Metamaterial-controlled nonlinear ultrasonic guided waves for structural health monitoring

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ABSTRACT

This paper reports the recent research progress of the Active Materials and Intelligent Structures (AMIS) Lab at Shanghai Jiao Tong University in utilizing metamaterials to control guided waves for enhancing the performance of nonlinear ultrasonics based SHM systems. In the first part, an elastic metamaterial is designed as a mechanical filter to eliminate the inherent second harmonic wave component from the interrogative wave field. A stub unit cell was proposed by examining the dispersion curves and the spectral response curves, which achieves high transmission of the inspection wave and band stopping of second harmonic frequency. Numerical and experimental demonstrations were carried out, showcasing the obvious improvement of diagnostic accuracy and reliability of the SHM system for a fatigue crack. The second part presents a rainbow trapping metamaterial system for accumulating the second harmonic component at the sensing location. A graded metamaterial system was designed to create a zero-group velocity mode through a smoothly transitional metamaterial area. Due to the energy accumulation, the originally weak second harmonic component could be amplified, thus greatly enhancing the sensitivity of the SHM system to incipient structural changes. It was found that by controlling the guided wave field, the amplitude of second harmonic waves could reach 8 times of the case without the metasurface. The third part presents utilizing the nonreciprocal transmission property of the crack-metamaterial system for damage detection. A forward stopband and backward transmission wave feature will be shown. It was found that such a nonreciprocal transmission performance can provide sensitive indication for fatigue crack evaluation. These three aspects of work demonstrate that metamaterials possess great potential in controlling guided wave features for improving the performance of SHM systems. The presentation finishes with summary, concluding remarks, and suggestions for future work.

Keywords: elastic metamaterial, guided waves, nonlinear ultrasonics, damage detection, Structural Health Monitoring

1. INTRODUCTION

Ultrasonic guided waves have been widely investigated as a powerful tool for Structural Health Monitoring (SHM)[1]. They can propagate long distances without much energy loss, enabling them to inspect large structural areas from distributed sensing locations[2]. Nonlinear ultrasonic techniques have attracted increasing interest among researchers due to their even higher sensitivity to incipient structural changes, such as small fatigue cracks and material degradations[3-5]. However, considerable challenges exist in their practical applications. First, the inherent nonlinearity from the electronic device is hard to avoid, leaving the nonlinear signature in the sensing signals in a doubtful situation. Second, the nonlinearity generated by wave damage interaction itself is very weak, making the early identification considerably difficult. Therefore, the approach to eliminating the inherent nonlinearity from the interrogative wave field and amplifying the weak nonlinearity in the sensing signal plays a vital role in enhancing the reliability, accuracy, and sensitivity of the nonlinear ultrasonic SHM system.

Elastic metamaterials (EMM) are engineered structural systems that exhibit superior mechanical and dynamic properties beyond the natural materials. Their development over the past decades has shown great performances for manipulating waves and vibrations, which makes them a promising solution for controlling guided waves in SHM applications[6-9]. Pioneer research endeavors have shown that EMM can achieve guided wave focusing, directional emitting, blackhole trapping, special wave path guiding, etc[10-16]. Research on ultrasonic EMM super and hyper lenses also demonstrated their

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potential in improving wave sensing and diagnostic resolution[17-19]. There are many excellent existing results and on-going efforts for incorporating EMM's wave control capability with structural sensing applications[20, 21]. The authors' research group, the Active Materials and Intelligent Structures (AMIS) Lab at Shanghai Jiao Tong University, has also conducted systematic research on utilizing EMM for ultrasonic guided wave control, aiming at enhancing the damage evaluation caliber of SHM systems. These efforts can be casted into two major categories, i.e., the linear regime and the nonlinear regime, associated with linear and nonlinear ultrasonic SHM techniques. The linear ultrasonic guided wave methods benefit much from the control of interrogative wave modes and scanning directions[22]. The authors have put forward an EMM for selective mode wave transmission, which can provide pure S0 or A0 waves for structural inspection in a considerably wide spectral range[23]. Investigations on converting Lamb modes into Shear Horizontal (SH) modes were also conducted, for switching interrogative wave field sensitivity to various crack orientations[24, 25]. Moreover, in order to achieve wide spectral control capability, AMIS Lab has also explored integrating active materials such as Shape Memory Alloys (SMA) and magnetic fluids for the tunable control of guided wave propagation, resulting a direction-switchable emitting radar and a ultrawide range of bandgap shifting[26-29]. In addition to these aforementioned research endeavors on linear ultrasonic SHM methods, the authors' group has also explored utilizing controlled ultrasonics for enhanced performance in nonlinear ultrasonic techniques[30, 31].

This paper aims at comprehensively presenting the recent progress of metamaterial-controlled nonlinear ultrasonic guided waves for SHM from AMIS Lab. It tackles the challenges in nonlinear ultrasonics from three aspects, i.e., the wave generation site, the wave reception terminal, and the special wave-damage-structure interaction phenomena. The concept and roadmap of metamaterials for nonlinear ultrasonic SHM will be delivered. Then, three cases studies will be elaborated: (1) eliminating inherent nonlinearity from interrogative waves; (2) enhancing superharmonic amplitude in sensing signals; (3) establishing nonlinear nonreciprocal transmission behavior. Each case study will focus on the idea of integrating EMM functionality with SHM purpose, as well as the numerical and experimental demonstration of the performance improvements. This research shows that by controlling ultrasonic guided wave transmission, reception, and wave damage interaction, enhanced active sensing capability can be achieved in SHM systems.

2. METAMATERIALS FOR NONLINEAR ULTRASONIC SHM

A guided wave based SHM procedure generally consists of three physical links, i.e., wave generation, wave-damage-structure interactions, and wave reception. Metamaterials can play a significant role in improving the nonlinear ultrasonic diagnostic performance from all three aspects.

Figure 1 presents the fundamental concept and roadmap of utilizing metamaterials for controlling nonlinear ultrasonic guided waves in pitch-catch active sensing. The transmitter generates waves into the structure, carrying both fundamental frequency and inherent nonlinear superharmonic components. On the transmission side, the metamaterials can purify the interrogative wave field by removing the inherent nonlinearity from electronics and bonding agent. Subsequently, the waves will interact with the damage, generating nonlinear superharmonics from contact acoustic nonlinearity at fatigue cracks. At this stage, the involvement of metamaterials can create a nonreciprocal propagation phenomenon, which can assist with damage detections. Then, the nonlinear ultrasonic signal will be picked up by the receiver. On the reception side, the metamaterial can further control the waves, so that the originally weak second harmonic energy can accumulate and undergo further enhancement, elevating the system's sensitivity to probe nonlinear signal components. The following sections will demonstrate each aspect with a case study.

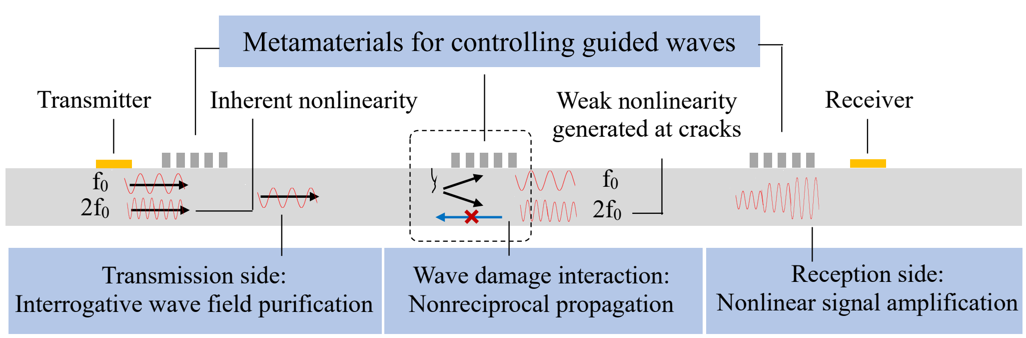

Figure 1: Schematic diagram of Metamaterials for controlling guided waves in nonlinear ultrasonic SHM.

3. TRANSMISSION SIDE: ELIMINATING INHERENT NONLINEARITY FROM INTERROGATIVE WAVES

This section presents the control of ultrasonic guided waves on the transmission side for removing inherent nonlinearity from the interrogative wave field. It has been found that the inherent nonlinearity from electronic equipment and bonding layers of the transmitter is hard to avoid. It will contaminate the interrogative wave field and make the diagnostic evaluation by superharmonics ambiguous and unreliable, because it is hard to tell the source of the nonlinearity. This section will demonstrate that EMM can physically filter away the inherent second harmonic, achieving interrogative wave field purification.

3.1 Bandgap effect for stopping wave propagation

Figure 2 presents the equivalent stress responses of the metamaterial structure at different frequencies (50 kHz, 100 kHz, and 150 kHz). The results demonstrate that the wave motion outside the bandgap can propagate through the metamaterial, while the frequency component within the bandgap will be effectively stopped and filtered away. The spectral response in the middle collum also proves such a stopping-band effect around 100 kHz. Furthermore, if one sets the interrogative waves at 50 kHz, such a EMM not only can achieve second harmonic filtration, it can also ensure a high transmission amplitude for structural interrogation as well. The dispersion curves on the right column also confirms the phenomenon from modal analysis.

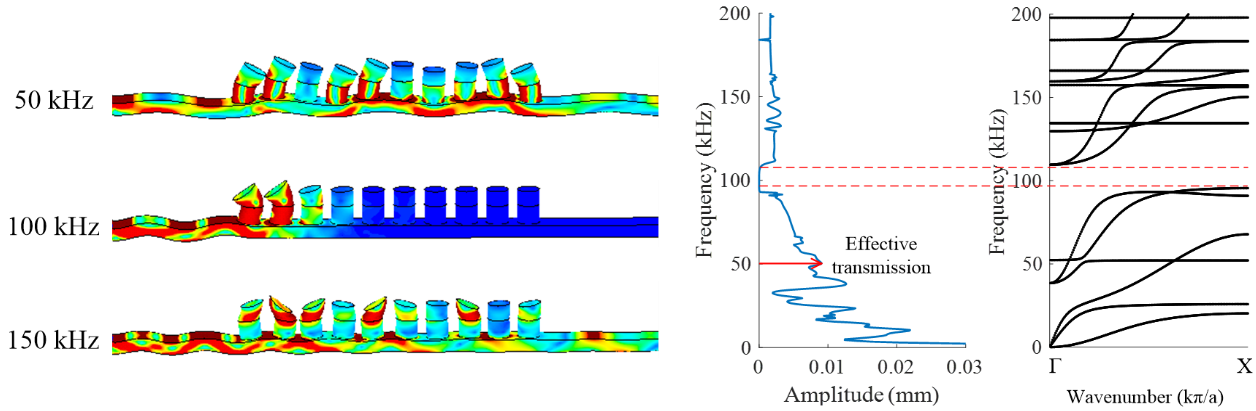

Figure 2: Metasurface for stopping second harmonic and passing fundamental frequency.

3.2 Eliminating second harmonic components

A numerical investigation on pitch-catch active sensing was conducted to demonstrate the interrogative wave field purification results. Figure 3 shows the model schematic. One 5-mm×5-mm×0.2-mm square piezoelectric wafer active sensor (PWAS) was bounded on the left side of the plate 5 mm away from the metamaterial. The crack was located at 65 mm away from the transmitter PWAS (T-PWAS). Another circular 3.5-mm diameter and 0.2-mm thickness receiver PWAS (R-PWAS) was bounded on the right side of the crack at a 12.5-mm distance to pick up the sensing signals. The inherent nonlinearity was induced into the excitation signal, i.e., the transmitter would generate ultrasonic guided waves into the structure, carrying both the fundamental frequency waves (50 kHz) and superharmonic components (100 kHz and 150 kHz) simulating the inherent nonlinear sources. It should be pointed out that only the first three harmonics were included in the simulations, which should be sufficient for demonstrating the main idea. After the waves propagate through the metamaterial, the second harmonic participation at 100 kHz would be diminished. In a further step, the guided waves would interact with the crack, carrying crack information with them, and were finally picked up by the receiver.

Figure 3 a-d present the time traces and the frequency spectra of the excitation and sensing signals. It can be noticed that the inherent higher harmonic components were present in the excitation signals, while in the sensing signal, the second higher harmonic disappeared, which means it was effectively filtered out by the metamaterial. After removement of second harmonic from the interrogative wave field, the purified waves would interact with any potential damage along the rest of the wave path.

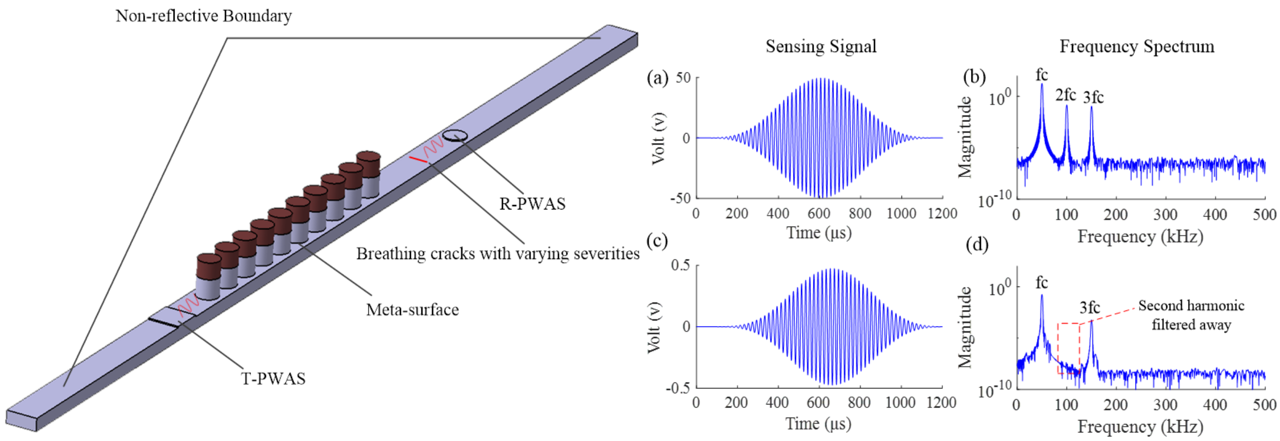

Figure 3: Finite element model for numerical investigation; sensing signals in temporal and spectral domain for cases without metamaterial (a and b) as well as with metamaterial (c and d).

3.3 Improved sensitivity, accuracy, and reliability

Figure 4 demonstrates the pitch-catch active sensing experiment with metamaterials. The fatigue experiment was carried on the MTS Machine. A CCD (ALLIED-GC2450C) industrial camera was used to obtain high-resolution images of the fatigue crack. During the experiment, the maximum loading was set to 100 MPa (average stress); the minimum loading was 6 MPa; the loading frequency was controlled between 3-5 Hz, determined by the crack growth stage. When the loading cycle reached respectively 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 then carried out to measure the magnitude of the second higher harmonic in the ultrasonic signals. For the active sensing experiments, 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 100 vpp was applied on the transmitter PWAS. The sensing waveforms were collected by the Keysight DSO-X 3014T digital storage oscilloscope.

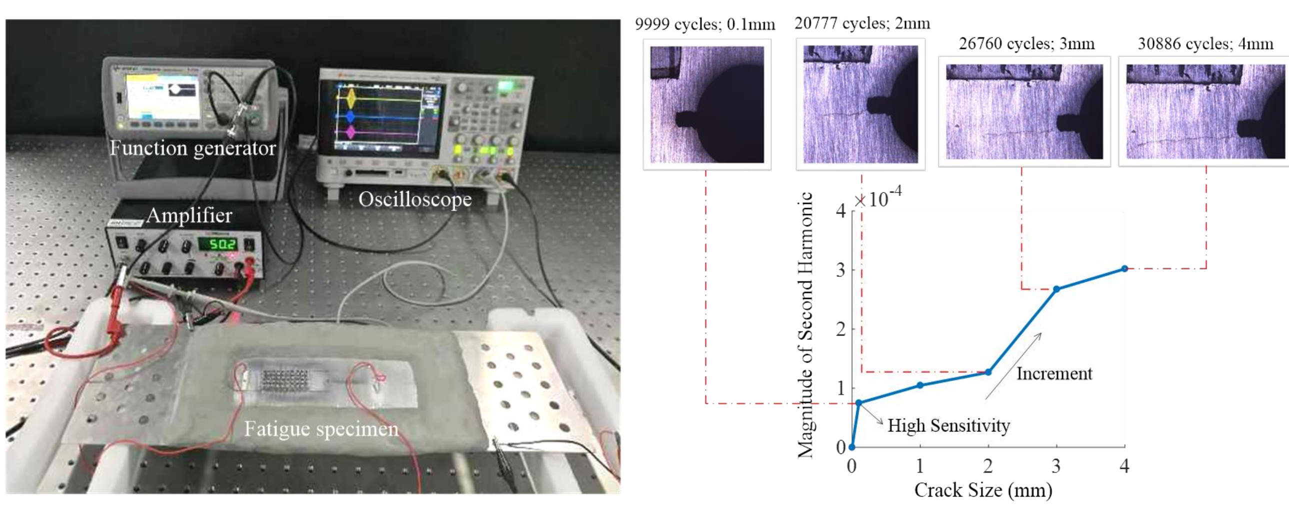

Figure 4: Experiential demonstration of improved performance on fatigue crack evaluation.

The right-hand side of Figure 4 shows the second harmonic amplitude vs. the fatigue cack size. It can be observed that the amplitude started with an approximate zero value (after subtracting the noise base), corresponding to 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.

4. WAVE-DAMAGE INTERACTION: ESTABLISHING NONLINEAR NONRECIPROCAL TRANSMISSION BEHAVIOR

Different from the case study in the previous section, if the metamaterial is placed in the middle of the structure, the wave-damage-metamaterial interactions may introduce new possibility for achieving fatigue crack detection. This section presents the results of active sensing by taking advantage of nonreciprocal propagation behavior of guided waves in the damage-metamaterial system. The forward and backward transmission of guided wave signals will show a one-way transmission phenomenon of wave energy at the second higher harmonic.

4.1 Model setup for nonlinear nonreciprocal wave propagation

Figure 5 presents the numerical model setup for studying the nonreciprocal wave propagation behavior in nonlinear ultrasonics. Two PWAS transducers were mounted on two ends of a plate structure. Metamaterial with a bandgap covering 53 kHz to 73 kHz and a passing band around 116 kHz was implemented in the middle of the plate. Each PWAS transducer could function as the transmitter and the receiver. If the structural is pristine and the transducers excite waves at 58 kHz, then forward and backward transmission should both be prohibited due to the bandgap effect. Nevertheless, if a fatigue crack grew on the lefthand side of the structure, as depicted in Figure 5, then the forward transmission (from left to right) would generate second harmonic components at 116 kHz, which could readily transmit through the metamaterial as a passing band frequency and got picked up the receiver PWAS. On the contrary, for the backward propagation wave (from right to left) the waves would first enter the metamaterial region and would be stopped right away before interacting with the crack. Therefore, very little energy could be received by the PWAS on the left. By comparing the amplitude difference, one could arrive at the diagnostic decision for crack monitoring.

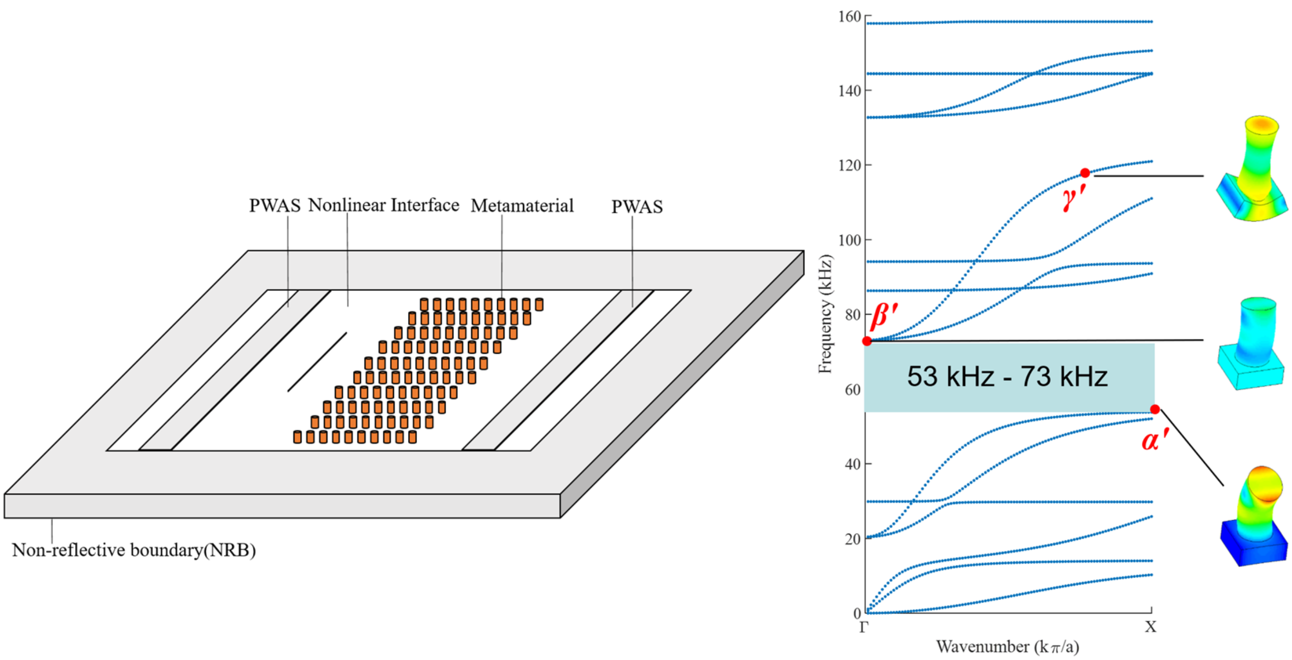

Figure 5: Schematic diagram of wave-damage-metamaterial interaction system for nonreciprocal wave propagation (left); bandgap dispersion curve of the metasurface.

4.2 Numerical results for demonstrating crack detection using the nonreciprocal propagation behavior

Figure 6 showcases the simulation results of forward and backward propagation wave fields. It can be noticed that the waves generated by the PWAS on the left-hand side interacted with the crack, producing higher harmonics with shorter wave lengths. The second harmonic at 116 kHz correspond to the passing mode as shown in the dispersion curve. Thus, obvious transmission of wave energy is observed, showing a wavefield arriving at the PWAS on the right-hand side. By comparison, the waves generated by the right-hand side PWAS directly entered the metamaterial region and was stopped by the unit cells, leaving very little energy passing through. Therefore, the left-hand side PWAS would not receive much wave energy in the backward propagation case.

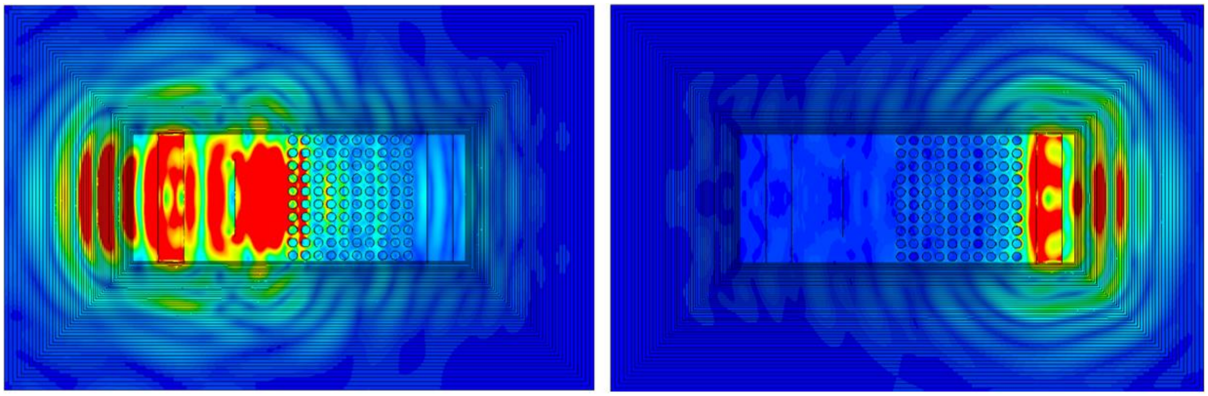

Figure 6: Forward (left) and backward (right) propagation wave field.

Figure 7 illuminates the forward and backward propagation active sensing signals in both temporal and spectral domain. It can be observed that a much higher wave amplitude was received in the forward transmission case, while the backward propagation only presented a much lower amplitude. Another interesting aspect is that the forward wave signal consisted of smaller period wave components. Those are the superharmonics generated by wave crack interactions. On the contrary, the backward wave signal mainly contained the fundamental frequency component. This phenomenon is evident in the spectral representation of the sensing signals, for the forward wave signal mainly focused on the second and third higher harmonic frequencies (116 kHz and 174 kHz), while the backward wave signal showed the major peak at the fundamental frequency (58 kHz). Such a nonlinear nonreciprocal transmission behavior from wave-damage-metamaterial interactions could provide clear insights into damage detection.

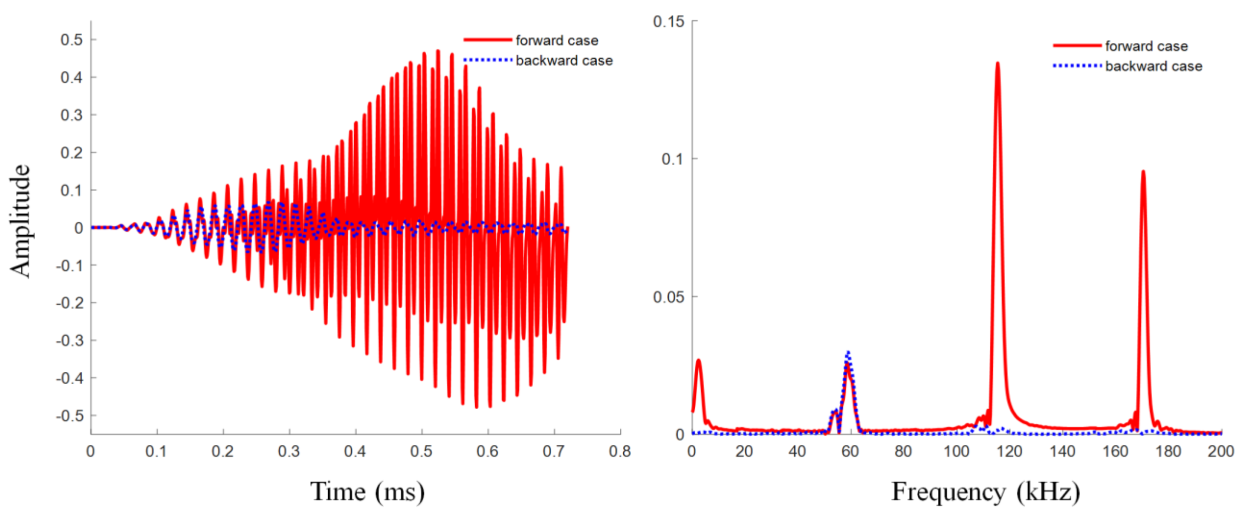

Figure 7: Forward and backward propagation active sensing signals in temporal (left) and spectral (right) domain.

5. RECEPTION SIDE: ENHANCING NONLINEAR SUPERHARMONIC AMPLITUDE IN SENSING SIGNALS

The nonlinear interactions between guided waves and fatigue cracks are weak by their nature, which would also generate weak nonlinear signal components. The second harmonic amplitude is usually two orders of magnitude lower than that of the fundamental wave component. Thus, it is essential to develop a methodology to amplify the originally weak nonlinear signal. By achieving the second harmonic amplification, a much more sensitive SHM system can be obtained.

5.1 Rainbow trapping effect for accumulating wave energy

The rainbow trapping effect has been investigated for its capability of separating and trapping wave energy of various frequencies at distinctive locations along the wave propagation path. This is achieved by a Gradient Metamaterial (GM) design with unit cells gradually changing their dimensions. For instance, Figure 8 shows the dispersion curves for stub units of an increasing height. The slope of the curve represents group velocity of guided waves. For a targeting frequency of 110.9 kHz, it is obvious that with the increment of the stub height, the group velocity of the wave mode gradually decreases, approaching zero, and finally developing a bandgap. If guided waves propagate into a GM system with gradually increasing stub heights, the wave energy at 110.0 kHz will be trapped at the zero-group-velocity (ZGV) location.

Considering the scenario of nonlinear ultrasonics, after wave damage interaction, the guided waves will carry nonlinear superharmonics, but with weak amplitudes. If a GM is set afterwards and the target frequency is designed at the second harmonic, then the second harmonic component will be slowed down and accumulates by the rainbow trapping effect. Therefore, the nonlinear second harmonic signal will be much stronger than the case without GM. If a receiver is placed at the trapping location, the sensitivity of the system can be much enhanced.

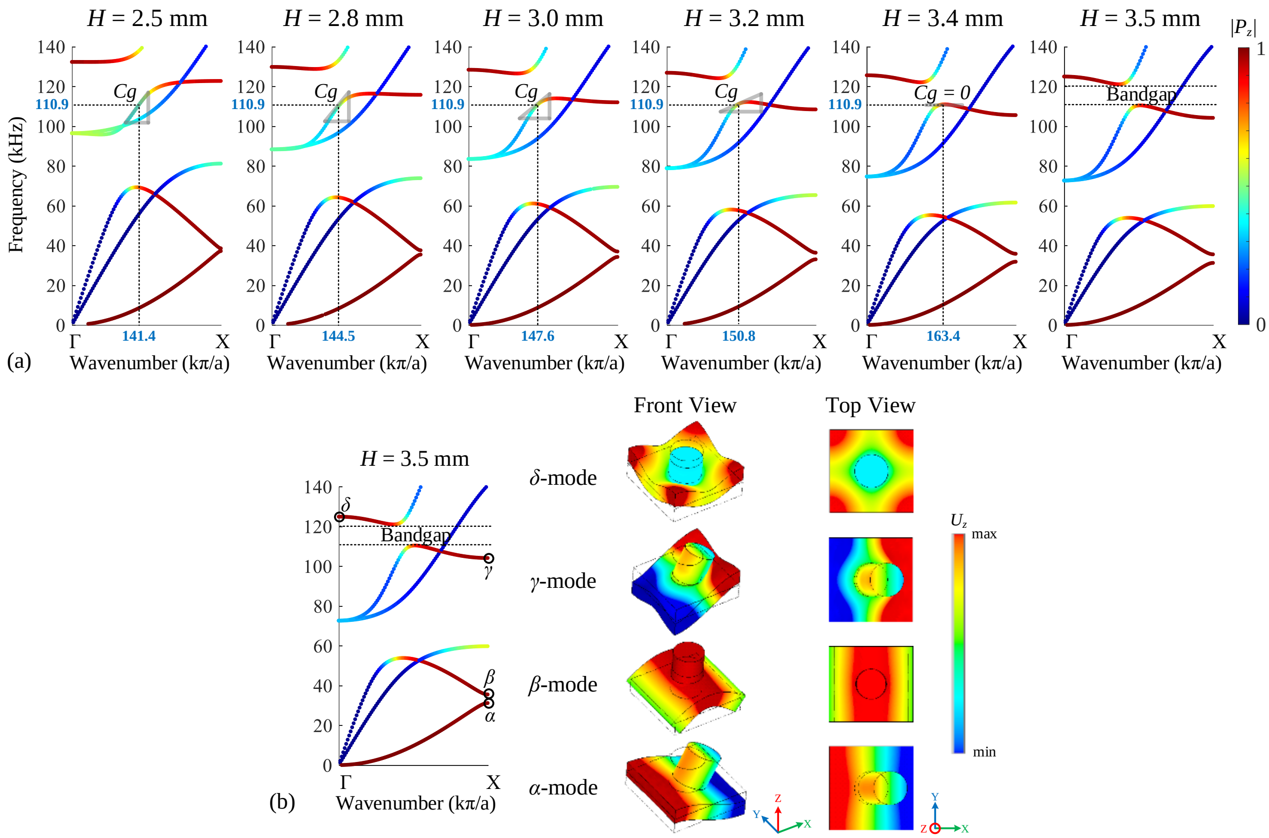

Figure 8: Rainbow trapping effect by slowing down guided waves in the gradient metamaterial units.

5.2 Experiential demonstration of second harmonic enhancement in the sensing signal

In order to demonstrate the performance of the Meta-Enhancer (EM), experimental validation was further conducted for a fatigue rack specimen with gradient metamaterials. An experimental setup utilizing Scanning Laser Doppler Vibrometer (SLDV) is employed, as shown in Figure 9. A Keysight 33500B arbitrary function generator was employed to generate excitation waveforms, further amplified to 75 vpp by a Krohn-hite 7602 M wideband power amplifier. A T-PWAS, measuring 50 mm × 10 mm × 0.5 mm, was adhered to a 2 mm-thick aluminum plate (6061 alloy) with dimensions of 500 mm × 210 mm × 2 mm. To pick up the A0 mode within the wavefield, 1-D SLDV was vertically projected to gauge the out-of-plane wave motion (along the z-axis). The scanning procedure was iteratively repeated, adjusting the laser focal point along the detection lines.

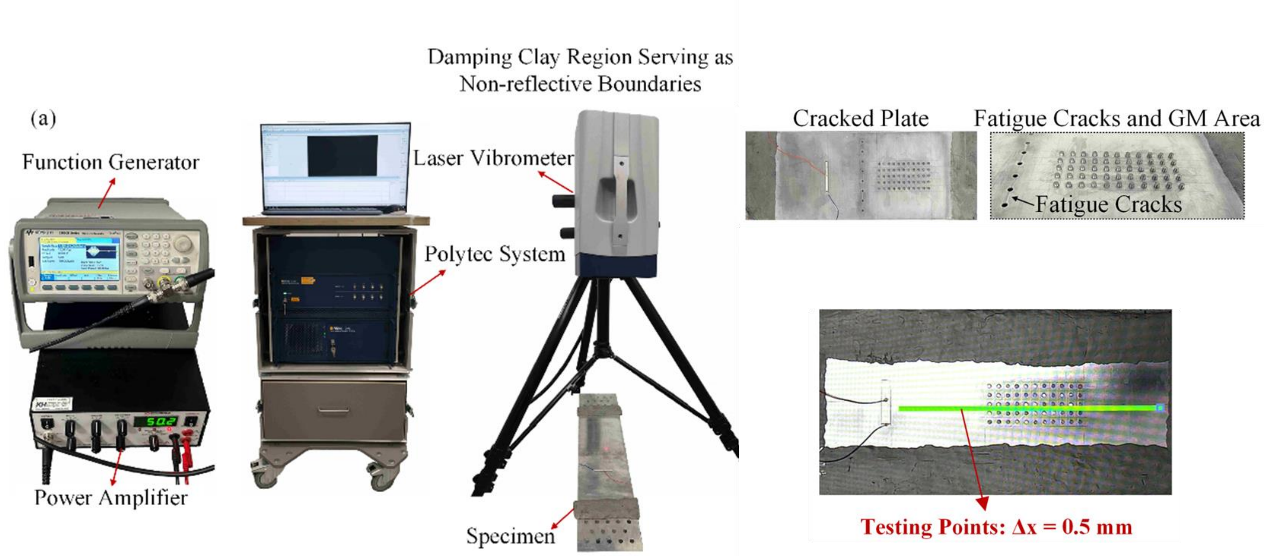

Figure 9: Experimental setup using 1D-SLDV with specimen and zoom-in details of the metamaterial arrays as well as experimental discretization of measurement points.

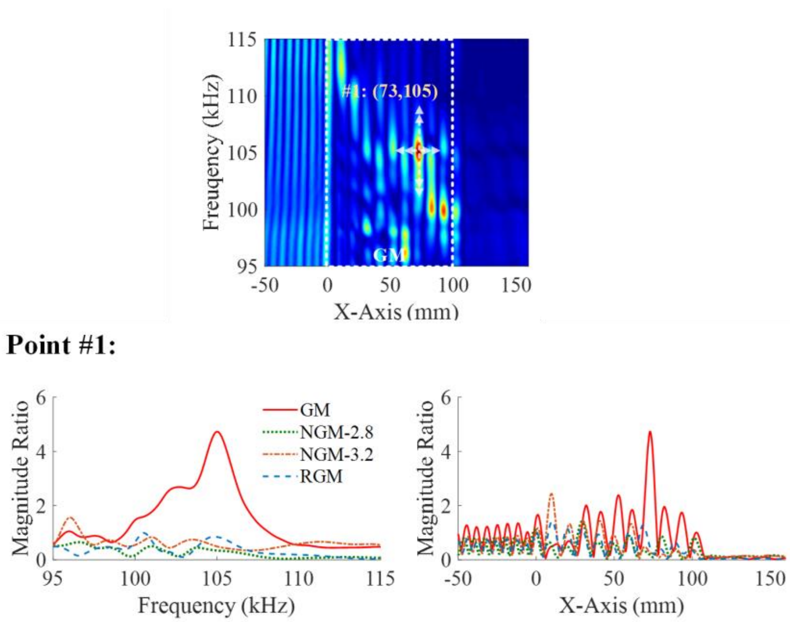

Figure 10: Enhanced sensing capability for second harmonic component: spatial-spectral representation of the sensing signal.

Figure 10 presents the spatial-spectral representation of the sensing signal. It can be observed that obvious energy accumulation happened at 105 kHz at 70 mm along the wave path. The magnitude ratios of various cases were calculated and compared, including GM plate case, non-gradient metamaterial plate with 2.8 mm stub (NGM-2.8) case, NGM-3.2 case, and randomly gradient metamaterial (RGM) case. The magnitude ratio is defined as the ratio between the metamaterial case and the smooth plate case. It should be noted that, in theory, wave accumulation would only happy in the GM case. From the experimental results, this hypothesis was proved. It is obvious that the magnitude ratio of GM case reached as high as 5, which means that the second harmonic picked up that sensing location was enhanced five times more than a smooth plate without the meta-enhancer. The spatial domain distribution of magnitude ratio also demonstrated the wave energy accumulation from rainbow trapping effect. Therefore, by employing the metamaterial, the originally weak second harmonic was enhanced, which considerably proved the sensitivity of the nonlinear ultrasonic SHM system.

6. CONCLUDING REMARKS AND SUGGESTIONS FOR FUTURE WORK

This paper comprehensively presented utilizing metamaterials to control nonlinear ultrasonic guided waves for achieving improved performance of SHM systems. Case studies were demonstrated for metamaterial implementation at wave transmission side, wave damage interaction region, and wave reception side. In the first case study, it was found that EMM can eliminate inherent nonlinearity, rendering a purified interrogative wave field. The damage detection sensitivity and reliability were considerably enhanced. For the second case study, it was also found that the special nonreciprocal propagation phenomenon caused by wave-damage-metamaterial interactions gave new possibilities of detecting fatigue cracks. The forward and backward propagation energy differed much from each other, when fatigue cracks existed. The third case demonstrated a gradient metamaterial formed a rainbow trapping effect, which could accumulate the second harmonic energy at the sensing location. The originally weak nonlinear signal was amplified as much as five times more than the smooth plate case. It was found that such an accumulation phenomenon greatly enhanced the sensitivity of the SHM system.

For future work, more control capability should be explored to combine with guided wave based SHM techniques. Miniaturization of the metamaterial system should be carried out. Integration of EMM with transcoders should be performed to establish meta-transducers for flexible wave control purpose in SHM and NDE.

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