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STEERABLE UNIDIRECTIONAL WAVE EMISSION FROM A SINGLE PIEZOELECTRIC TRANSDUCER USING A SHAPE MEMORY ALLOY COMPOSITE METASURFACE

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ABSTRACT

Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) systems generally adopt piezoelectric transducers which emit omnidirectional wave fields. The achievement of directionality of guided wave generation will benefit the structural sensing purpose, which allows better detection and localization of the damage sites

In this study, a type of metamaterial ultrasonic radar is proposed for the steerable unidirectional wave manipulation. It contains a circular array of unit cells stuck in an aluminum plate which are delicately arranged in a circular fashion. Each unit cell is composed of a shape memory alloy substrate and a lead stub. The controllable bandgap of such metamaterial system can be achieved due to the stiffness change of nitinol between its martensite phase and austenite phase under a thermal load. This research starts with a Finite Element Model (FEM) of the unit cell to compute its frequency-wavenumber domain dispersion characteristics, demonstrating the adjustable bandgap feature. Then, numerical modeling of the metamaterial radar is performed by shifting the bandgap of one sector of the metasurface away from the excitation frequency. The modeling results demonstrate that the martensite phase metasurface area forms a bandgap region where guided wave energy cannot penetrate, while the bandgap of the austenite sector shifts away from the excitation frequency, opening up a transmission path for the ultrasonic waves. By rotating the austenite sector, the metamaterial structure can work like a wave emission radar, realizing of the steerable unidirectional wave radiation with a single transducer. Such an active metasurface possesses great application potential in future SHM and NDE systems.

Keywords: steerable unidirectional wave emission, metamaterial, shape memory alloy, ultrasonic radar, structural health monitoring

1. INTRODUCTION

Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) systems play a crucial role in civil, mechanical, and aerospace industries for enhancing the safety and reliability of these engineering infrastructures. Guided waves have been widely investigated as a powerful tool for damage detection and quantification. Generally, SHM systems adopt piezoelectric transducers which emit omnidirectional wave fields. However, such a sort of wave generation method cannot concentrate the actuated wave energy. The directionality of the guided wave generation will benefit the structural sensing purpose, which allows better detection and localization of the damage sites. Thus, the unidirectional wave emission approaches are attracting increasing attention.

To date, a lot of investigations have been performed for searching the directionality-controllable wave generation method. Early in 2008, Cesnik et al. proposed the Composite Long-range Variable-direction Emitting Radar (CLoVER) transducer comprised of active sectors arranged in a circular array [1]. By applying the electric field in the selected sector, controllable directive wave emitting can be achieved. Compared with the traditional piezoelectric wafer active sensors, this special design can conform to the curved surfaces and is also capable of increasing the excited signal intensity in the desired directions. Another type of transducer design was contributed by Ruzzene et al. [2]. They presented a novel spiral macro fiber composite transducer which can perform the directional emission of interrogating guided waves based on spatial domain wavenumber matching. Continuous beam steering can be realized through the proper selection of the excitation frequency.

In addition to the direction-steerable transducer design, another category of the unidirectional wave emission method takes advantage of the peculiar wave and vibration control capability of the elastic metamaterials (EMMs). Elastic

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metamaterials are a class of artificially designed microstructural system. Unlike the Bragg scattering mechanism of phononic crystals (PCs), elastic metamaterials are based on the principle of local resonance (LR) [3]. With the specially designed LR microstructures, the elastic metamaterials can achieve, e.g., negative mass density and negative elastic modulus, rendering a marvelous elastic wave manipulation capability.

A great number of researchers have devoted their efforts to the elastic metamaterial design. In 2014, Semperlotti et al. designed an anisotropic resonant metamaterial with flat equi-frequency contours to control the unidirectional wave propagation [4]. Subsequently, Zhu et al. proposed a lens using the principle of the acoustic drop-channel. By tuning the frequency of excitation, wave can be control to propagate in the selected direction [5]. These type of unidirectional wave manipulation methods can be realized by means of a single transducer and possess a finer angular resolution compared with the aforementioned directionality-controllable transducer design. However, once the metamaterial structure is manufactured, the dynamic behavior of the EMMs and the propagation direction of the elastic wave is fixed, which considerably limits EMMs' application to realize the steerable wave emission purpose.

Active elastic metamaterials are drawing increasing attention for its adjustable features and superb capabilities in flexible wave manipulation. Shape memory alloy (SMA), as a special energy transduction material, processes the unique thermal and mechanical behaviors. The peculiar phase transformation of nitinol, a type of SMA, under a thermal load will cause the elastic modulus change of itself. This phenomenon happens between martensite phase which is usually found at a lower temperature and austenite phase which generally exists at a higher temperature. It provides the feasibility to actively adjust the natural property of the unit cells, e.g., resonance frequency, which can be integrated into the active metamaterial design.

Recent investigations have been carried out for adopting SMA for the active metamaterial systems. Canidido et al. proposed a metamaterial beam with shape memory alloy resonators for low frequency vibration control [6]. The underlying martensite phase and austenite phase transformation for a sufficient temperature change enables a significant shift of bandgaps and bandwidth increment. Chuang et al. put forward another design for creating tunable bandgaps in the shape memory alloy beam attached with a steel ball, taking advantage of the elastic modulus adjustable capability of SMA beams [7]. The concentrated mass-based beam facilitates the suppression of the unwanted vibration. However, few investigations have been performed towards controlling the ultrasonic guided waves via the shape memory alloy metamaterial structure.

In this study, to realize the directionally manipulation of ultrasonic guided waves, a new shape memory alloy stubbed metamaterial structural system is proposed. The guided waves are steered for emitting a unidirectional wave field from a single piezoelectric transducer via this metasurface design. Systematic modal analysis and harmonic analysis are conducted to explore the tunable bandgap feature of this metamaterial and demonstrate the excellent control capability for the purpose of steerable unidirectional wave emission.

2. FINITE ELEMENT MODELING OF THE SHAPE MEMORY ALLOY METAMATERIAL UNIT CELL AND ITS BAND STRUCTURE

Figure 1a shows the schematic of the proposed metamaterial unit cell structure. It is comprised of a shape memory alloy stub bonded on a 1 mm thick aluminum plate and a lead stub stacked on top of the SMA stub. This microstructure works as a mass-spring resonator system. The lead stub with a high density works as a mass, whereas the shape memory alloy substrate serves as a stiffness-adjustable spring. The radius of shape memory alloy stub and lead stub are both 1.75 mm. The heights of these two cylinders are also identical, designed to be 3 mm. The lattice constant of the unit cell is set to be 5 mm. It should be noticed that the spatial arrangement of the resonators will not affect the response of the metamaterial system [8], which supports the annulus arrangement of the unit cell in the following metamaterial system to achieve the directionality of the wave control.

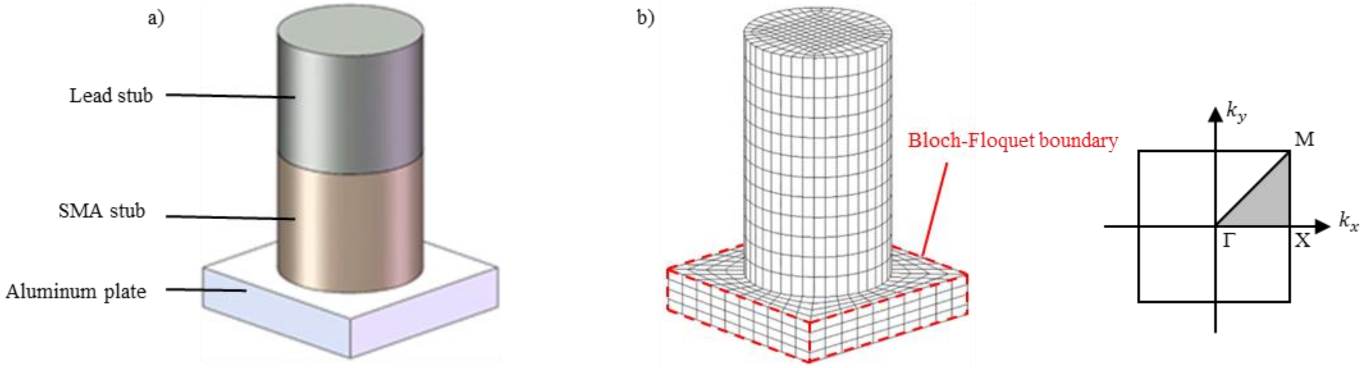

FIGURE 1: a) UNIT CELL OF THE PROPOSED SHAPE MEMORY ALLOY METAMATERIAL; b) FINITE ELEMENT MODEL OF THE METAMATERIAL UNIT CELL AND THE APPLIED BLOCH-FLOQUET BOUNDARY.

The finite element model (FEM) of the unit cell was constructed using the commercial software ANSYS 15.0. The Bloch-Floquet boundary condition (Figure 1b) was applied to the unit cell in the modeling procedure to simulate an infinite metasurface for both the martensite phase state and the austenite phase state. The phase transformation between martensite and austenite under the thermal load was numerically simulated by changing the elastic modulus of the shape memory alloy stub. Elastic modulus of martensite was set to be 30 MPa, while that of the austenite was assumed to be 70 MPa. Subsequently, modal analysis was conducted to compute the frequency-wavenumber domain dispersion relationship. The calculated band structures of unit cells in different material phase states are illustrated in Figure 2. Figure 2a and b present the finite element models of the unit cell in martensite state and austenite state respectively. Figure 2c shows the band structure of the unit cell in the martensite phase state, whereas Figure 2d displays the band structure of the unit cell in the austenite phase state. It can be observed that the stop bands were developed here, indicating that the guided waves cannot pass through the metamaterial structure under the corresponding frequency region. The martensite state structure with a lower elastic modulus had a bandgap appearing from 63.1 kHz to 82.5 kHz. On the other hand, the bandgap moved to a higher frequency range from 71.6 kHz to 91.7 kHz, when the shape memory alloy state shifted to the austenite which possesses a larger elastic modulus.

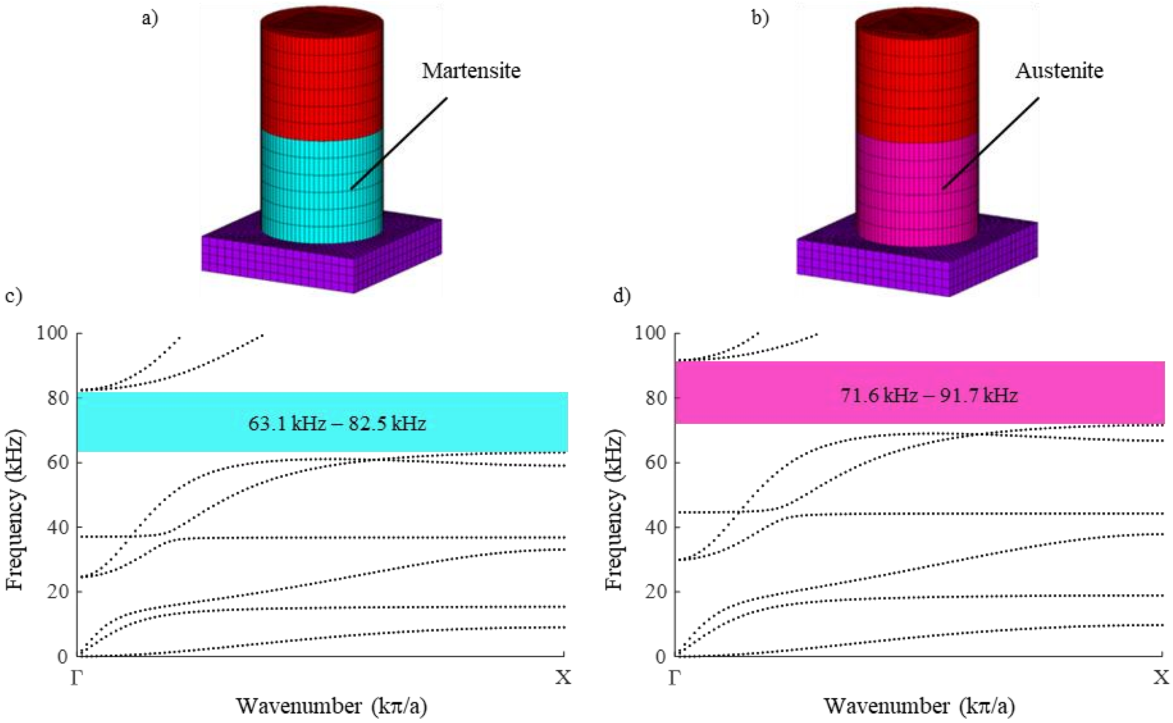

FIGURE 2: a) FINITE ELEMENT MODEL OF THE UNIT CELL IN THE MARTENSITE PHASE STATE; b) FINITE ELEMENT MODEL OF THE UNIT CELL IN THE AUSTENITE PHASE STATE; c) BAND STRUCTURE OF THE UNIT CELL IN THE MARTENSITE PHASE STATE; d) BAND STRUCTURE OF THE UNIT CELL IN THE AUSTENITE PHASE STATE.

Such a result depicts a considerable bandgap location movement, demonstrating the tunable property of the bandgap in the proposed shape memory alloy stubbed metamaterial. Furthermore, it is foreseeable that, by controlling the excitation frequency and state of the unit cell in the metamaterial plate, the wave energy can be steered precisely. This phenomenon provides the feasibility to actively control the wave propagation and facilitates the unidirectional wave manipulation.

3. HARMONIC ANALYSIS OF THE SHAPE MEMORY ALLOY METAMATERIAL ULTRASONIC RADAR

To investigate the steerable wave emission by using a single ultrasonic transducer, the shape memory alloy metamaterial radar was constructed using 180 stubbed unit cells stuck in an aluminum plate which were delicately arranged in 5 circles. The model is displayed in Figure 3.

In this schematic plot, the unit cells were arranged on an annular area of the plate. The inner circle of the annular metasurface has a radius of r_1 = 30 mm and that of the outer circle is r_2 = 50 mm. Each sector is composed of 3×5 unit cells as illuminated in the dot-dash region, forming a 30-degree controllable area. A piezoelectric wafer active sensor (PWAS) with a 3.5 mm radius and 0.2 mm thickness was bonded in the center of the metamaterial area to generate both symmetric and antisymmetric guided wave modes. Another annular aluminum plate with the inner and outer radius of 55 mm and 100 mm served as the wave field demonstration area around the outer edge of the metamaterial region, for the purpose of observing the directional wave propagation phenomenon. Non-reflective boundary (NRB) [9] was implemented around the numerical setup to eliminate the influence of the boundary reflection, simulating wave propagation in an infinite plate using a finite-size model. The phase velocity dispersion curves in the host aluminum plate can be calculated by solving the Rayleigh-Lamb equation [10] and is displayed in Figure 4a. At the same time, the wavelength was evaluated via Eq. (1) and the corresponding wavelength – frequency curve is plotted in Figure 4b.

$$\lambda = \frac{c}{f} \tag{1}$$

where λ is wavelength, c denotes the wave speed in this aluminum plate and f represents the frequency of the wave. The length of the non-reflective boundary should exceed twice the maximum wavelength propagating in the plate. From Figure 4b, it can be concluded that when the guided wave excitation frequency is designated at the martensite bandgap region as 68 kHz (which will be introduced in the following part), guided waves of S_0 mode have a wavelength of 79.5 mm. Hence, a 160 mm length of non-reflective boundary is sufficient to fully eliminate the reflected waves.

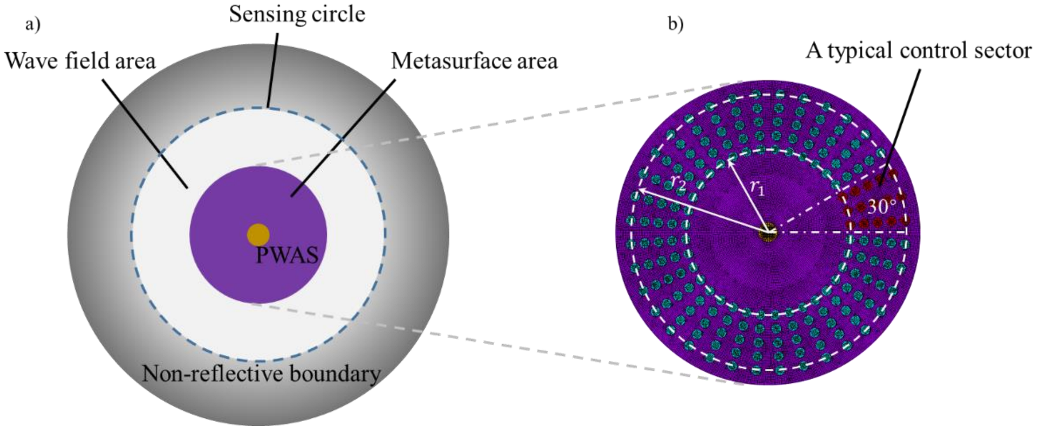

FIGURE 3: a) THE SCHEMATIC OF THE ULTRASONIC RADAR MODEL WITH NON-REFLECTIVE BOUNDARY; b) FINITE ELEMENT MODEL OF THE ZOOM-IN METAMATERIAL AREA.

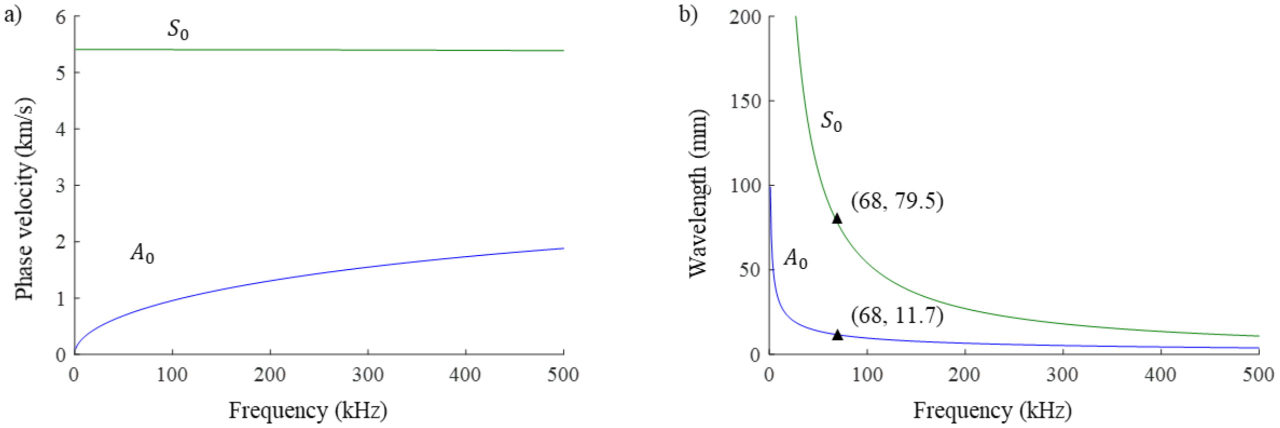

FIGURE 4: a) PHASE VELOCITY DISPERSION CURVE OF GUIDED WAVES IN 1-MM THICK ALUMINUM PLATE; b) WAVELENGTH OF GUIDED WAVES IN THE ALUMINUM PLATE.

For this model, harmonic analysis was conducted to verify the steerable unidirectional wave emission effect via controlling the state of shape memory alloy stub in each sector. A 50-volt excitation was applied on the PWAS. From the band structures of the shape memory alloy unit cell calculated in the modal analysis, it can be observed that two bandgap regions ranging from 63.1 kHz to 82.5 kHz and from 71.6 kHz to 91.7 kHz were formed in the martensite phase state and the austenite state respectively. In order to provide a more intuitive perspective of the relationship between the two band structures, the overlapped figure is illustrated in Figure 5. The bandgaps can be divided into three regions. 82.5 kHz to 91.7 kHz represents the wave propagation suppression frequency only for martensite structure; 71.6 kHz to 82.5 kHz corresponds to the stop band for both martensite structure and austenite structure; 82.5 kHz to 91.7 kHz proves to be the wave prohibition region just for unit cell in the austenite state. Thus, when the excitation frequency is set to be 68 kHz, falling within the bandgap of martensite structure; at the same time below the austenite structure's bandgap, i.e., only the waves in the austenite sector can pass through the metamaterial area. Rotating the austenite sector, the corresponding wave emission direction can be steered.

To demonstrate this phenomenon, the dynamic behavior of the metamaterial plate was investigated with all of the unit cells beginning with the room-temperature (martensite) state. Different cases were realized by shifting the state of one sector of the metasurface to be the heating (austenite) state to form a wave emission tunnel. The obtained equivalent stress wave fields of the metamaterial plate are depicted in Figure 6 with the guided wave excitation frequency at 68 kHz. Because of the central symmetry of the metamaterial radar design, the austenite sectors were only rotated a half cycle, i.e. 180 degrees, to show the scanning phenomenon of the wave emission field. Figure 6a presents the equivalent stress wave field of the metamaterial plate with the sector within 0 to 30 degree being austenite phase, guided waves were steered to propagate along this direction accurately. Figure 6b displays the equivalent stress of the metamaterial plate with 30 to 60 degree being austenite; wave energy also concentrated in the austenite region. In the same way, guided waves can be manipulated to propagate along 60 to 90 degree, 90 to 120 degree, 120 to 150 degree, 150 to 180 degree as shown in Figure 6c, 6d, 6e, 6f, respectively.

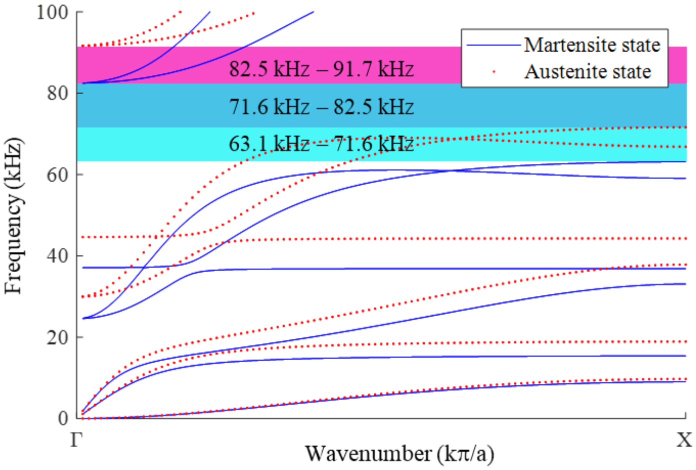

FIGURE 5: THE OVERLAPPED BAND STRUCTURES OF MARTENSITE STATE AND AUSTENITE STATE.

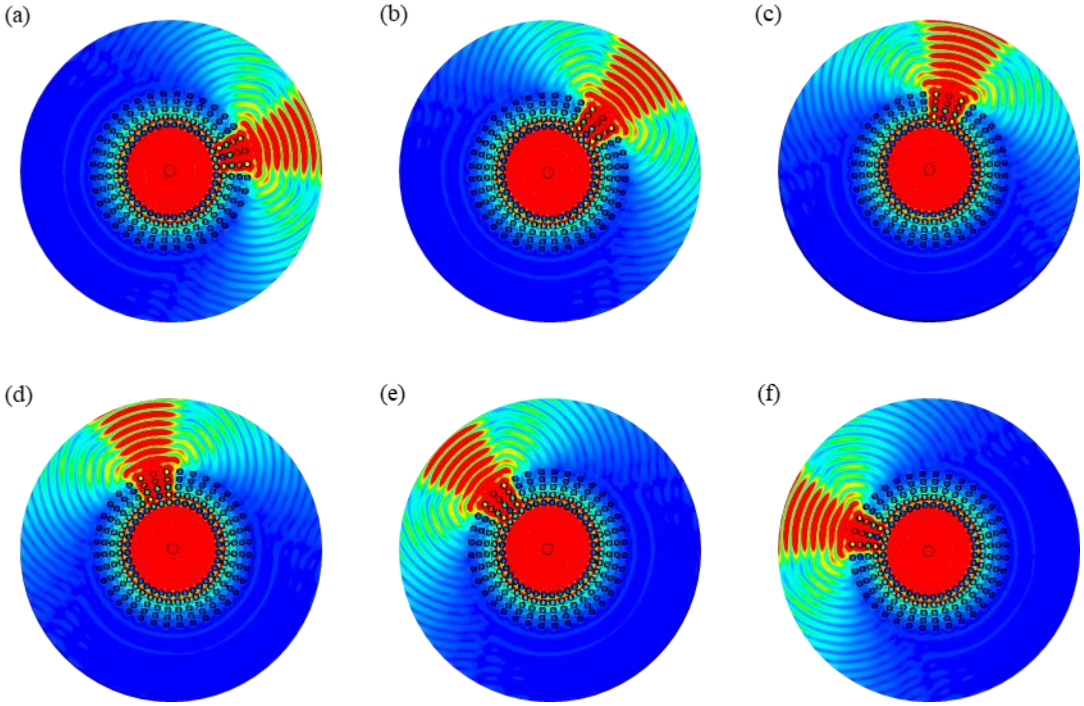

FIGURE 6: THE EQUIVALENT STRESS WAVE FIELD OF THE METAMATERIAL PLATE WITH CORRESPONDING SECTORS SHIFTING FROM MARTESITE TO AUSTENITE, DEMONSTRATING THE STEERABLE WAVE EMISSION PHENOMENON.

To further quantitatively evaluate the unidirectional wave emission effect, a series of sensing points were selected in the position of the aluminum plate’s upper surface at a radius of 100 mm. The out of plane displacements of these locations were extracted representing the steady state response of the metamaterial radar.

The directionality plots of the metamaterial ultrasonic radar are illustrated in Figure 7 and are exhibited in a polar coordinate. The blue circles in each plot represent the shape memory alloy stub in martensite phase, while the red circles indicate the unit cells in austenite phase. Figure 7a, 7b, 7c, 7d, 7e, 7f correspond to Figure 6a, 6b, 6c, 6d, 6e, 6f, respectively.

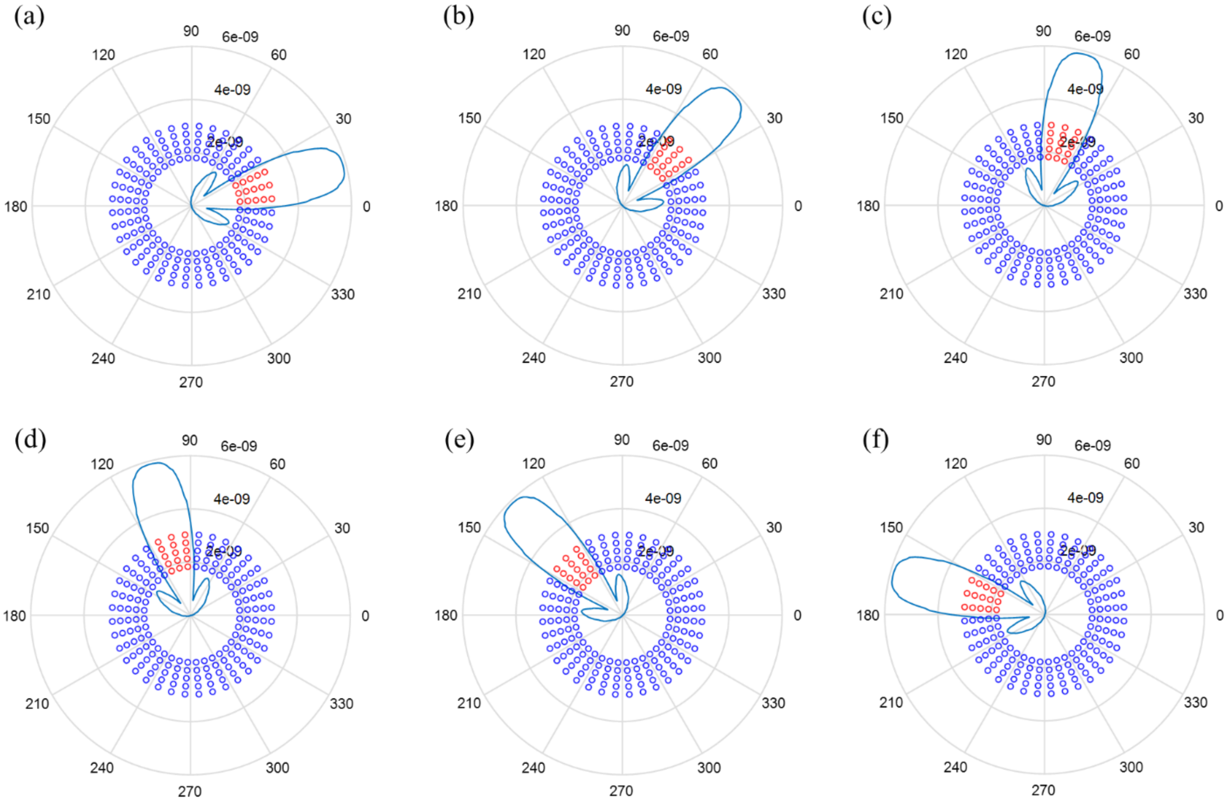

FIGURE 7: WAVE DIRECTIVITY PLOT OF THE METAMATERIAL ULTRASONIC RADAR.

It is apparent that the austenite sectors opened up a transmission path for the ultrasonic guided waves. This plot further shows a great resolution of the wave directionality control and demonstrates the superb wave directionality manipulation capability of this proposed metamaterial design. Such a shape memory alloy metasurface radar provides a new and alternative approach to achieving the steerable ultrasonic guided wave emission by utilizing a single piezoelectric wave active transducer. The selective directional interrogation for structural health monitoring can be further attempted. It possesses the capability to send the ultrasonic energy in a preferential direction which will dramatically increase the interaction between the guided wave and the damage developed in an engineering structure. The increased detection sensitivity may benefit the precise damage localization and identification in future SHM and NDE applications.

4. CONCLUDING REMARKS

In this paper, a new metamaterial ultrasonic radar was presented to achieve the unidirectional wave emission via a single transducer. Shape memory alloy which possesses the elastic modulus change property between martensite and austenite provides the feasibility to actively tune the dynamic performance of the metasurface unit cells. Finite element models of the shape memory alloy metamaterial unit cell in the two states were constructed. Modal analysis demonstrated the movement of stop bands of the wave propagation in the metamaterial structures. Subsequently, a radar structure was designed with 180 stubbed unit cells sitting on an aluminum host plate which were delicately arranged in 5 circles. Numerical modeling of this metamaterial radar was performed by shifting the bandgap of one sector of the metasurface (from martensite phase to austenite phase) away from the excitation frequency to form a wave emission tunnel. The equivalent stress plots of the ultrasonic radar indicated that the delicately controlled austenite sector opened up a transmission path for the ultrasonic waves. By rotating the austenite sector, the corresponding wave emission direction can be steered. Furthermore, a type of quantitative directionality plots were obtained to present the intensity and amplitude of guided wave in all the directions, further demonstrating the superb wave steering capability of this proposed metamaterial radar. Such a metamaterial design possesses a great application potential in future SHM and NDE applications.

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