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Exploring and manipulating guided wave features for structural health monitoring

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ABSTRACT

Ultrasonic guided waves have been investigated as a class of powerful tool for Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE). The key towards a highly sensitive structural sensing system resides in whether it can take full advantage of the favorable features of the interrogative wavefield. This paper reports recent research progress in SHM and wave mechanics from Active Materials and Intelligent Structures (AMIS) Lab at Shanghai Jiao Tong University. It addresses two major aspects in this regard: (1) effective and efficient methodology of exploring guided wave characteristics for damage detection and quantification; (2) recent progress on manipulating guided waves for enhanced SHM/NDE performance. In particular, the first aspect presents efficient modeling strategies for understanding linear and nonlinear guided wave signatures, including semi-analytical finite element method, local interaction simulation approach, and small-size regional numerical models. Examples of fatigue crack evaluation will be demonstrated with the extracted guided wave information in both linear and nonlinear regions. The second aspect puts forward the concept of engaging elastic metamaterials for inspection wave field control. It will demonstrate four different wave manipulation case studies: frequency component filtering, selective wave mode transmission, complete mode conversion, as well as tunable wave control with active elastic metamaterials. The paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: guided waves; ultrasonics; wave control; structural health monitoring; nondestructive evaluation; metamaterial

1. INTRODUCTION

1.1 Guided wave based Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE)

Structural Health Monitoring (SHM) strives to establish online, embedded Nondestructive Evaluation (NDE) strategies for assessing the structural health status and functional integrity via advanced sensing technologies [1]. SHM systems enable the detection of structural damage and the estimation of the remaining useful life (RUL) [2]. By doing so, the structural safety and reliability can be ensured, while reducing the maintenance cost by transforming schedule-based maintenance to conditional based maintenance. The SHM principles can be casted into two categories: (a) passive sensing, which records the sensing data during the structural operations, such as stress, strain, acceleration, vibration, and acoustic emission; (b) active sensing, which interrogates the structure using defined excitations, while listening to the response. It is apparent that the active sensing scheme can provide online, real-time, and on-demand evaluation of the structural health status [3].

Guided waves have shown their superb capability in active sensing and damage detection applications. They have been explored as a powerful interrogative tool for SHM and NDE purpose. This is due to several of their preferable features [4]:

(1) The energy of guided waves is confined within the structural surfaces, enabling them to travel a long distance without much energy loss. Thus, large area/long distance inspection is made possible from local transducer instrumentations;

(2) Guided waves are multimodal, possessing complex mode shapes over the entire cross-sectional areas of the host structures. Such a feature allows the inspection of hidden damage sites under the structural surface deep into the solid medium;

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(3) They can propagate through geometric curvatures and mechanical joints. This makes them ideal candidates for the health monitoring of structural connections, adhesive joints, and bolted lap joints;

(4) Guided waves are sensitive to incipient structural changes with a choice of high frequency and short wavelength combination. After interacting with the damage, they would carry the damage information with them, shown as the signal variations in amplitude, frequency, phase, etc.

Capable as they are, guided waves still encounter many challenges in practical SHM/NDE applications. This is mainly attributed to the following aspects [5]:

(1) Guided waves are multimodal and dispersive. A general waveform may contain several packets arriving at various instances with different shapes. This will bring considerable difficulty for sensing signal comprehension and post-processing;

(2) Their interactions with structural damage are complex. Delamination, fatigue cracks, corrosion may impose totally distinctive features in the sensing signals. The frequency component, mode shape, interrogative direction will also influence the active sensing sensitivity.

Thus, it is very important to develop an in-depth understanding of the guided wave features, in order to take full advantage of their favorable aspects and overcome the challenges.

1.2 Key procedures in a guided-wave SHM approach

There are several key procedures in a guided-wave SHM approach: wave generation, propagation, interaction with structural damage, signal processing, and structural health status evaluation. The first step deals with the generation of an effective interrogative wavefield into the host structure. Excitation frequency, mode shape, and amplitude directivity will all contribute to a sensitive probing wave. It relies on the knowledge of transducers to produce the optimum performance. It also counts on the development of novel transducers which usually brings about revolutions in SHM. The second procedure is associated with the structural characteristics, i.e., how a host structure will guide the wave energy through its body. Developing a thorough understanding of wave propagation behavior would cement the solid foundation for comprehending the sensing signals. It usually employs analytical or numerical models to unfold the mechanism behind. The third key element underlines the wave damage interaction phenomena, including, but not limited to scattering, mode conversion, and frequency component modification. An in-depth appreciation of these phenomena will provide guidelines for sensor array design and damage information extraction. The fourth key procedure processes the sensing signals and performs structural diagnostics to address important information on the existence, location, type, and severity of structural damage. This is a progressive interrogation from qualitative evaluation towards quantitative evaluation. The fifth one utilizes the diagnostic results to predict the remaining useful life (RUL) of the host structure, providing suggestions on timely maintenance, repair, and replacement of mechanical parts. Therefore, the development of SHM technology stems from the advancements in the aforementioned five key procedures. It should be noted that they all depend on the comprehension of the wave and structural mechanics behind, which readily highlights the importance of modeling and simulation techniques [6].

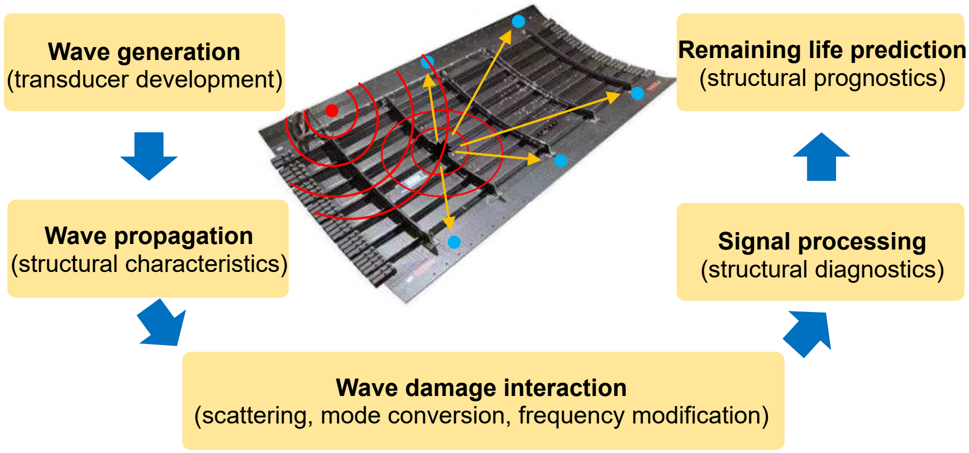


Figure 1：Key procedures in a guided-wave SHM approach.

1.3 Opportunity of manipulating guided wave features for enhanced SHM/NDE performance

Considering the challenges encountered by the ultrasonic guided wave based SHM/NDE techniques, researchers have extended their investigation into novel methodology to overcome the difficulties. The rising of metamaterials provided an emerging opportunity to enhance SHM/NDE performance by their ability to control and manipulate guided waves. The unique characteristics of metamaterials have been drawing increasing attention. They can achieve novel properties, such as bandgap, negative density, negative modulus, and so on [7, 8].

Figure 2 presents the roadmap of utilizing metasurfaces for the manipulation of guided waves in an SHM system. The wave control may take place in three regions of the active sensing setup. In the wave generation region, in general, the transmitter will send out a multimodal wavefield with rich frequency components, the metamaterial can perform mode selection and physical frequency filtering, which allows the modification of the transducer tuning effect. The waveguiding capability of the metasurface further enables the leading of interrogative energy from the wave source to a location difficult for transducer implementation. In the monitoring region, the metamaterials could also facilitate the energy focusing, beam forming, and even scanning of the host structure, forming an adaptive mode, frequency, directivity possibility. After the wave damage interaction, guided waves will carry the damage information with them and arrive at the wave reception region, where the metasurface potentiates to improve the signal-to-noise ratio and enhance the sensitivity via principles of hyper lenses for super resolution imaging, etc. It should be pointed out that the tunable metamaterial design can further expand the adaptiveness and flexibility of wave control for tackling the challenges of ultrasonic guided wave based SHM/NDE systems.

The Active Materials and Intelligent Structures (AMIS) Lab at Shanghai Jiao Tong University conducted a series of research actions on achieving the above wave manipulation purposes. Examples and case studies will be demonstrated in this paper. Their application in SHM/NDE systems will be discussed.

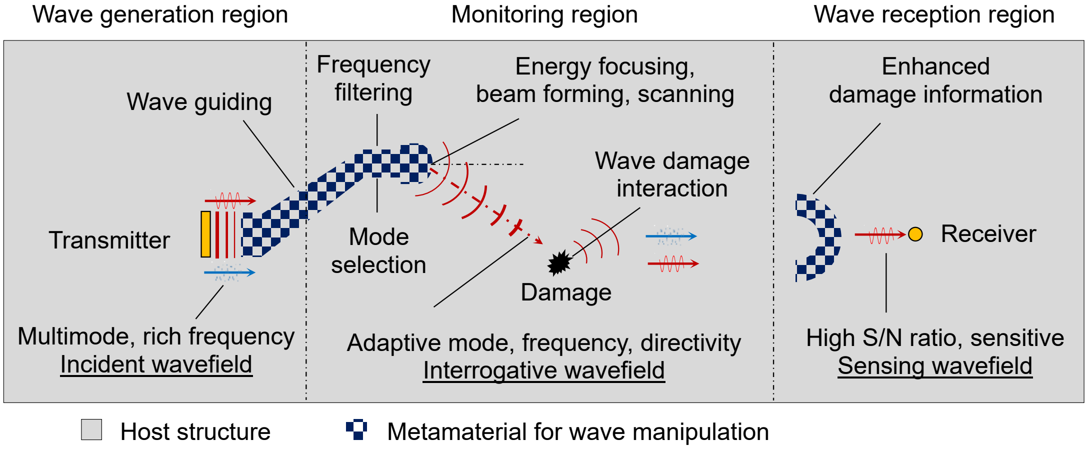


Figure 2:Roadmap of utilizing metasurfaces for the manipulation of guided wave features in an SHM setup.

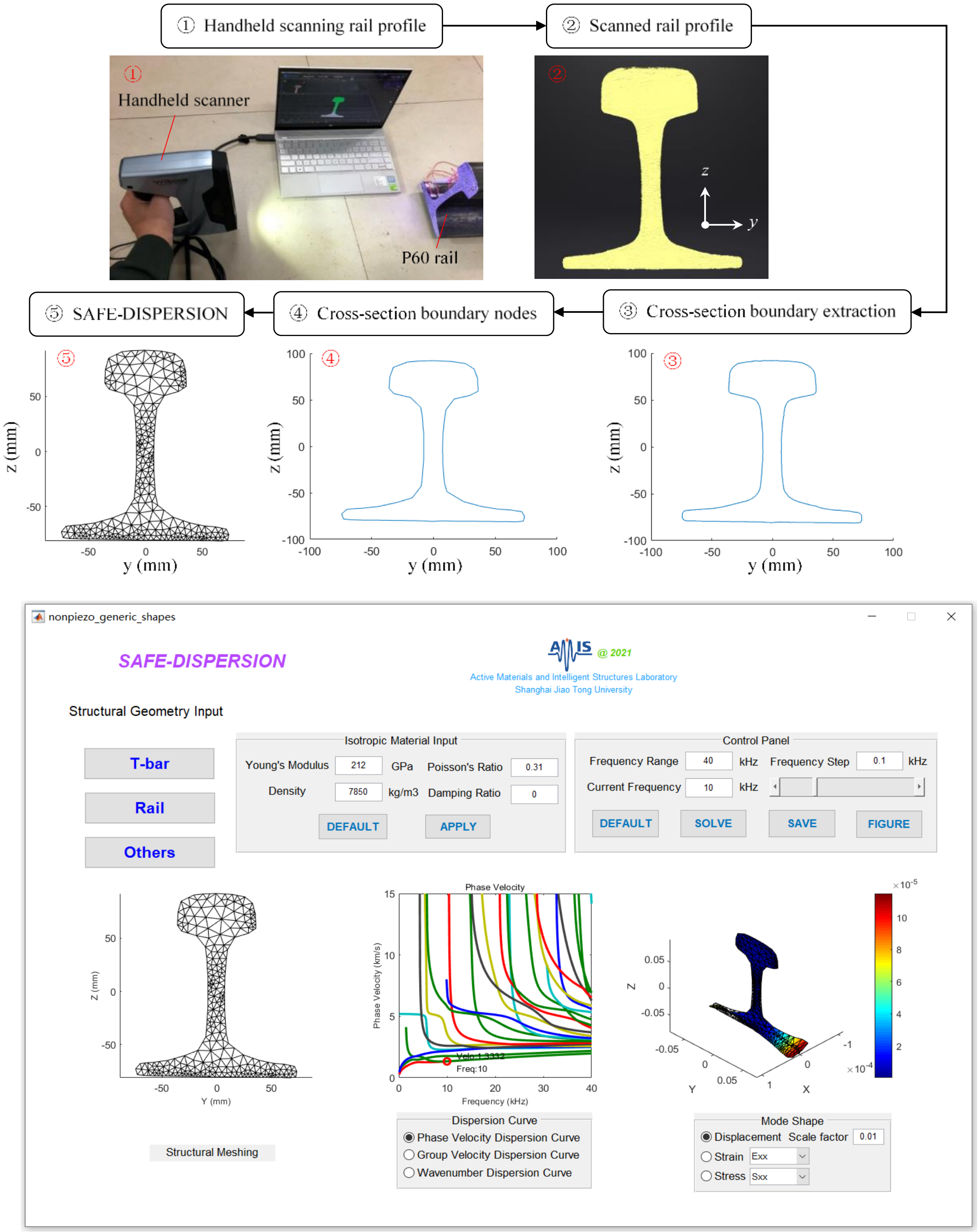
2. NUMERICAL METHODS FOR EXPLORING GUIDED WAVE FEATURES

Numerical methods have been extensively investigated by the SHM/NDE community for exploring the guided wave features. Several aspects of needs should be addressed: (1) clear understanding of multimodal and dispersive waves in complex waveguides; (2) high computational efficiency for simulating SHM procedures; (3) insightful excavation of wave damage interaction phenomena. A desired numerical model should possess characteristics of accuracy, efficiency, and versatility [9].

2.1 Semi-analytical finite element (SAFE) method

There exist a large family of computational methods for obtaining the dispersion curves and mode shapes of guided waves, such as the global matrix method, the transfer matrix method, the semi-analytical finite difference approach, the Bloch boundary finite elements, and the semi-analytical finite element (SAFE) method [10, 11, 12, 13, 14]. Among these approaches, the SAFE method shows stable numerical behaviors and enables the analysis of waveguides with arbitrary cross-sectional areas.

Built upon the pioneer researches in SAFE, AMIS Lab developed the modeling software based on MATLAB GUI called SAFE-DISPERSION. Friendly user interfacing is achieved by a physical-virtual mapping function, i.e., users may easily obtain the guided wave dispersion curves and mode shapes by importing the geometric features through a handheld scanner. Furthermore, piezoelectric properties are implemented in the numerical solution. The computation of guided wave features in functional materials such as piezoelectric structures can be analyzed [15].



Young's Modulus 212 GPa
Poisson's Ratio 0.31
Density 7850 kg/m3
Damping Ratio 0
Frequency Range 40 kHz
Frequency Step 0.1 kHz
Current Frequency 10 kHz

● Phase Velocity Dispersion Curve
○ Group Velocity Dispersion Curve
○ Wavenumber Dispersion Curve

● Displacement Scale factor 0.01
○ Strain Exx
○ Stress Sxx

Figure 3. Physical-virtual interfacing for geometric importing; the GUI of SAFE-DISPERSION.

2.2 Local Interaction Simulation Approach (LISA)

A key character of numerical models for SHM system design and signal analysis should be the high computational efficiency. However, conventional finite element method cannot meet such a need while handling high frequency, short wavelength, long propagation distance guided waves. Local Interaction Simulation Approach (LISA) utilized finite difference formulation and sharp interface model, which can be readily fitted into a parallel computing scheme [16, 17, 18, 19, 20, 21]. Figure 4 presents a general LISA solution procedure. It should be noted that the computation is carried out by the graphics cards, enabled by the Compute Unified Device Architecture (CUDA). Thus, the simulation can be carried out with a superb efficiency. Furthermore, complex wave phenomena were implemented into the LSIA formulation to capture anisotropic damping behavior in composites and Contact Acoustic Nonlinearity (CAN) at fatigue cracks [22, 23, 24].

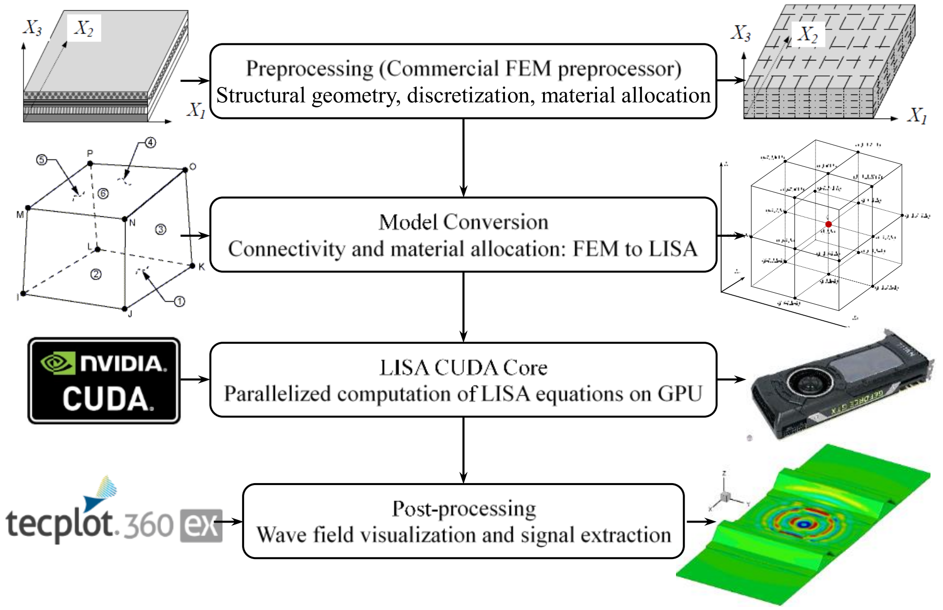
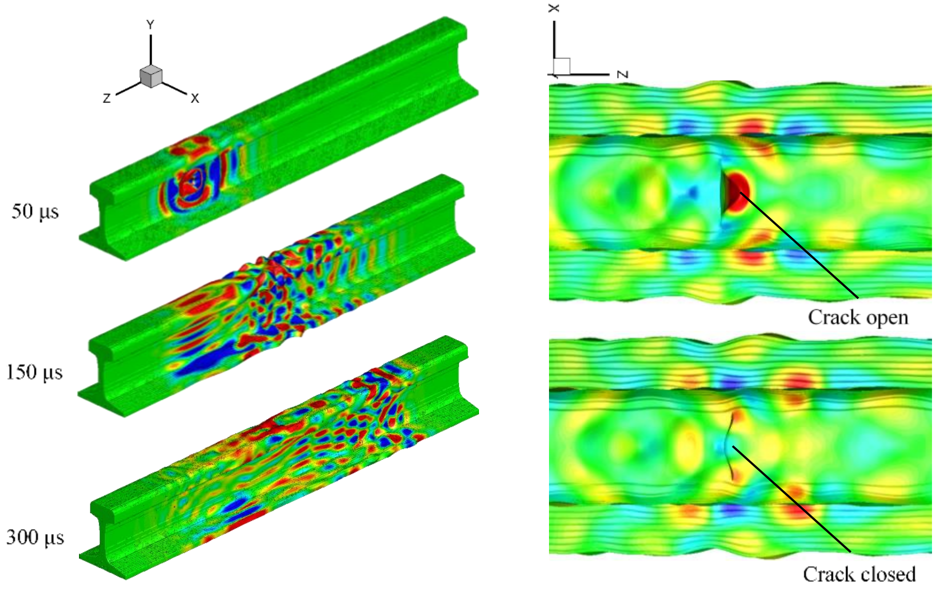


Figure 4. A general LISA solution procedure.

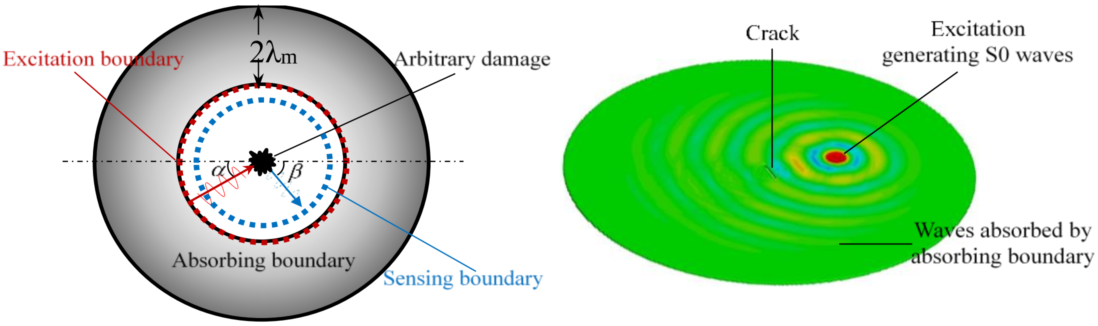


(a) (b)

Figure 5: (a) Guided wave generation, propagation, and interaction with a fatigue crack in the rail track; (b) guided wave interacting with crack with crack open and close phenomenon [25].

2.3 Small-size regional numerical models

An efficient way of studying wave damage interaction phenomena is utilizing the small-size regional numerical models. Figure 6 shows the layout of the model with excitation points for generating various incipient wave modes from arbitrary directions, sensing points unfolding the scattered wave mode amplitudes in all the orientations, an absorbing boundary eliminating boundary reflections and simulating wave propagation in an infinite domain using a finite size model [26]. Due to the flexible nature of the numerical model, arbitrary damage types can be easily investigated.



(a) (b)

Figure 6: (a) Small-size LISA regional model with an absorbing boundary to study wave damage interaction; (b) LISA simulation of wave interaction with a crack damage.

Figure 7 presents a general case of the scattered wave field from an S0 mode incident wave centered at 250 kHz. The specialty of this case study resides in that the wave interacted with an ideal "breathing crack" [27]. The scattered wavefield contains superharmonics at all possible higher-order wave modes [28]. The results shown here represent the Wave Damage Interaction Coefficients (WDIC) at the third superharmonic (750 kHz) into the symmetric higher-order wave modes. It is apparent that if a sensor is located off the incident direction, then it cannot pick up the third harmonic S0 mode. The scattering analysis may provide guidelines for sensitive sensor array designs.

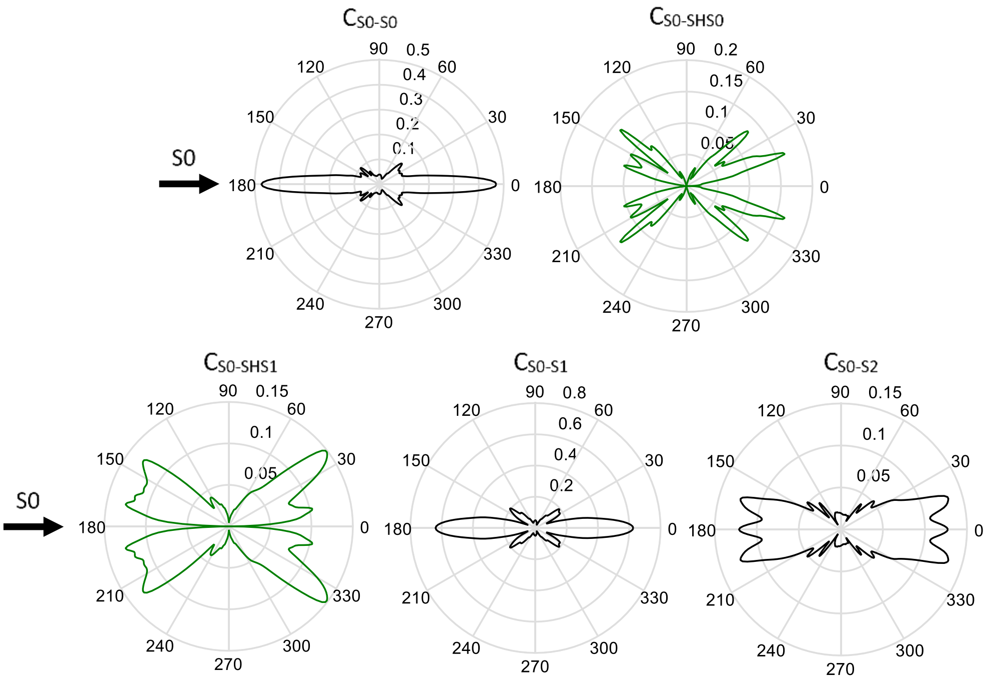


Figure 7: WDICs for S0 incident wave at the third harmonic frequency f3 (750 kHz). Note: mode conversion does not happen from incident S0 mode to A0, SHA0, and A1 modes. S0 mode was scattered as the symmetric modes (S0, SHS0, SHS1, S1, and S2) [29].

2.4 Utilizing guided wave features for SHM/NDE

This section provides a showcase of taking advantage of special features of guided waves for SHM/NDE. AMIS Lab pushed the numerical barrier forward by considering the rough nature of fatigue crack surfaces. Figure 8 demonstrates the scattering results from a "rough crack". It should be noted that the conventional ideal "breathing crack" shows the selective scattering behavior, indicating that symmetric modes can only be scattered and converted to symmetric waves. This is evident from the results in Figure 7. On the other hand, at a rough crack, the mode conversion from S0 into A0 is made possible by the unsymmetric distribution of prestressed closures and void openings. Moreover, such a scattering can be found in all the superharmonic frequencies.

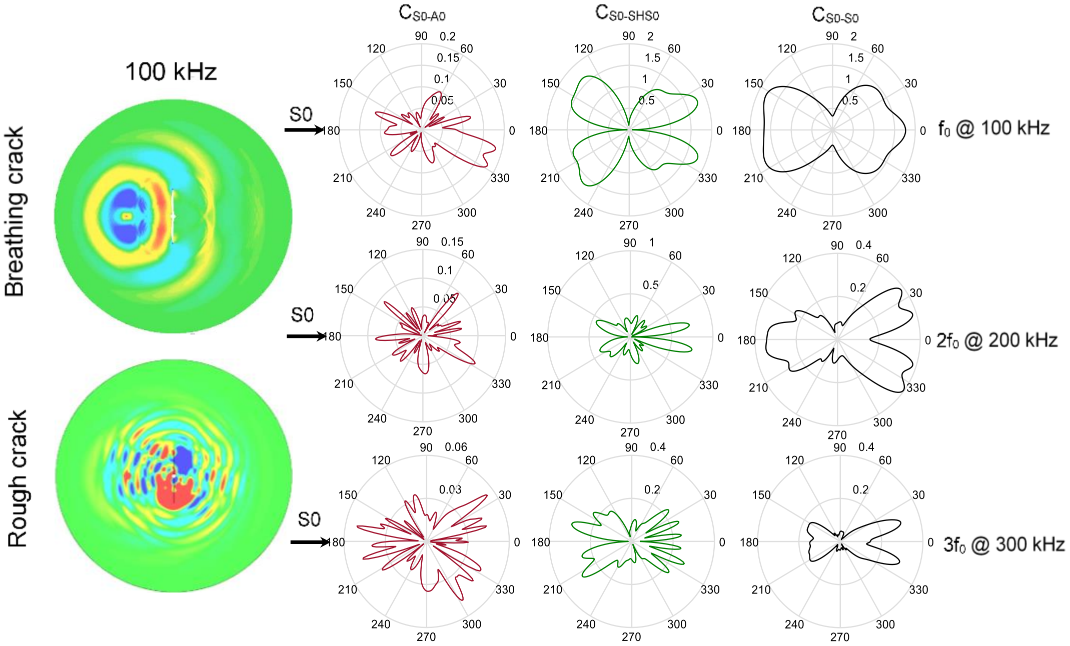


Figure 8: Random scattering and mode conversion features due to the crack roughness [30].

Utilizing such a guided wave feature, fatigue crack detection was carried out using the Scanning Laser Doppler Vibrometer (SLDV) [31]. Instead of measuring the fundamental excitation frequency, Fourier filtering was carried out to highlight the scattered A0 waves at the second harmonic. Figure 9 presents the wavefield imaging results. It can be noticed that compared with the linear wave information, the nonlinear wavefield is more effective for detecting the fatigue crack [32].

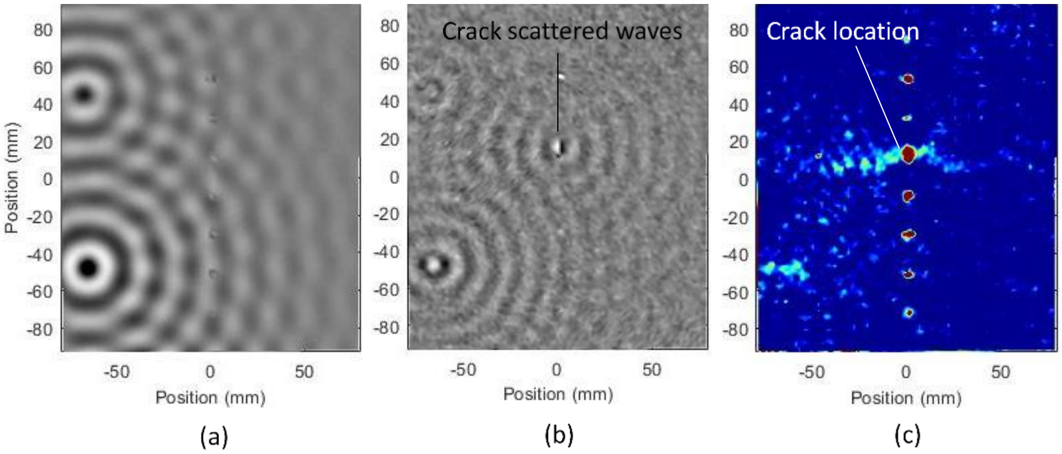


Figure 9: Improved imaging result of the fatigue crack: (a) linear wave field; (b) nonlinear wave field; (c) wave energy spatial distribution showing nonlinear wave sources.

3. MANIPULATING GUIDED WAVE FEATURES FOR ENHANCED SHM/NDE

Built upon many seminal researches in elastic metamaterials for ultrasonic wave control [33, 34], the AMIS Lab excreted much effort in realizing novel wave control behavior for the purpose of enhancing guided wave SHM/NDE systems. Several case studies will be provided, and their potential use in an SHM procedure will be discussed. It should be noted that all of these wave control capabilities stem from the need to overcome challenges and difficulties in current SHM techniques.

3.1 Frequency component filtering for enhancing nonlinear ultrasonics performance

The nonlinear ultrasonic technique based on the detection of superharmonics have been reported as a sensitive approach for detecting fatigue cracks [35, 36]. However, a major challenge encountered in this technique is that it is hard to eliminate the influence of inherent nonlinearity from electronic equipment at the wave generation side, especially after modified by the amplifier [37]. It is difficult to judge whether the superharmonics come from the wave damage interaction or from the inherent nonlinearity of the electronic system. AMIS Lab has combined the bandgap behavior of metamaterials with a pitch-catch active sensing setup as shown in Figure 10. The metasurface functions as a physical filter, creating a bandgap targeting at the second harmonic frequency, so as to remove the inherent nonlinearity from the interrogative wavefield.

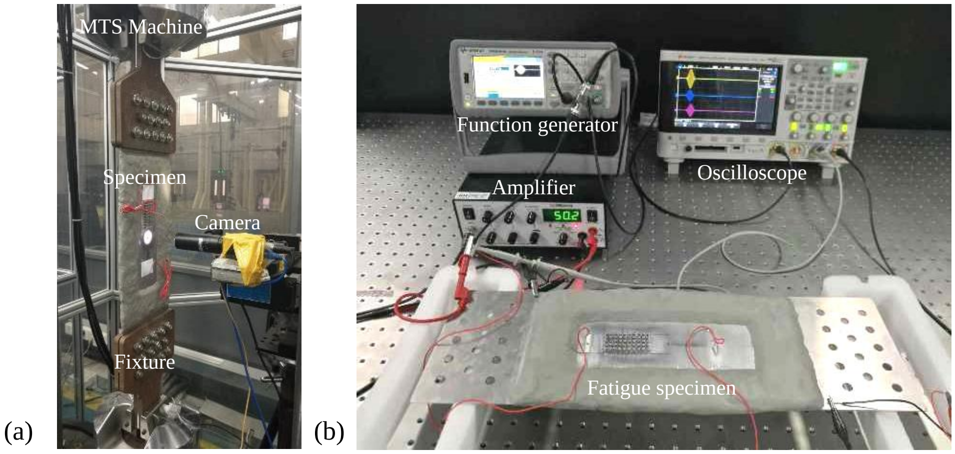


Figure 10: (a) Experimental setup for the fatigue experiment; (b) Experimental setup for the nonlinear ultrasonic tests.

Figure 11 showcases the frequency domain sensing results, indicating the successful removal of the second harmonic of the inherent nonlinearity, providing a clean base for the pristine case. After the fatigue process, the second harmonic grows with the increment of the fatigue crack. In this way, the sensitivity and reliability of the nonlinear ultrasonic technique can be enhanced.

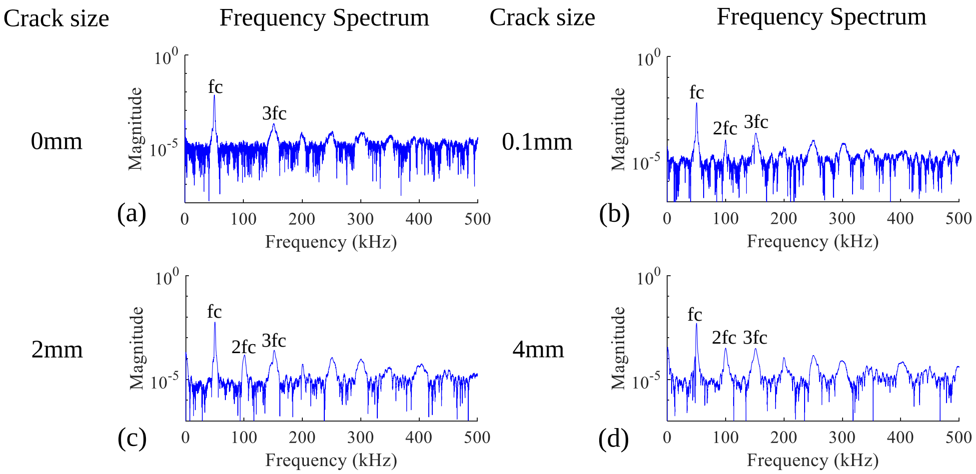


Figure 11: The frequency spectrum of the sensing signals: (a) pristine case; (b) 0.1-mm crack case; (c) 2-mm crack case; (d) 4-mm crack case [38].

3.2 Selective mode transmission for forming single-mode interrogative wavefield

The sensitivity of different wave modes at different frequencies to various types of structural damage are not the same. Transmitting the most sensitive wave mode frequency combination as the interrogative wavefield could considerably improve the SHM/NDE results. In addition, single mode excitation will greatly reduce the signal processing complexity due to the reduction of multimodal wave packets and the damage scattered packets from each mode. Most common practice in conventional SHM systems takes advantage of the transducers' tuning behaviors to obtain a pure wave mode [39]. Researchers also name it as the "sweet point", where when the excitation frequency meets a special value, one of the wave modes will tends to a small value, leaving the other mode as the dominant wave packet. However, the tuning behavior has a strict and narrow working frequency range, which may not be the most sensitive frequency to interact with the structural damage. AMIS Lab put forward a metamaterial design, which can achieve selective wave mode transmission in a relatively large frequency range for the purpose of single-mode interrogation.

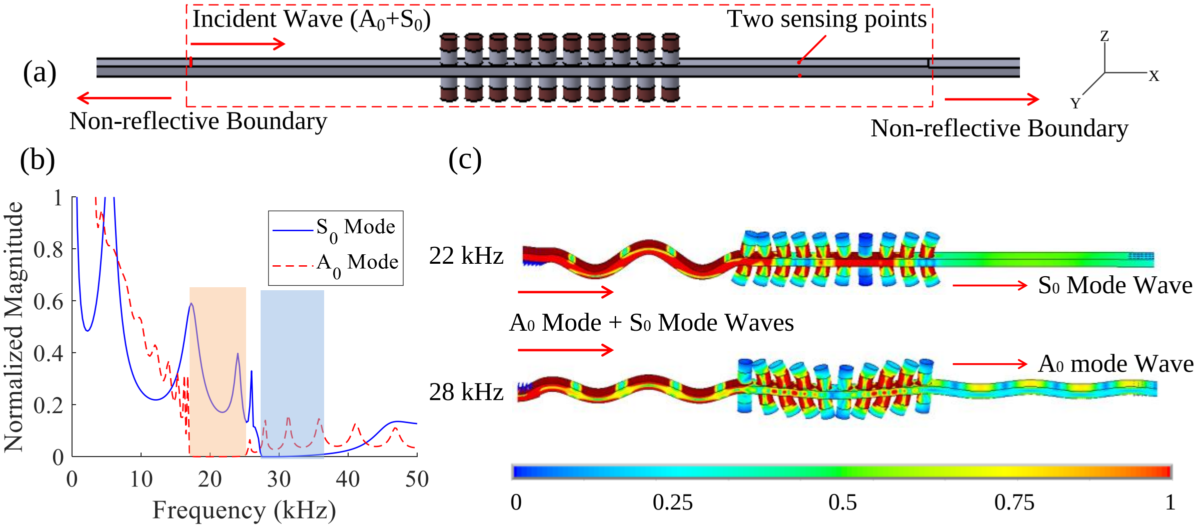


Figure 12: (a) Numerical model of a 10×1 unit-cell-chain structure; (b) the frequency spectra of A0 and S0 modes from harmonic analysis; (c) the equivalent stress responses of the structure under 22 kHz (within A-mode bandgap) and 28 kHz (within S-mode bandgap) [40].

Figure 12 presents the simulation results of the design. A mixed mode wavefield was generated from the left-hand side, mimicking a general working frequency of the transducer, simultaneously sending out S0 and A0 modes. Stub-shape unit cells arranged in a regular fashion was instrumented on the wave path. It is noticed that the metasurface opened up bandgaps for each wave mode with different frequency ranges. Thus, the selective transmission of either S0 mode or A0 mode can be achieved. This is also evident from the wavefield demonstration and the experiments reported in this work. With such an effort, it provides the possibility of utilizing conventional piezoelectric wafer active sensors (PWAS) to send out selectively pure single mode in a wide frequency range.

3.3 Complete mode conversion for selective Lamb and shear horizontal wave active sensing

Another important aspect associated with guided wave modes is the switching between Lamb modes and shear horizontal (SH) modes. Fundamental SH wave possesses outstanding features for SHM/NDE due to the fact that it is nondispersive. Thus, many efforts have been devoted to develop SH wave transducers [41, 42]. However, employing SH waves should not be achieved at the cost of giving up the Lamb waves. The ideal situation for an SHM system can be envisioned to have the ability to freely choose the interrogative wavefield between Lamb waves and SH waves.

AMIS Lab conceptualized an elastic metamaterial system, which enables the complete conversation from Lamb modes into SH mode. The inherent difficulty lies in that Lamb waves dominated by the pressure and shear vertical motions are totally decoupled with shear horizontal motions [43]. Figure 13 presented the skewed stub-shape design of the metamaterial system. Lamb waves were generated on the left-hand side, propagating into the metamaterial region. The metasurface converted the Lamb motion into the SH motion due to the skewed setup, while the Lamb modes fall into the bandgap region created by the unit cell chain at the same time. In this way, complete conversion from Lamb waves into SH mode was achieved. Such a metamaterial creates the possibility of selectively changing the interrogative modes between Lamb waves and SH waves, making the SHM system sensitive to various types of damage oriented in different directions.

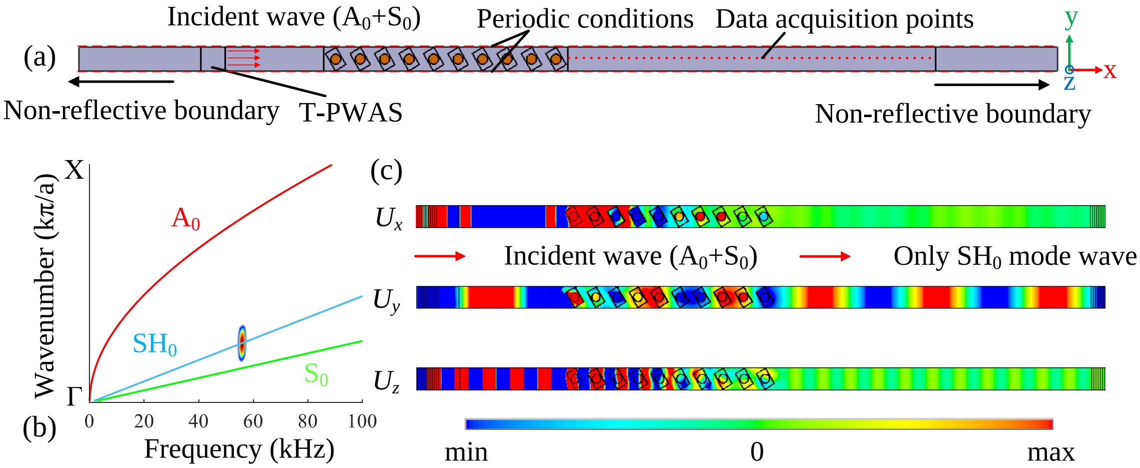


Figure 13: (a) Numerical model setup of a plate implemented with the new metamaterial unit cells for the transient analysis. (b) Frequency-wavenumber analysis of wave fields in a metamaterial plate structure at 56 kHz. (c) Displacement fields of the metamaterial strip along x-, y-, and z-direction at 56 kHz (within the mode conversion band) [44].

3.4 Tunable wave control with active elastic metamaterials for achieving adaptive SHM systems

Although metamaterials can achieve desirable wave control capability for serving SHM/NDE purpose, one major challenge of applying them in practice comes from their passive nature, i.e., most metamaterials only function in a fixed frequency range and cannot achieve adaptive changes according to the needs. Thus, it is significant to push the ideal forward to form tunable metamaterial systems.

AMIS Lab has employed active materials in unit cell designs. A case study shown in Figure 14 demonstrates the bandgap behavior of a metamaterial system made of Shape Memory Alloys (SMA). The design takes advantage of the elastic modulus change between the martensite and austenite phases. Obvious bandgap shift can be achieved by heating up the unit cells with electro-thermal effects of attached heating pads.

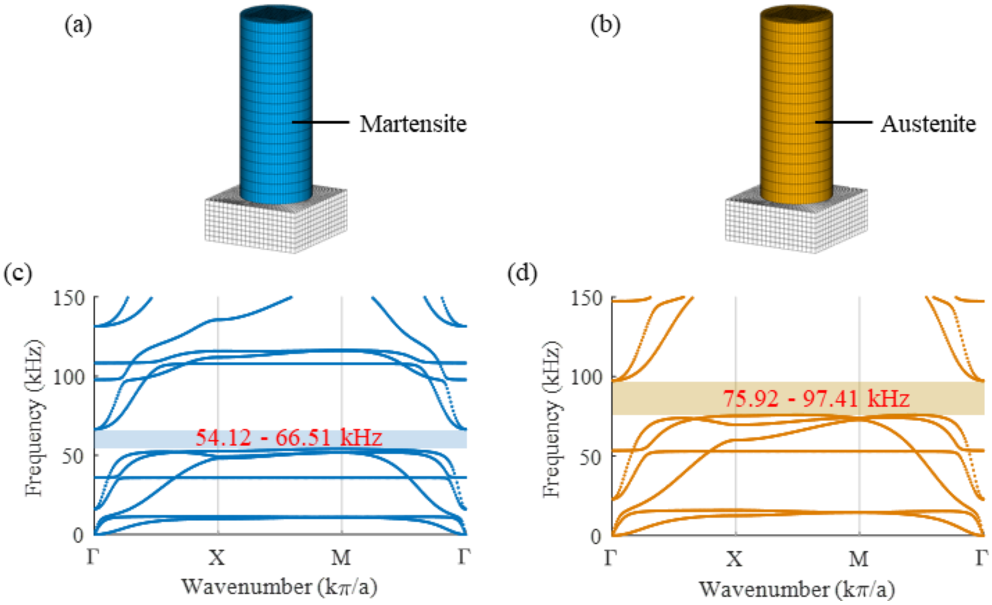


Figure 14. (a) Finite element model of the unit cell in the martensite phase state. (b) Finite element model of the unit cell in the austenite phase state. (c) Band structure of the unit cell in the martensite phase state. (d) Band structure of the unit cell in austenite phase state [45].

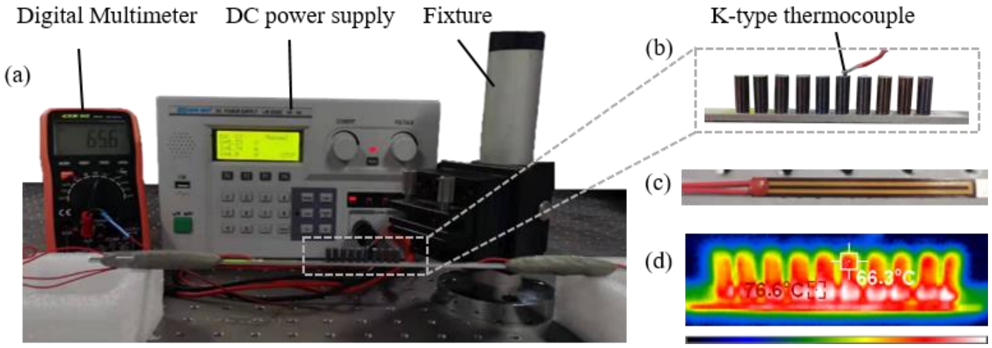


Figure 15. (a) Temperature measurement system for the phononic crystal (PC) unit cells. (b) K-type thermocouple attached on the top surface of the SMA cylinder. (c) Front view of the heating patch. (d) Infrared image of the PC unit-cell-chain when the heating patch was working [45].

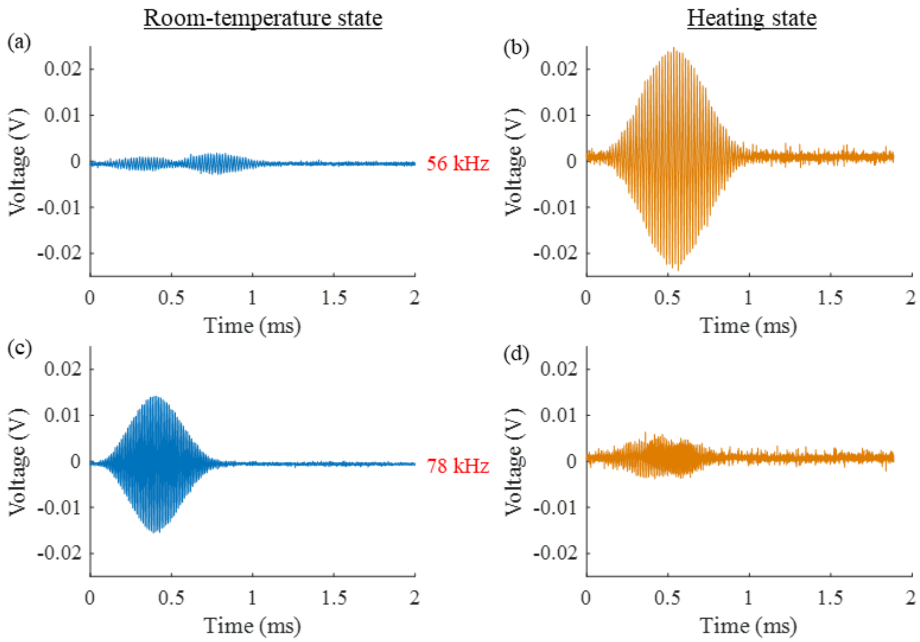


Figure 16. Time traces of the experimental sensing signals captured by the PZT receiver for (a) 56 kHz in room-temperature state. (b) 56 kHz in heating state. (c) 78 kHz in room-temperature state. (d) 78 kHz in heating state.

Figure 15 presents experimental setup for demonstrating the tunable wave control behavior. It can be seen that the thin-film heating pads can effectively elevate the temperature of the SMA stubs above the phase change point. Figure 16 shows the totally different wave transmission behaviors for the room temperature state and the heating state. This example demonstrates the potential of achieving tunable metamaterial design for adaptive ultrasonic guided wave control to enhance the SHM/NDE performance [45].

4. SUMMARY, CONCLUDING REMARKS, AND FUTURE WORK

4.1 Summary and concluding remarks

This paper presented the recent research progress in SHM and wave mechanics from Active Materials and Intelligent Structures (AMIS) Lab at Shanghai Jiao Tong University. Two major aspects of our research were reported: (1) numerical modeling techniques for exploring and understanding guided wave features; (2) preliminary results and conceptual designs of metamaterials for manipulating guided wave features to improve SHM/NDE performance.

It was demonstrated that semi-analytical finite element (SAFE) method can provide the dispersion curves and wave modes of complex waveguides with arbitrary cross-sections. AMIS software SAFE-DISPERSION allows users to obtain the solution via a friendly physical-virtual interfacing environment. Furthermore, the Local Interaction Simulation Approach (LISA) was found to be able to generate efficient simulation results for SHM system design and signal interpretation purposes. Small-size regional numerical models could facilitate the in-depth understanding of wave damage interactions including nonlinear features and mode conversion towards higher-order modes. It was found that by taking advantage of these special features obtained from numerical simulations, remarkable SHM/NDE results can be achieved.

The second half of the paper demonstrated the concept of engaging elastic metamaterials for inspection wavefield control. Case studies were presented. It was found that the metamaterial with bandgap effects can physically filter the inherent second harmonic away from the interrogating wavefield. The reliability and sensitivity of nonlinear ultrasonic technique was thus enhanced. The selective mode transmission of Lamb waves and complement mode conversion from Lamb waves into SH waves were achieved. It enables the free choice of the most sensitive mode and frequency combination for improving the SHM/NDE performance. Furthermore, active materials, like the Shape Memory Alloy (SMA) was used to achieve the tunable metamaterial design. It was found that the wave control behavior became programable, enabling the adaptive wave manipulation for SHM/NDE purpose.

4.2 Suggestions for future work

Suggestions for future work include (1) extension of the LISA framework to capture dispersion relationships of complex structures; (2) establishment of SHM/NDE oriented modeling software platform with comprehensive functions; (3) miniaturization of metamaterials for practical implementation in engineering structures; (4) incorporating various kinds of active materials for tunable metamaterial designs; (5) integrating multiple functionalities of metamaterials for successful SHM/NDE demonstrations.

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