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PROGRAMMABLE WAVEGUIDING OF ULTRASONIC WAVES FOR REGIONAL DAMAGE DETECTION USING ELASTIC METAMATERIALS

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ABSTRACT

This study puts forward a metasurface design which allows the flexible tuning of the elastic wave propagation path, enabling the interrogating wave field guiding into desired monitoring regions for damage detection. As a demonstrative case study, the metasurface plate contains a rectangular array of unit cells sitting in an aluminum plate. Each unit cell is comprised of a shape memory alloy substrate and a lead stub. The controllable bandgap of such a metamaterial system can be achieved due to the stiffness change of nitinol between its martensite phase and austenite phase under a thermal load. First, a Finite Element Model (FEM) of the unit cell is constructed to calculate the band structure of the metasurface plate, demonstrating the adjustable bandgap behavior. Then, numerical modeling of the metamaterial waveguide is performed by shifting the bandgap of a specific path of the metasurface away from the excitation frequency. The modeling results demonstrate that the martensite metasurface area forms a bandgap region where guided wave energy cannot penetrate. While, the bandgap of the austenite part shifts away from the excitation frequency, opening up a transmission path for the ultrasonic waves. By delicately selecting the austenite state unit cell path, four 'S', 'J', 'T', 'U' shaped routes with a fine resolution are tailored to show a SJTU logo, demonstrating the excellent waveguiding capability and the programmable waveguide feature of this shape memory metamaterial system. The proposed tunable waveguiding methodology possesses great application potential in future Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) applications.

Keywords: programmable waveguiding, metamaterial, shape memory alloy, structural health monitoring

1. INTRODUCTION

Traditional Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) systems play a crucial role in civil and mechanical engineering disciplines for the structural damage detection and evaluation purpose. As a common practice, guided waves are generated by Piezoelectric Wafer Active Sensors (PWAS) to detect incipient changes developed in the diagnosed facilities. However, this kind of system generally face a great challenge in the extreme detection conditions. It's hard to work normally for the PWAS in harsh environmental conditions, such as the high temperature or corrosive contaminations. Far-field guided wave generation and guiding manipulation into the detection areas will benefit SHM procedures under these extreme conditions.

Elastic Metamaterials (EMMs) are drawing increasing attention over the past decades for their superb capability in elastic wave manipulation and control. EMMs are a class of artificially designed microstructural systems. Unlike the Bragg scattering mechanism as Phononic Crystals (PCs), elastic metamaterials are based on the principle of Local Resonance (LR) [1]. 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. Therefore, the applications of elastic metamaterials will open an avenue for steering the wave propagation and facilitate the wave guiding into the desired interrogation regions.

A great number of researchers have devoted their efforts to the active elastic metamaterials designs. The achievements of the metamaterial waveguide are also burgeoning. In 2017, Huang et al. designed a waveguide equipped with a fan-shape array of electrorheological elastomer metasurfaces subjected to an adjustable electric field. A transformation method was developed to predict the steered elastic wave direction [2]. A counterpart

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waveguiding routes were also realized by a fluid-solid composite unit cell. By controlling the liquid distribution, effective mass density can be tuned and the wave propagation direction can be manipulated [3]. Thereafter, it was reported that a T-shaped 3D printed structure can also achieve the waveguiding properties with a circuit control system. Piezoelectric patches connected by the negative capacitance circuits were investigated to perform as the active control unit, facilitating the switchable waveguide design [4]. Furthermore, more complex wave guiding paths can be achieved through other structures. Wang et al. put forward a design by adopting a 3D printed frame and the electromagnets to achieve the active control of the unit cell configuration. By switching the current in the designated unit cells, electromagnets can be attached and detached from each other, achieving the transformation between two different configurations [5]. Bilal et al. also achieved a reprogrammable metamaterial by adjusting the magnet embedded in a spiral-spring, the wave velocity distribution plot of the metamaterial plate could display an ETH logo with a proper configuration of the unit cells [6].From the aforementioned examples, it is apparent that the metamaterial design propels the development of the waveguiding achievements. Current and prevalent realization method of an adjustable waveguide includes the usage of the electromagnetic structures and shunted patches. Although the idea of active metamaterials are desirable, successful designs are still limited.

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 its elastic modulus change. This phenomenon happens between martensite phase and austenite phase. Martensite phase is usually found at a low temperature and possesses a smaller elastic modulus. Whereas the austenite phase is generally found at high temperature and owns a larger value of elastic modulus. Such a special phase transformation mechanism provides the shape memory alloy with the feasibility for active metamaterial design. This lies in the fact that the adjustable stiffness of this active material could achieve the controllable natural property of the unit cells, e.g., resonance frequency, which will further enable the adjustable wave manipulation. However, to date, few investigations have been reported to implement the fantastic dynamic-property-adjustable feature of the shape memory alloy for programmable ultrasonic waveguiding. The utilization of shape memory alloy will facilitate a more compact and easy-fabricated controllable microstructural design without any redundant control structures. It will provide a completely new alternative approach to guiding the wave energy into a preferential location. The shape memory alloy metamaterial design can be readily bonded on the engineering structures without reducing the structural strength which may process a great potential for future SHM and NDE system designs.

In this study, an active metasurface based on the active property of shape memory alloy is proposed. Systematic modal analysis is performed to explore the tunable bandgap capability of the shape memory alloy metasurface under a thermal load. Subsequently, harmonic analysis is conducted for a couple of representative metasurface configurators with different shape memory alloy state patterns to demonstrate their excellent programmable waveguiding capability. The metasurface can guide the ultrasonic wave energy in the designated path, manipulating the wave propagating into the specific detection areas, which could help address the damage detection issue in harsh conditions.

2. FINITE ELEMENT MODEL AND BAND STRUCTURE OF THE SHAPE MEMORY ALLOY METASURFACE UNIT CELL

The schematic of the metasurface unit cell is presented in Figure 1. It was constructed by a shape memory alloy stub deposited on the surface of a 1-mm thick aluminum plate and a lead stub stacked on top. This unit cell can be regarded 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 r of shape memory alloy stub and lead stub are uniform as 1.75 mm and the height of these two cylinders are also identical, designed to be 3 mm. The lattice constant of the unit cell was set to be 5 mm. Due to the greater stiffness of the shape memory alloy compared with the lead, it can be expected, the effective stiffness is mainly dominated by the shape memory alloy cylinder.

Finite element model (FEM) of the unit cell was implemented using the commercial software ANSYS 15.0. The material density as well as the elastic modulus of the lead are 11340 kg/m3 and 14 Gpa; for the shape memory alloy, the mass density is 6400 kg/m3 and the elastic moduli are 30 Gpa and 70 Gpa for martensite phase and austenite phase, respectively. In the numerical simulation, the element meshing size is crucial for the accuracy of the calculation and for the saving of the computational time. Proper mesh size will benefit the accurate and efficient computation purpose. The choice of the element size was carefully chosen according to the wavelength propagating in the structure.

The wave speed in the 1-mm aluminum plate can be calculated by solving the Rayleigh-Lamb equation [7]. The relationship between wave speed and frequency is shown in Figure 2a. At the same time, the wavelength dispersion curves were evaluated via the following equation.

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

where the λ is the wavelength, c denotes the wave speed in this aluminum plate and f represents the frequency of the wave. The wavelength-frequency relationship is exhibited in Figure 2b. It can be observed that when the guided wave excitation frequency is designated as high as about 100 kHz, which is expected to be the maximum excitation frequency in this study, A_0 mode guide waves possess a minimum length of 10.2 mm. In general, a preferable mesh size is determined as one-twentieth as long as the minimum wavelength of the guided waves propagating in the structure. Thereafter, the mesh size can be confirmed as 0.5 mm, satisfying the described requirements.

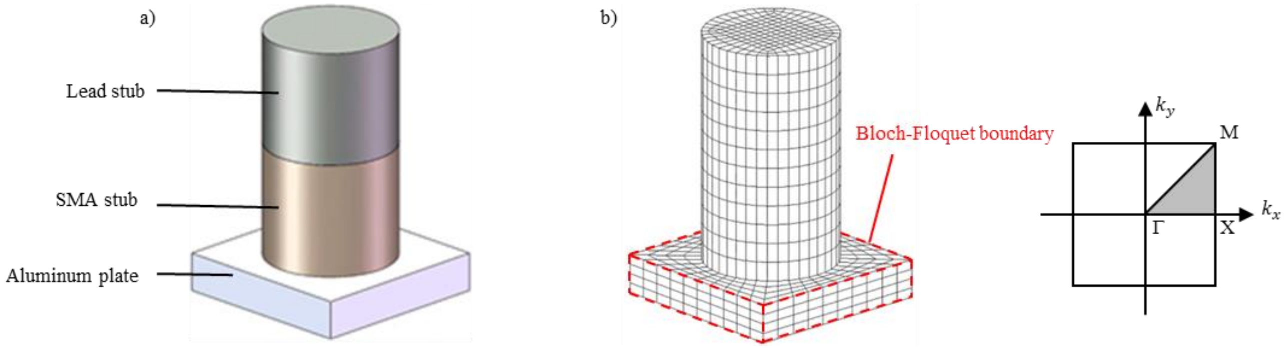

Figure 1: a) UNIT CELL OF THE PROPOSED SHAPE MEMORY ALLOY METASURFACE; b) FINITE ELEMENT MODEL OF THE METASURFACE UNIT CELL AND THE APPLIED BLOCH-FLOQUET BOUNDARY.

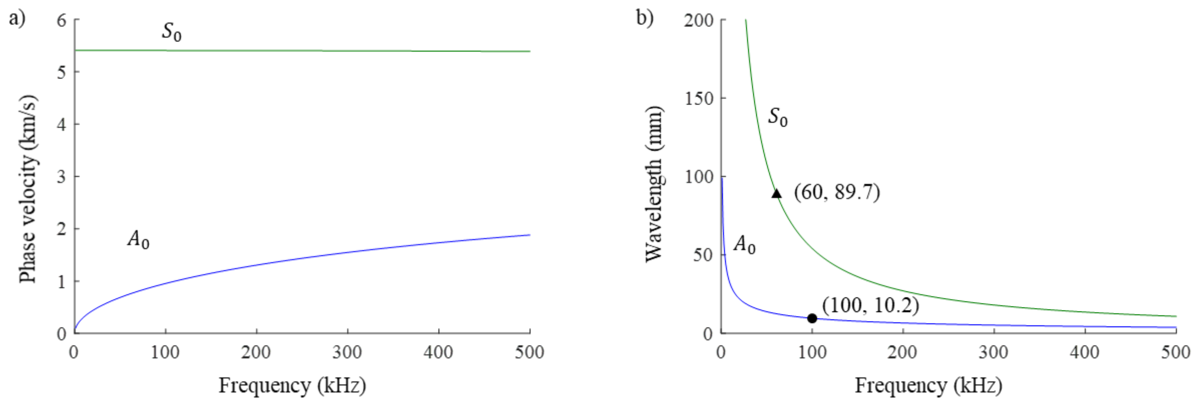

FIGURE 2: a) PHASE VELOCITY CURVE OF GUIDED WAVES IN A 1-MM THICKNESS ALUMINUM PLATE; b) WAVELENGTH DISPERSION CURVE OF GUIDED WAVES IN THE 1-MM THICKNESS ALUMINUM PLATE.

Furthermore, Bloch-Floquet boundary condition was applied to simulate the periodically arranged unit cells and obtain the frequency-wavenumber dispersion characteristic of the guided waves in this metasurface structure via modal analysis. In this study, the change of elastic modulus of the shape memory alloy stub was considered as a result of phase transformation between the martensite state and the austenite state. The finite element model is presented in Figure 1b. The calculated band structures of unit cells at different states are shown in Figure 3. Figure 3a and b presents the finite element models of the unit cell at the martensite phase and austenite phase states, respectively. Figure 3c exhibits that the band structure of the unit cell in the martensite phase, whereas Figure 3d illustrates the band structure of the unit cell in the austenite phase. It can be noticed that the stop bands were opened, indicating that the guided waves cannot pass through the metamaterial structure within the corresponding frequency region. The martensite state structure with a lower elastic modulus rendered a bandgap appearing from 63.1 kHz to 82.5 kHz. On the other hand, the bandgap moved to higher frequency range from 71.6 kHz to 91.7 kHz when the shape memory alloy state shifted to the austenite phase which possesses a larger elastic modulus. It is apparent that the dynamic properties of this shape memory metamaterial are adjustable. This phenomenon agrees well with the prediction of the mass-spring model given by Ref [8], verifying the underlying Local Resonance (LR) mechanism. A considerable bandgap location movement is thus proven, demonstrating the tunable property of the bandgap in this shape memory alloy metasurface. Furthermore, it is foreseeable that, by delicately selecting the guided wave excitation frequency and the state of the specific unit cells in the metasurface, the wave propagation path can be defined precisely. To provide a more intuitive perspective of the relationship between these two band structures in the martensite and austenite state unit cells, the overlapped bandgap plot is illustrated in Figure 4. The stop band range is thus divided into three regions. 82.5 kHz to 91.7 kHz corresponds to the wave propagation suppression frequency only for martensite structure; 71.6 kHz to 82.5 kHz represents 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 cells in austenite state. If the bandgap of a designated path of the regularly arranged unit cells is shifted away from the excitation frequency, a wave propagation route can be formed, leading to the concept of the tunable waveguide. Based on such a mechanism, the interrogating wave field can be guided into a desired monitoring region for the damage detection.

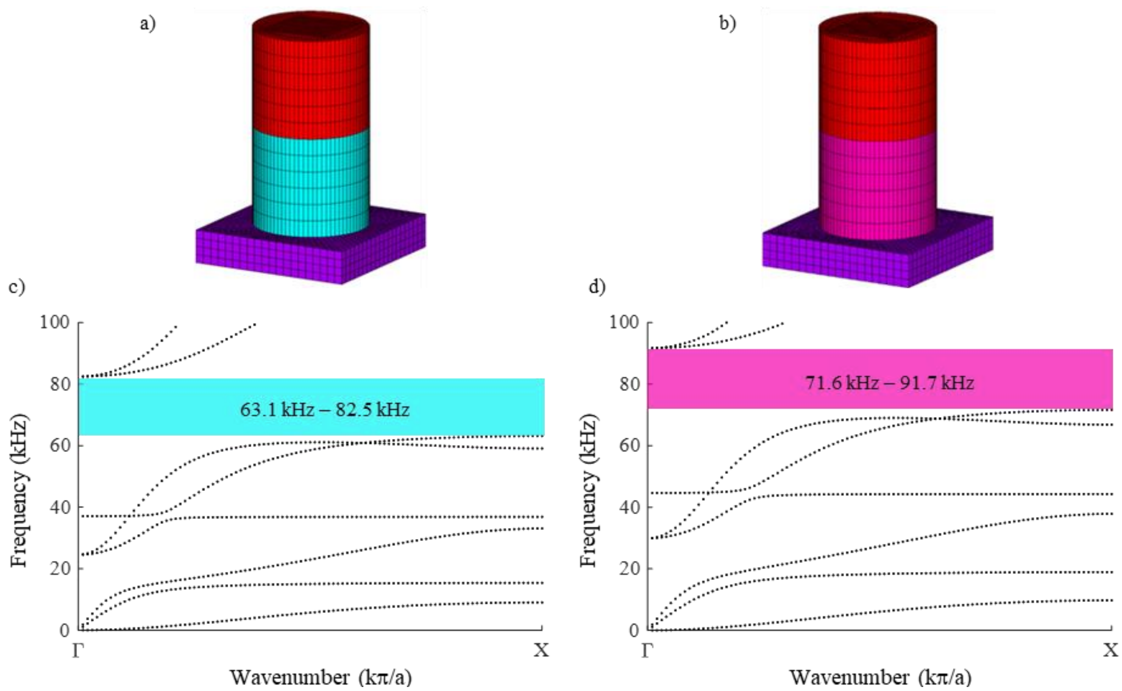

FIGURE 3: a) FINITE ELEMENT MODEL OF THE UNIT CELL IN THE MARTENSITE PHASE; b) FINITE ELEMENT MODEL OF THE UNIT CELL IN THE AUSTENITE PHASE; c) BAND STRUCTURE OF THE UNIT CELL IN THE MARTENSITE STATE; d) BAND STRUCTURE OF THE UNIT CELL IN THE AUSTENITE STATE.

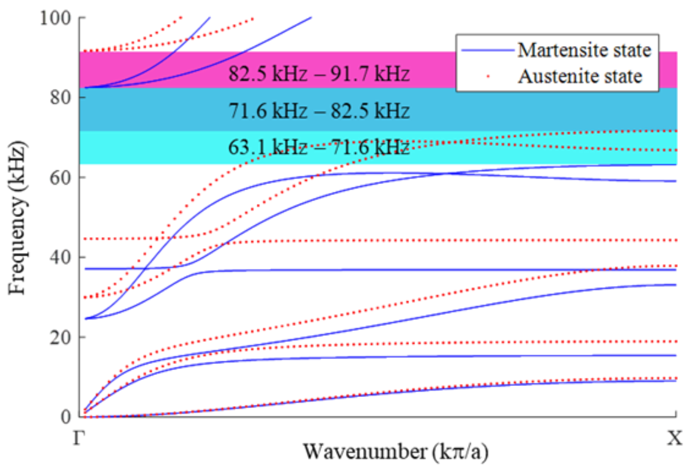

FIGURE 4: THE OVERLAPPED BAND STRUCTURES OF MARTENSITE STATE UNIT CELL AND AUSTENITE STATE UNIT CELL.

3. HARMONIC ANALYSIS OF THE SHAPE MEMORY ALLOY WAVEGUIDE

To investigate the waveguiding capability of the proposed metamaterial plate, a demonstrative case study was conducted. The metamaterial area was composed of 525 shape memory alloy unit cells sitting in an aluminum plate, periodically arranged to form a 21×25 rectangular array. The schematic of this structure is illustrated in Figure 5. In this numerical model, unit cells were arranged to forms a region of 105 mm×125 mm. A rectangular piezoelectric wafer active sensor with a size of 5 mm×125 mm×0.2 mm was bonded in adjacent to the longer side of the metasurface area. Guided waves with both symmetric and antisymmetric modes were generated, propagating into the metasurface system. Non-reflective boundary (NRB) condition [9] was implemented around the metasurface plate to eliminate the influence of the boundary reflections. According to the calculated wavelength in the previous section as shown in Figure 2b, it can be observed that when the excitation frequency is designated as 60 kHz, the lower edge of the bandgap region, S_0 mode has a wavelength of 89.7 mm. In general, the length of the non-reflective boundary should be twice as long as the maximum wavelength of the guided waves. Therefore, the non-reflective boundary length is set to be 180 mm.

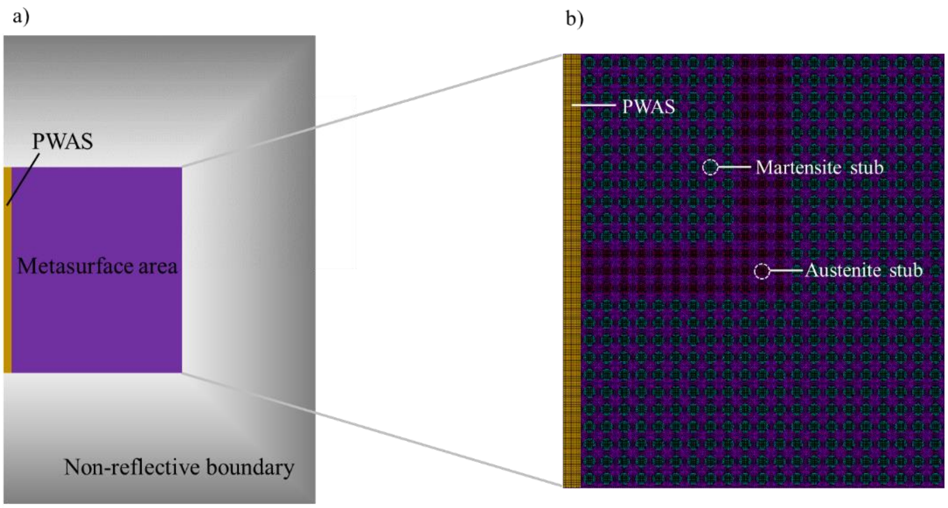

FIGURE 5: a) THE SCHEMATIC OF THE METASURFACE WAVEGUIDE WITH NON-REFLECTIVE BOUNDARY CONDITION; b) FINITE ELEMENT MODEL OF THE ZOOM-IN METASURFACE AREA.

For this model, harmonic analysis was carried out to verify the wave guiding capability of the proposed shape memory alloy metasurface. A 50-volt excitation was applied on the PWAS and the generated guided waves were swept from 60 kHz to 75 kHz. From the overlapped band structure results presented in the modal analysis, when the guided wave excitation frequency is around 63.1 kHz to 71.6 kHz, falling within the bandgap of the martensite structure at the same time outside austenite structure's bandgap, only the wave energy in the austenite state unit cells can pass through the metasurface area. Delicately shifting the specific unit cells from martensite to austenite via the thermal load, the wave propagation path can be tailored, facilitating the formation of a programmable waveguide.

A case study was first performed by controlling a specific 'L' shaped path of unit cell, shifting from the martensite to austenite. The schematic diagram is shown in Figure 6a. A rectangular region was plotted to represent the metasurface area in the metamaterial plate. Within the metasurface region, the black circle indicates that the unit cell is at the room temperature, i.e., the martensite state. While the red circle represents the unit cell of the austenite state in a high temperature, forming an L-shaped route. The steady-state equivalent stress wave field of the metamaterial plate for this pattern was obtained and plotted in Figure 6b, with the best waveguiding results appeared at 69 kHz. It can be observed that each unit cell formed a highlighted pixel in this simulation and the designated austenite pixels are illuminated. In this case, the horizontally generated guided wave front can be manipulated to propagate along the vertical direction. This phenomenon illustrates the successful achievement of the waveguiding via this proposed metasurface design.

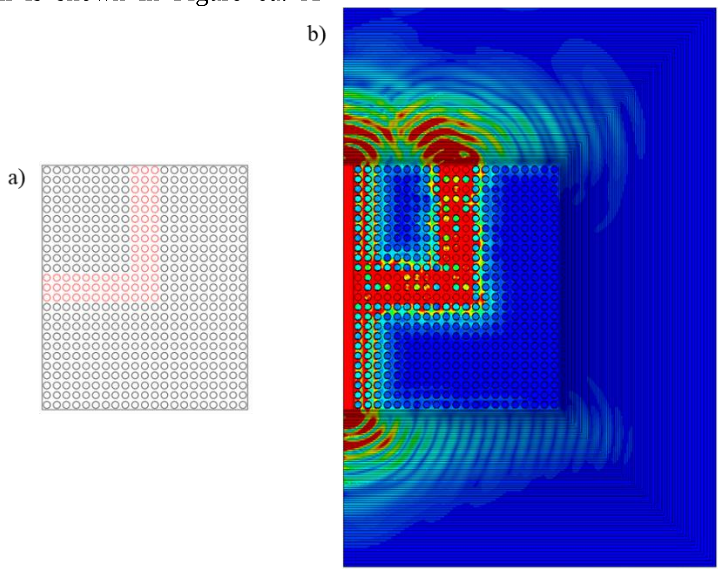

FIGURE 6: a) THE SCHEMATIC OF THE WAVEGUIDE FORMING A 'L' SHAPED PATH; b) THE EQUIVALENT STRESS WAVE FIELD OF THIS WAVEGUIDE.

To further verify a more complex waveguiding capability of this metasurface system, four ‘S’, ‘J’, ‘T’, ‘U’ shaped paths of austenite state unit cells in this waveguide were simulated. The equivalent stress field of the metasurface plate in these four cases were extracted at 69 kHz, 69.6 kHz, 69.6 kHz and 67.2 kHz respectively (all within the frequency range from 63.1 kHz to 71.6 kHz) for the best waveguiding effect, exhibiting a marvelous SJTU logo and a fantastic resolution as shown in Figure 7. Again, the waveguiding capability of this proposed shape memory alloy metamaterial was substantiated. The controllable state of the shape memory alloy unit cell and a couple of complex waveguiding shapes further demonstrated the programmable feature of the waveguide. This metasurface design opens an avenue for directing the interrogating wave field into a designated region. It possesses great application potential in future SHM and NDE systems for regional damage detection where the conventional transducers cannot survive.

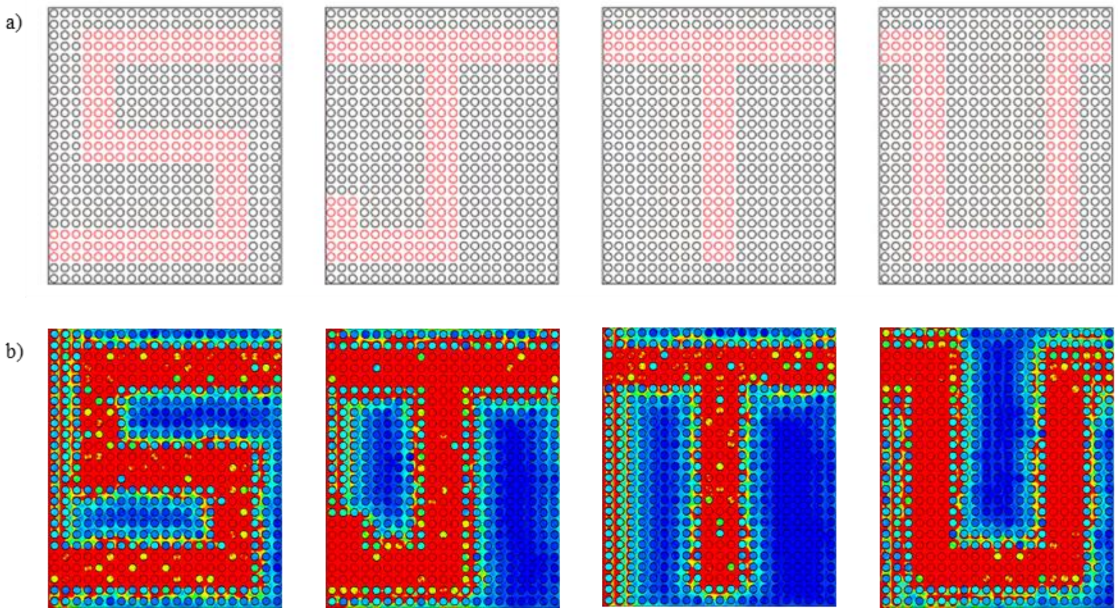

FIGURE 7: a) THE SCHEMATIC OF THE WAVEGUIDE IN THE CAPITALIZED ‘S’, ‘J’, ‘T’, ‘U’ SHAPED PATH; b) THE EQUIVALENT STRESS FIELD OF THIS WAVEGUIDE.

4. CONCLUSION

In this paper, we put forward a new programmable waveguide via a metamaterial design which allowed the flexible tuning of the elastic wave propagation path, enabling the interrogating wave field guiding into desired monitoring regions for damage detection. Shape memory alloy which possesses the elastic modulus change property between martensite phase and austenite phase during a heating procedure provide the feasibility to actively guide the wave propagation. Finite element models of the shape memory alloy unit cell in both martensite and austenite states were constructed and modal analysis was performed to explore the adjustable stop bands feature of this metamaterial structure. Then, a demonstrative waveguide which contained a 21×25 array of unit cells was modeled. Designating the excitation frequency only within the bandgap of martensite unit cell, different patterns of the waveguiding were realized by shifting the phase of shape memory alloy stub from martensite to austenite to establish a wave propagation route. Harmonic analysis was performed for a ‘L’ shaped configuration. The equivalent stress field was extracted and indicated a great waveguiding phenomenon. Finally, four ‘S’, ‘J’, ‘T’, ‘U’ shaped routes with a fantastic resolution were exhibited to show a SJTU logo in the stress contour plot, demonstrating the marvelous waveguiding capability and the programmable feature. This proposed metasurface design possesses a great application potential in future SHM and NDE systems for monitoring structural regions in harsh conditions where conventional transducers cannot survive.

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