAS. The sensing waveforms were collected by the Keysight DSO-X 3014T digital storage oscilloscope.

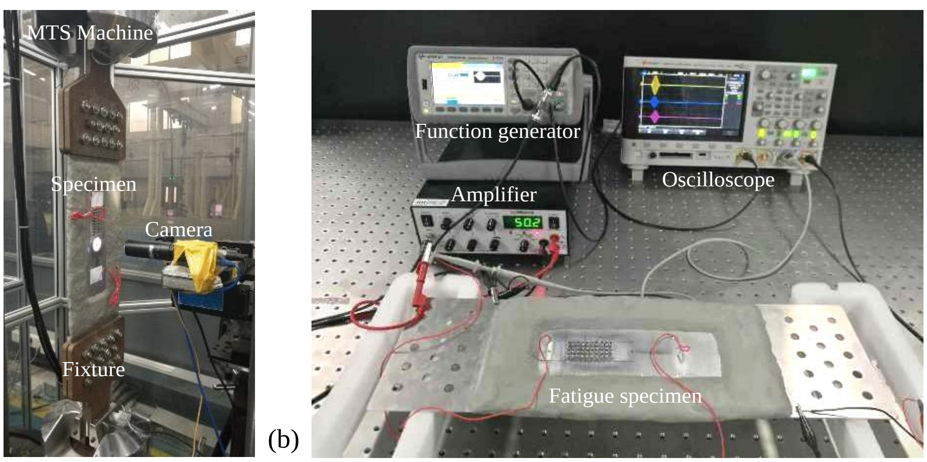
(a) (b)


Figure 4. (a) Experimental setup for the fatigue experiment; (b) Experimental setup for the nonlinear ultrasonic tests.

3.2 Enhanced nonlinear ultrasonics

Figure 5 shows the time traces and frequency spectra of the sensing signals for the pristine plate before and after the implementation of the meta-surface. Figure 5b demonstrates that even for a pristine case without any fatigue damage, obvious higher harmonics appeared in the sensing signal due to the inherent nonlinearities. Thus, the conventional nonlinear ultrasonic technique based on the measurement of higher harmonic generation may face great challenge for fatigue crack identification and quantification. On the other hand, Figure 5d shows that, after the implementation of the meta-surface, the second higher harmonic component was completely eliminated from the sensing signal. This comparative study illustrates the promising high sensitivity and outstanding reliability of our improved nonlinear ultrasonic technique enabled by the meta-surface. After such a filtration procedure, the guided waves would interact with the possible fatigue crack and attain the CAN without mixing up with the irrelevant inherent nonlinear noises.

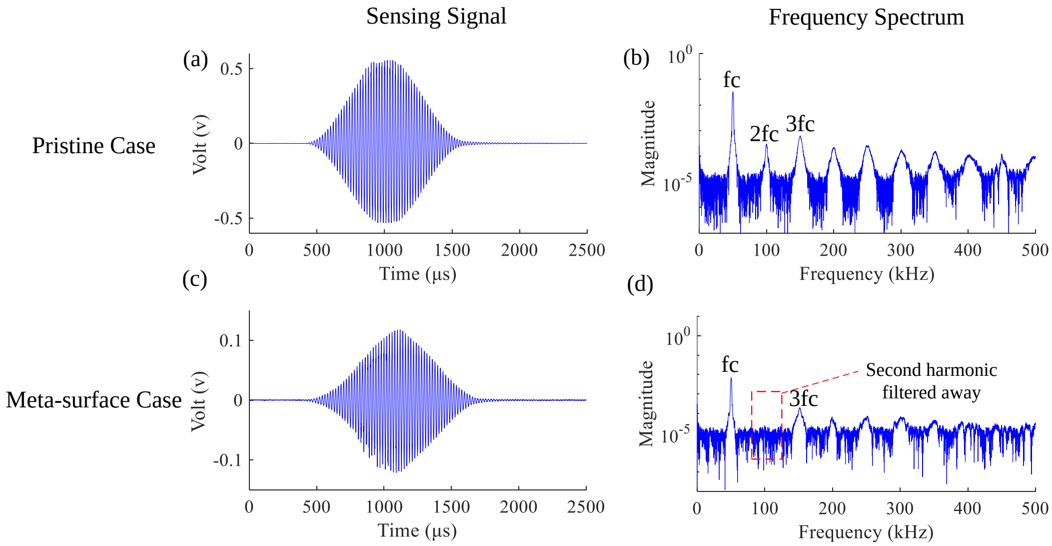


Figure 5. Experimental sensing signals of the pristine plate before and after the implementation of the meta-surface: (a) time trace of the sensing signal before the implementation; (b) frequency spectrum of the sensing signal before the implementation; (c) time trace of the sensing signal after the implementation; (d) frequency spectrum of the sensing signal after the implementation.

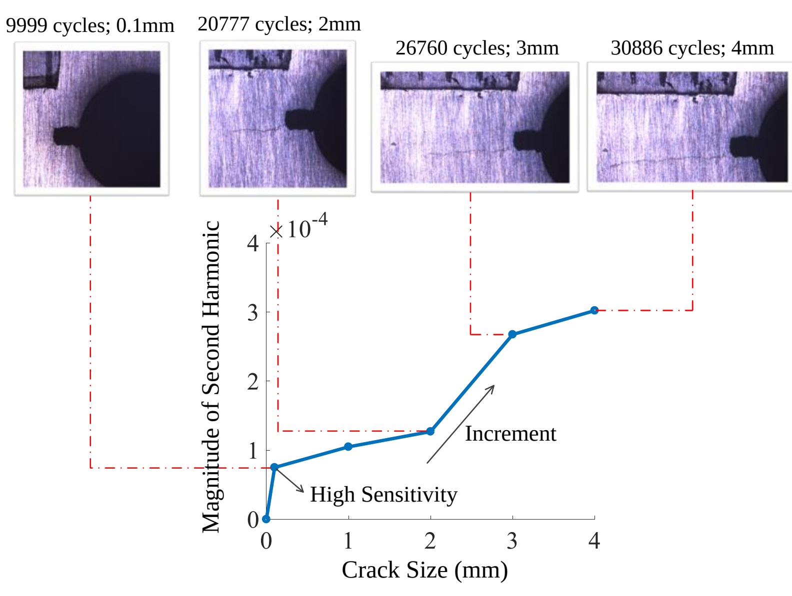


Figure 6. Fatigue crack snapshots and second harmonic amplitudes for different damage severities.

The magnitude of the second higher harmonic versus crack size is plotted in Figure 6. It can be observed that the amplitude started with an approximate zero value (after subtracting the noise base), indicating a pristine structure. Then, the amplitude grew monotonically with the increasing fatigue crack size. The results demonstrate an outstanding sensitivity and reliability of the improved damage detection strategy, with a clear threshold behavior for crack nucleation alarming and a nice monotonic trend for crack growth monitoring[22].

4. CONCLUDING REMARKS AND FUTURE WORK

This paper presents an improved nonlinear ultrasonic technique by combining the capability of the meta-surface for wave control. The designed meta-surface can open up desired bandgaps for filtering out the second higher harmonic component introduced by the inherent nonlinearities from the electronic instruments and the adhesive layer. Harmonic analysis was then investigated to verify the spectral bandgap effect.

Both the numerical and experimental results demonstrated that the inherent second higher harmonic could be eliminated by the meta-surface. Such a phenomenon facilitated the improved identifiability of CAN from wave crack interactions. In the damaged cases, the second higher harmonics appeared again after guided waves interacted with the cracks. It was found that the magnitude of the nonlinear second harmonic increased monotonically with the growth of the crack. The proposed method processes great potential in future SHM and NDE applications.

For future work, adaptive and tunable meta-surface structures should be explored for flexible bandgap establishment. Other wave control capabilities of the meta-surface should be investigated for improved SHM and NDE applications.

5. ACKNOWLEDGEMENTS

The support from the National Natural Science Foundation of China (contract number 51605284) is thankfully acknowledged.

REFERENCES

[1] Liu, Z. Y., Zhang, X. X. and Mao, Y. W., "Locally resonant sonic materials," Science 289(5485), 1734-1736 (2000).
[2] Li, Y., Zhu, L. and Chen, T., "Plate-type elastic metamaterials for low-frequency broadband elastic wave attenuation," Ultrasonics 73, 34-42 (2017).
[3] Qureshi, A., Li, B. and Tan, K. T., "Numerical investigation of band gaps in 3D printed cantilever-in-mass metamaterials," Sci Rep 6(28314), (2016).
[4] Sui, N., Yan, X., Huang, T. Y., Xu, J., Yuan, F. G. and Jing, Y., "A lightweight yet sound-proof honeycomb acoustic metamaterial," Applied Physics Letters 106(17), (2015).
[5] Zhu, R., Huang, G. L., Huang, H. H. and Sun, C. T., "Experimental and numerical study of guided wave propagation in a thin metamaterial plate," Physics Letters A 375(30-31), 2863-2867(2011).
[6] Tian Y. and Shen Y., "Improved nonlinear ultrasonic guided wave damage detection using a bandgap meta-surface," ASME International Mechanical Engineering Congress and Exposition, V009T12A006 (2018).
[7] Lee, S. H., Park, C. M., Seo, Y. M., Wang, Z. G. and Kim, C. K., "Acoustic metamaterial with negative density," Physics Letters A 373(48), 4464-4469(2009).
[8] Zhu, R., Liu, X. N., Huang, G. L., Huang, H. H. and Sun, C. T., "Microstructural design and experimental validation of elastic metamaterial plates with anisotropic mass density," Physical Review B 86(14), (2012).
[9] Fang, N., Xi, D. J., Xu, J. Y., Ambati, M., Srituravanich, W., Sun, C. and Zhang, X., "Ultrasonic metamaterials with negative modulus," Nat Mater 5(6), 452-456(2006).
[10] Zhu, R., Liu, X. N., Hu, G. K., Sun, C. T. and Huang G. L., "Negative refraction of elastic waves at the deep-subwavelength scale in a single-phase metamaterial," Nat Commun 5(5510), (2014).
[11] Wu, T. T., Huang, Z. G. and Tsai, T. C., "Evidence of complete band gap and resonances in a plate with periodic stubbed surface," Applied Physics Letters 93(111902), (2008).
[12] Zhu, R., Chen, Y. Y., Wang, Y. S., Hu, G. K. and Huang, G. L., "A single-phase elastic hyperbolic metamaterial with anisotropic mass density," J Acoust Soc Am 139(6), (2016).
[13] Hsu, J. C. and Wu, T. T., "Lamb waves in binary locally resonant phononic plates with two-dimensional lattices," Applied Physics Letters 90(201904), (2007).
[14] Oudich, M., Li, Y. and Assouar, M. B., "A sonic band gap based on the locally resonant phononic plates with stubs," New Journal of Physics 12(083049), (2010).
[15] Jhang, K. Y., "Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review," International Journal of Materials 10(1), 123-135 (2009).

[16] Kruse, W. and Zagrai, A., "Investigation of linear and nonlinear electromechanical impedance techniques for detection of fatigue damage in aerospace materials," 7th international workshop on structural health monitoring, Stanford, CA, 9-11 September.
[17] Shen, Y. and Giurgiutiu, V., "Predictive modeling of nonlinear wave propagation for structural health monitoring with piezoelectric wafer active sensors," Journal of Intelligent Material Systems and Structures 10, 506-520 (2014).
[18] Shen, Y. and Cesnik, C., "Modeling of nonlinear interactions between guided waves and fatigue cracks using local interaction simulation approach," Ultrasonics 74, 106-123 (2017).
[19] Shen, Y. and Giurgiutiu, V., "Combined analytical FEM approach for efficient simulation of Lamb wave damage detection," Ultrasonics 69, 116-28 (2016).
[20] Aberg, M. and Gudmundson, P., "The usage of standard finite element codes for computation of dispersion relations in materials with periodic microstructure," Acoustical Society of America 102, (1997).
[21] Shen, Y. and Giurgiutiu, V., "Effective non-reflective boundary for Lamb waves: Theory, finite element implementation, and applications," Wave Motion 58, 22-41 (2015).
[22] Shen, Y., Wang, J. Z. and Xu, W., "Nonlinear features of guided wave scattering from rivet hole nucleated fatigue cracks considering the rough contact surface condition," Smart Materials and Structures 27(10), (2018).