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Extended abstract

Perfect oblique-incidence ultrasound transmission across dissimilar solids

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ABSTRACT

Perfect ultrasound transmission from one medium to another is critical in many applications, including medical treatment, imaging, and diagnostics. However, an obliquely incident ultrasonic wave through the solid-solid interface inevitably generates multiple wave modes (longitudinal waves and transverse waves). Accordingly, the well-known impedance matching theory considering only single wave mode fails to achieve the perfect oblique-incidence ultrasound transmission even from one isotropic solid to another. Here, we present the generalized matching theory that is newly established to enable the perfect transmission of ultrasonic waves across dissimilar solids at an arbitrary incidence angle and frequency. We also design a novel single-phase anisotropic solid-void metamaterial layer that can fulfill all conditions stated by the theory. It is shown that the insertion of the proposed metamaterial layer between metal (aluminum) and plastic (polyether ether ketone) plates achieves nearly perfect wave transmission over 98% energy efficiency, without which transmission reduces to 20%-40%. Our findings are validated numerically and experimentally.

Keywords: Ultrasound, Matching layers, Anisotropic metamaterials

1. INTRODUCTION

It is well-known that perfect transmission from one medium to another is possible if an impedance matching layer is inserted between two dissimilar media [1, 2]. However, the actual application is limited to single-mode wave fields only. Obliquely incident ultrasonic waves in solids (i.e. elastic waves) inevitably generate both longitudinal (L) and transverse (T) waves at an interface between two dissimilar solids (Fig. 1, left) [3]. Due to this intrinsic multi-modal property of elastic waves, the perfect transmission of obliquely incident ultrasonic waves across dissimilar solids has been impossible by inserting the conventional impedance matching layer.

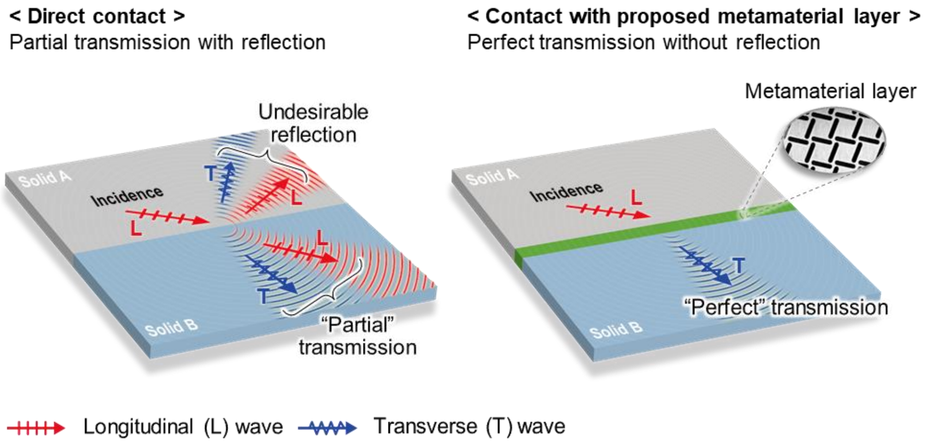


Fig. 1. An overview of perfect oblique-incidence ultrasound transmission across dissimilar media. Both longitudinal (L) and transverse (T) waves are reflected and transmitted at dissimilar solid-solid interfaces (left). However, a single-mode wave is fully and solely transmitted without any reflection by inserting the proposed metamaterial layer at the interface (right). Longitudinal-to-transverse perfect transmission is illustrated as an example.

Here, we present a novel theory enabling perfect oblique-incidence ultrasound transmission at solid-solid interfaces and design a new metamaterial layer realizing the theory (Fig. 1, right). This theory is valid for any form of wave transmission, either mode-preserving (longitudinal-to-longitudinal and transverse-to-transverse) or mode-converting (longitudinal-to-transverse and transverse-to-longitudinal). Perfect ultrasound transmission across dissimilar media is critical in various applications such as biomedical ultrasound [4] and nondestructive testing [5]. The dramatic transmission amplification at solid-solid interfaces can be a promising strategy to develop a new kind of powerful medical or industrial ultrasound equipment.

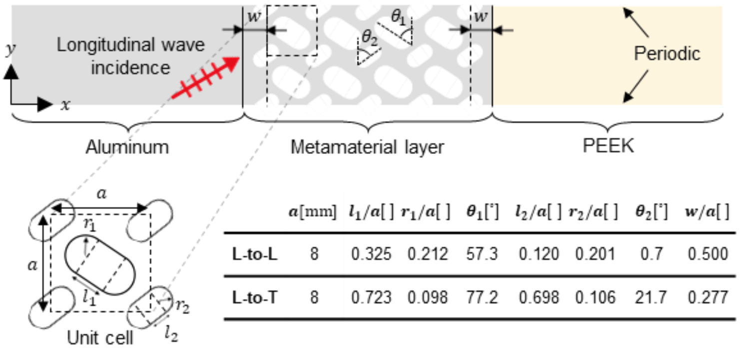
2. RESULTS

2.1 Theory and principle

We present a theory, established in Ref. [6], for perfect transmission of obliquely incident ultrasonic waves across two dissimilar isotropic solids. There are special conditions that an inserted metamaterial layer's material properties (mass density and elasticity tensor) should satisfy to achieve the perfect transmission. The physical significance of these conditions can be interpreted as the most generalized phase and impedance matching conditions. The detailed equations and derivations are not included here due to length limitations. (See Ref. [6] for the theoretical details.) The principle of the perfect transmission represents an interference among four longitudinal-transverse coupled waves (quasi-longitudinal and quasi-transverse waves propagating forward and backward) inside the proposed metamaterial layer.

2.2 Numerical and experimental results

A novel single-phase anisotropic solid-void metamaterial was designed and fabricated to realize the metamaterial layer satisfying the generalized phase and impedance matching conditions. Without loss of generality, target frequencies for the longitudinal-to-longitudinal (L-to-L) and longitudinal-to-transverse (L-to-T) perfect transmissions were determined as 79.5 kHz and 59.5 kHz. A target incidence angle for the perfect transmission was determined as 60°. As a case study, an aluminum-based metamaterial layer was designed at the interface between aluminum and polyether ether ketone (PEEK), where the longitudinal and transverse transmittances were only 39.4% and 20.2%, respectively, due to their very high impedance mismatch. As a unit cell of the metamaterial, we considered the one shown in Fig. 2 which has two different oblique slit-shaped voids with geometries characterized by nine design parameters (a, N, l_1, r_1, θ_1, l_2, r_2, θ_2 and w). The unit cell layouts for the L-to-L and L-to-T perfect transmissions were optimally designed based on the Method of Moving Asymptotes algorithm.

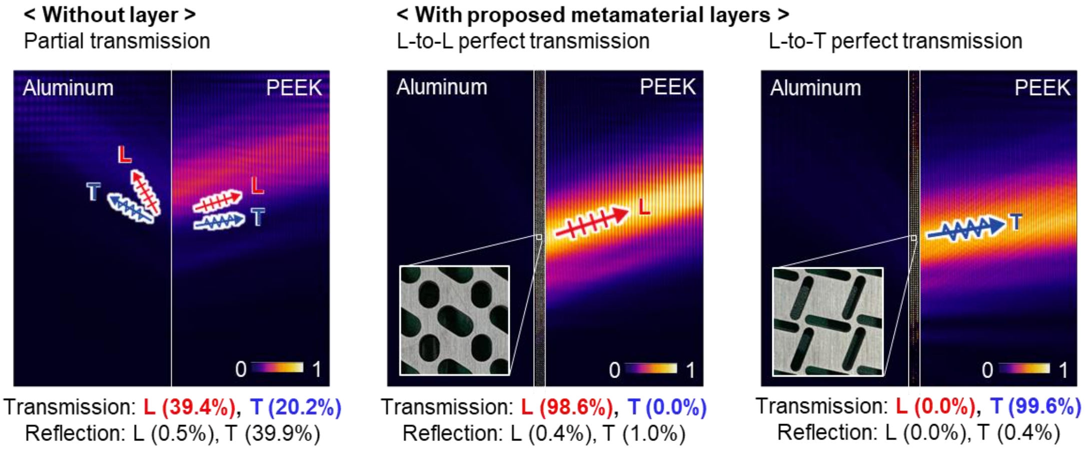


	a[mm]	l_1/a[ ]	r_1/a[ ]	θ_1[°]	l_2/a[ ]	r_2/a[ ]	θ_2[°]	w/a[ ]
L-to-L	8	0.325	0.212	57.3	0.120	0.201	0.7	0.500
L-to-T	8	0.723	0.098	77.2	0.698	0.106	21.7	0.277

Fig. 2. Realization of an anisotropic solid-void metamaterial layer. Geometric dimensions of the designed metamaterial layers for the longitudinal-to-longitudinal (L-to-L) and longitudinal-to-transverse (L-to-T) perfect transmissions are presented.

Several numerical simulations and experiments performed with the designed metamaterial layers confirmed the validity of the established theory and our metamaterial design. Numerical simulations in Fig. 3 reveal that the transmittance from an incident longitudinal wave to a transmitted longitudinal (transverse) wave can be enhanced from 39.4% (20.2%) without the metamaterial layer to 98.6%

(99.6%) with the metamaterial layer at the interface between 5 mm thick aluminum and PEEK plates under the plane-stress condition. The experimental results also supported nearly perfect transmission; the measured displacement amplitudes of the transmitted longitudinal (transverse) wave were amplified by 2.59 (4.55) times when the metamaterial layer was inserted. (See Ref. [6] for the numerical and experimental details.)


< Without layer >
Partial transmission

< With proposed metamaterial layers >
L-to-L perfect transmission
L-to-T perfect transmission

Transmission: L (39.4%), T (20.2%)
Reflection: L (0.5%), T (39.9%)

Transmission: L (98.6%), T (0.0%)
Reflection: L (0.4%), T (1.0%)

Transmission: L (0.0%), T (99.6%)
Reflection: L (0.0%), T (0.4%)

Fig. 3. Verification of mode-preserving and mode-converting perfect oblique-incidence ultrasound transmission. Scattered energy densities without and with the proposed metamaterial layers were numerically simulated. A longitudinal wave entered from aluminum to PEEK with an incidence angle of 60°. Longitudinal-to-longitudinal (L-to-L) and longitudinal-to-transverse (L-to-T) perfect transmissions were realized via the designed metamaterial layers at frequencies of 79.5 kHz and 59.5 kHz, respectively.

3. CONCLUSION

This paper presents a theory that enables both mode-preserving and mode-converting perfect transmissions of ultrasonic waves across dissimilar isotropic solids at an arbitrary incidence angle and frequency. Furthermore, the applicability of the theory is practically demonstrated by designing a single-phase anisotropic solid-void metamaterial, the use of which enabled the perfect oblique-incidence ultrasound transmission. The findings from this paper are expected to open new avenues for manipulating ultrasonic waves in solids.

ACKNOWLEDGEMENTS

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