Shear Horizontal Waves Converted from Piezoelectric-Transducer-Activated Lamb Waves Using Topologically Designed Meta-Converters

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ABSTRACT

Shear horizontal (SH) waves exhibit appealing features like non-dispersion (SH0 waves) and immunity to material nonlinearity, which benefit a range of applications, such as structural health monitoring (SHM). However, their effective excitation is challenging in practice due to the weak intensity of generated waves or the installation inconvenience of transducers. In this study, we propose an SH wave generation scheme based on mode conversion from piezoelectric-transducer-activated Lamb waves, with the help of add-on metamaterials. To this end, meta-converters, in conjunction with topology optimization methods, are employed to achieve high-efficiency conversion from Lamb waves to SH waves. 3D finite element models are employed to enable the destruction of structural symmetry in the out-of-plane, which is necessary for Lamb-wave-to-SH-wave conversion. In a broad band around the operation frequency, typical scenarios involving incident Lamb waves of varying modes and frequencies are considered, leading to a series of meta-converter designs. Taking incident waves as a baseline, the efficiency of the conversion is quantified in terms of the magnitude of the transmitted SH waves. Time-domain responses are analyzed to verify the efficient generation of SH waves. Finally, representative meta-converters are 3D-printed using the selective laser melting technique, with their capability for SH wave enhancement further validated by experiments. The proposed method offers an alternative and more generic route for SH wave generation, and paves the way for further SH-wave-based SHM applications.

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1. INTRODUCTION

Shear horizontal (SH) waves are characterized by their out-of-plane polarization of particle motion that is perpendicular to the direction of wave propagation [1]. They exhibit appealing features for structural health monitoring (SHM) applications, like the non-dispersion of SH0 waves [2]. However, the effective generation of SH waves is a crucial prerequisite for their SHM applications. For existing methods, the generated SH waves using shear-type piezoelectric transducers (PZTs) are rather weak in intensity, while practical implementation of magnetostrictive transducers (MsTs) is inconvenient due to the use of coils and unwieldy magnets.

It is well-known that Lamb waves can be readily excited in practice using typical d_{31} and d_{33} mode PZT transducers. This opens up the possibility of generating SH waves by means of converting Lamb waves into SH waves. To this end, the concept of metamaterials [3], a kind of artificially architectured materials/structures, can potentially be embraced. Relevantly, only a limited number of studies have investigated the mode conversion from other types of elastic waves to SH waves. For example, Kweun et al. [4] proposed the specific resonance and coupling conditions of realizing maximum mode conversion from longitudinal waves into SH waves by using porous elastic metamaterials. The study provides theoretical guidance for efficient mode conversion at a fundamental level. However, from a practical perspective, it is desirable for the converted SH waves to possess sufficiently high amplitudes to ensure effective wave-damage interaction, which is particularly critical for incipient damage monitoring. In addition, the surface-mounted configuration of metamaterials necessitates the use of three-dimensional (3D) models to break the inherent structural symmetry, which introduces additional complexity to the design process. These existing problems demand a systematic design of appropriate metamaterials to achieve more efficient and broadband generation of SH waves.

In this study, we propose an SH wave generation scheme based on the mode conversion from PZT-activated Lamb waves, with the help of tactically designed metamaterial-mediated converters (meta-converters) via topology optimization [5]. The meta-converters are consequently designed and fabricated to achieve high-efficiency conversion from Lamb waves to SH waves. In a broad operating frequency range (such as that of tone burst signals used in SHM [2]), typical scenarios involving incident Lamb waves of varying modes and frequencies are considered. After validating the effectiveness of the designed meta-converters by finite element (FE) simulations, some representative meta-converters are 3D-printed using the selective laser melting (SLM) technique, and then tested in experiments for SH wave generation.

2. TOPOLOGY-OPTIMIZATION-BASED DESIGN FRAMEWORK

As illustrated in Figure 1, meta-converters are installed in the vicinity of the transducer to convert the PZT-activated Lamb waves into SH waves. Fundamentally, the meta-converters need to be mounted on the surface of the host structure to ensure structural integrity. To improve the generation efficiency of SH waves, this section presents metamaterial designs using a topology optimization method.

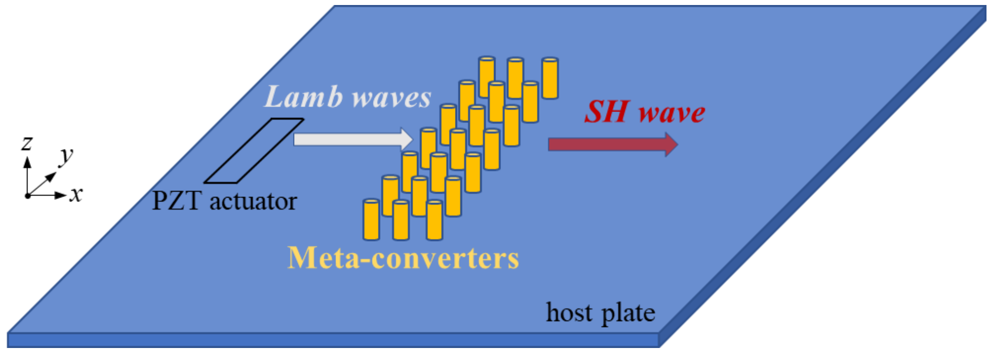

Figure 1. Schematic of SH wave generation converted from PZT-activated Lamb waves with meta-converters.

To maximize SH wave generation under the excitation of PZT transducers, topology optimization of meta-converters is carried out, with the corresponding 3D model illustrated in Figure 2(a). Specifically, Figure 2(b) presents the schematic of the meta-converter to be topology-tailored, which is to be attached to the surface of a host plate. To facilitate practical implementation, a thin base layer with a thickness of h_{con} is added to ensure structural connectivity, as depicted in Figure 2(b). The meta-converter on the base layer is discretized into $N\times N$ pixels in the *x*-*y* plane to enable the coupling between Lamb waves and SH waves. To reduce design variables, a 2D design domain is adopted in the *x*-*y* plane, as shown in Figure 2(c). In addition, the height h_{meta} of the meta-converter is set as a design variable as well. Tone burst signals, which are commonly employed in SHM, contain a certain bandwidth within which the operating frequency of meta-converters should be situated. This requires the designed meta-converter to possess a broadband feature. Taking these concerns into consideration, the objective function and constraints are formulated accordingly as:

$$maximizing: \sum_{i}^{n} a_i Amp_i^{SH}(\Sigma) \tag{1}$$

$$Subjected\ \ to: \theta_{ij} = 0 \text{ or } 1\,(i,\ j = 1, 2, \ldots, N), \tag{2}$$

$$h_{meta} \le h_{max}, \tag{3}$$

$$U(\Sigma) = U_1, \tag{4}$$

where Amp_i^{SH} represents the amplitude of SH waves at the *i*-th frequency component of the band, a_i is the corresponding weight, Σ denotes the material distribution inside the design domain, θ_{ij} represents the material selection of the *i*-*j* element, where 1 for solid materials and 0 for vacuum, and N is the dimension of the matrix. The height of meta-converters, h_{meta}, expressed by a binary vector, should be smaller than a prescribed value h_{max}. Eq. (4) defines a maximum number U_1 of interconnected blocks within the design domain.

Genetic algorithm (GA) [6] is employed as the searching method for updating design variables. The GA-based topological inverse-design scheme is readily available in our previous works [7].

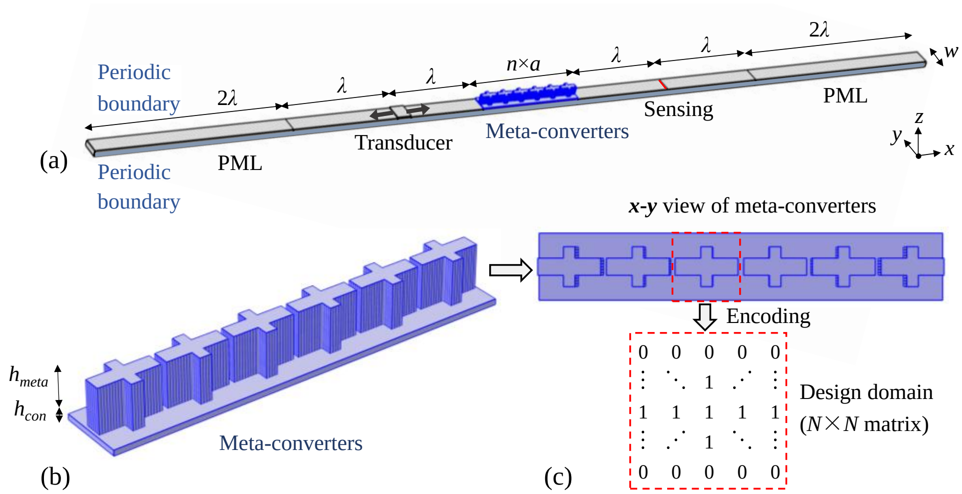

Figure 2. FE models used in the optimization procedure: (a) entire model, (b) schematic of meta-converters, and (c) *x-y* (top) view of the meta-converter model, including the design domain.

3. RESULTS AND DISCUSSIONS

3.1 TOPOLOGICALLY DESIGNED META-CONVERTERS

As a representative example, the central frequency is set to 150 kHz. Three discrete frequency points, namely 140, 150, and 160 kHz, are selected to represent the frequency band surrounding the central frequency. The corresponding assigned weights are a_i = [1, 1.2, 1], respectively, to account for their relative contributions according to the frequency spectrum. The steel meta-converter is constructed with six repeated unit cells, each with dimensions of a = 6 mm and w = 6 mm. The height of meta-converters is constrained to be less than 6 mm. The thickness of the base is set to 0.3 mm. An 8 mm-wide PZT patch is bonded on a 2 mm-thick aluminum plate. Boundary loads with an amplitude of 50e5 N/m^2 along the *x*-direction are applied to the left and right surfaces of the PZT transducer for Lamb wave excitation, as shown in Figure 2(a). The meta-converter and PZT transducer are attached to the host structure using 0.05 mm-thick adhesive layers. The material parameters of different components are shown in TABLE 1. Frequency-domain analyses are conducted using COMSOL Multiphysics 5.2a, where the amplitudes of SH waves are captured in terms of the *y*-direction displacement in the transmitted wave fields, as illustrated in Figure 2(a).

TABLE 1. MATERIAL PARAMETERS.

	Density (kg/m^3)	Poisson's ratio	Young's modulus (GPa)
Aluminum	2700	0.33	70
Adhesive	1080	0.4	1.31
Steel	7980	0.26	180

Three typical scenarios are considered, where the incident Lamb waves are set as (i) pure S (symmetric) mode Lamb waves, (ii) pure A (antisymmetric) mode Lamb waves, and (iii) a combination of S and A modes. Figure 3 presents the optimized meta-converters corresponding to the above three cases, namely MC#1, MC#2, and MC#3, respectively. It is evident that all structures exhibit complex yet interconnected topologies, largely owing to the imposed geometry constraints and the added base layer, which collectively facilitate their eventual fabrication.

In order to evaluate the performance of the designed meta-converters, the amplitudes of the incident Lamb waves and converted SH waves are extracted. Lamb waves are captured along the *x*-direction before the installation of meta-converters, whereas SH waves are captured along the *y*-direction with the deployment of the meta-converters. As evidenced by Figure 3, high-amplitude SH waves are generated in all cases with meta-converters installed considering different modes (S and A) and frequencies (140, 150, and 160 kHz). Notably, the amplitude ratio between the generated SH waves and the incident Lamb waves, which serves as an index to evaluate the performance of the meta-converters, can exceed one in some cases. The results demonstrate that effective mode conversions from Lamb waves to SH waves are achieved, thereby substantiating the efficacy of the designed meta-converters.

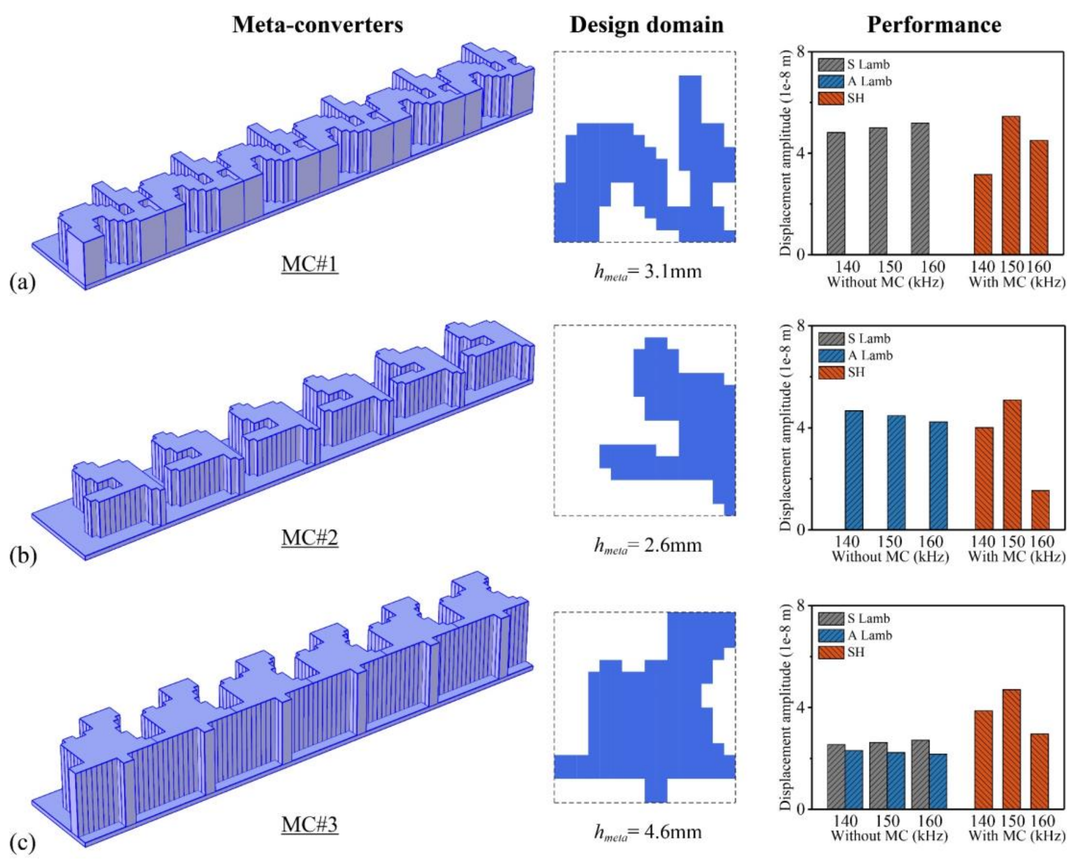

Figure 3. Optimization results of (a) pure S modes, (b) pure A modes, and (c) combinational S and A modes.

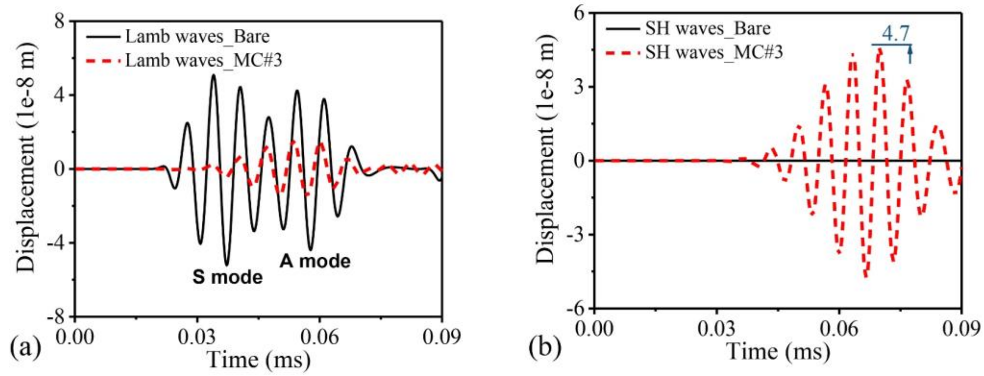

Figure 4. Numerical time-domain signals of (a) Lamb waves and (b) SH waves, with/without the optimized meta-converter MC#3.

3.2 NUMERICAL ANALYSES

Time-domain analyses are then conducted to assess the performance of the designed meta-converters by taking the structure MC#3 as a representative. The model in Figure 2(a) is employed again as the simulation model. 5-cycle tone burst signals with a central frequency of 150 kHz are used as excitations. Figure 4 presents the time-domain results corresponding to the meta-converter MC#3, where the bare plate cases serve as a reference to assess the intensity of the incident waves. In the bare plate, both S and A mode Lamb waves are excited, while SH waves are approximately zero. After deploying the meta-converter, high-amplitude SH waves are generated, as shown in Figure 4(b), accompanied by a reduction in the intensity of Lamb waves due to mode conversion (shown in Figure 4(a)). Specifically, the generated SH waves attain an amplitude of 4.7e-8 m, which is comparable in magnitude to that of the incident Lamb waves.

3.3 EXPERIMENTAL VALIDATIONS

Finally, experiments are carried out to validate the functionality of the designed meta-converters, with the structure MC#3 as an example. The meta-converters are fabricated using stainless steel 316 through the SLM technique, which ensures high-resolution topologies, as illustrated in Figure 5. Specifically, 9 layers of unit cells are adopted in the *y*-direction to ensure structural periodicity. In accordance with the simulation settings, 5-cycle tone burst signals with an amplitude of 150 V are applied on a PZT-5H transducer (8 mm × 30 mm × 0.3 mm) to excite Lamb waves. In addition, it is recognized that the extraction of SH waves from typical PZT-driven systems is challenging due to their weak intensity. To address this issue, MsTs are employed as the sensor. The MsT coil has a periodicity distance of 15.5 mm with a fold number of 4 to accommodate the current operating frequencies. Note that the MsTs used in this experiment solely serve as a means of measuring SH waves, which are fundamentally different from those discussed in the Introduction section in terms of purpose. All of the transducers and meta-converter samples are surface-affixed on a 2024 T3 aluminum plate with dimensions of 700 mm × 500 mm × 2 mm. The meta-converter sample and the sensor are positioned at distances of 30 mm and 270 mm from the PZT transducer, respectively.

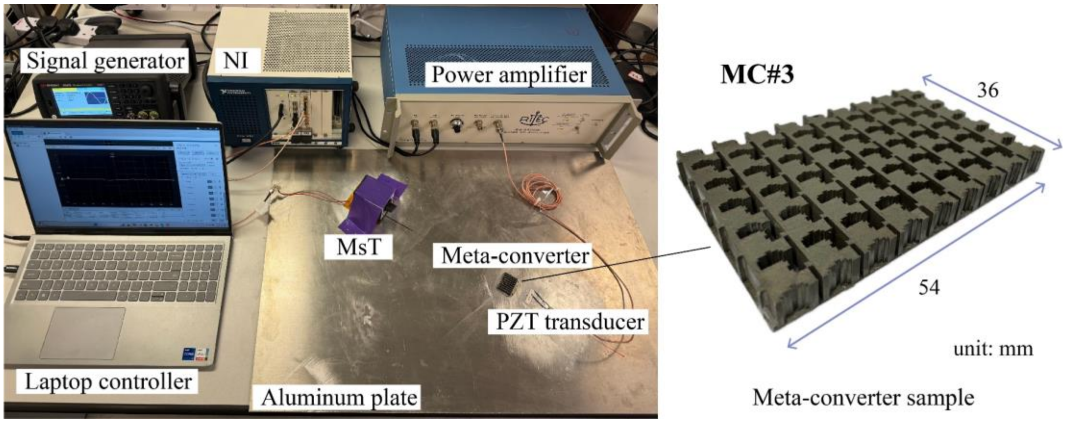

Figure 5. Experimental set-up, with the meta-converter sample MC#3 displayed.

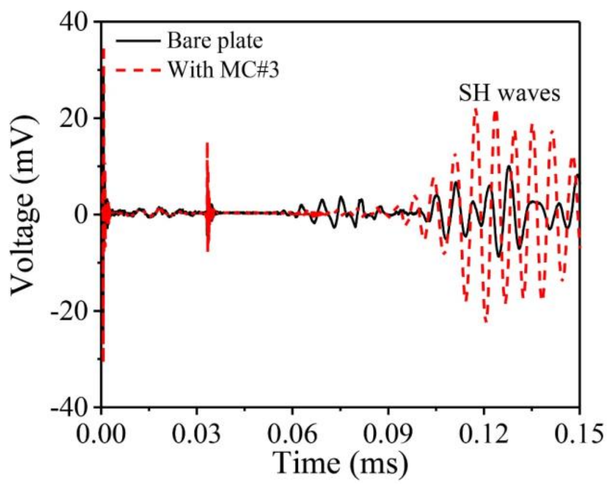

Figure 6. Experimental time-domain signals with/without the meta-converter sample MC#3.

The bare plate case is first tested to provide a reference. After that, the meta-converter samples are surface-attached to the plate to examine their mode-conversion capability through the measurement of SH waves. Figure 6 presents the time-domain results with/without MC#3. It is observed that the deployment of the meta-converters results in an apparent increase in the amplitudes of SH waves. The distinct comparison confirms the capacity of the proposed designs for effective generation of SH waves.

4. CONCLUSIONS

In light of the difficulty in efficient excitation of SH waves, this study proposes a meta-converter design for SH wave generation through tactical mode conversion from Lamb waves excited by PZT transducers. To achieve high-efficiency SH wave generation, topology optimization is conducted to tailor-make the add-on meta-converters on demand. The performance of the meta-converters is then systematically evaluated through both FE simulations and experimental validations. In all cases, including Lamb waves of different modes and frequencies, the optimized meta-converters enable effective SH wave generation. Furthermore, the time-domain responses confirm the efficient SH wave generation, with the assistance of meta-converters. Finally, the designed meta-converters are 3D-printed. Experimental tests validate the effective enhancement of SH waves achieved by the designed meta-converters. Specifically, the amplitude of SH waves is increased apparently with the aid of the meta-converter, highlighting its efficiency for SH wave generation. From an SHM perspective, the proposed method circumvents the installation inconvenience of MsTs in practical SHM implementations on one hand, and significantly improves the amplitudes of generated SH waves compared to traditional shear-type PZT transducers on the other hand.

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