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Ultrasonic Communication through a Metallic Barrier: Transmission Modeling and Crosstalk Minimization

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***Abstract*—For systems that require complete metallic enclosures (e.g., containment buildings for nuclear reactors), it is impossible to access interior sensors and equipment using standard electromagnetic techniques. A viable way to communicate and supply power through metallic barriers is the use of elastic waves and ultrasonic transducers, introducing several design challenges that must be addressed. The objective of this work is to investigate the use of piezoelectric transducers for both sending and receiving power and data through a metallic barrier using elastic waves at ultrasonic frequencies above 1 MHz. High-fidelity numerical and simplified analytical models are developed for ultrasonic transmission and novel strategies are explored to eliminate crosstalk between channels.**

***Index Terms*—Acoustic power transfer, acoustic data transfer, piezoelectric, guided waves, phononic crystal, metamaterial**

I. INTRODUCTION

For systems that require complete metallic enclosures, it is impossible to access interior sensors and equipment using standard electromagnetic techniques such as inductive power transfer [1]. One solution to this problem is the use of ultrasonic waves and transducers [2]. An electrical signal on one side of the barrier is provided as input to a transducer, generating an elastic wave that propagates to the receiving transducer on the other side of the barrier. Although there have been promising results for power and data transmission for a single communication channel [3]–[5], it is desirable to have both power transmission and data transmission through multiple channels on a single barrier. These multi-channel systems present a new design challenge: specifically, the actuation of each transmitter generates guided waves that propagate in the barrier, potentially generating unwanted signal crosstalk on receivers elsewhere on the barrier. This *electromechanical crosstalk* is especially important for data communication channels, which have more stringent operating envelopes for effective data transmission and may operate at a much lower voltage level than power transfer tiles.

The objective of this work is to investigate strategies for minimizing signal crosstalk received by mechanical data transmission tiles. First, numerical simulations show that appropriate tile layout can avoid significant wave propagation between tiles. Next, a phononic crystal/metamaterial machining strategy is proposed to block the guided waves generated by power transfer tiles, controlling the propagating guided wave modes by periodically machining grooves into the barrier.

II. TILE LAYOUT

The first strategy to reduce crosstalk between tiles is to place each communication channel such that it does not generate significant crosstalk in adjacent channels. This strategy relies on the fact that each communication channel uses “plate-type” transducers, with thickness much less than their characteristic width. As a result, guided waves at the operating frequency of the tiles (i.e., > 1 MHz) have wavelengths much smaller than the characteristic size of the tile. In this way, the use of square tiles results in very directional guided wave propagation, with most of the wave energy propagating perpendicular to the tile edges. This phenomenon is illustrated using numerical finite element simulations of a 3×3 grid of piezoelectric

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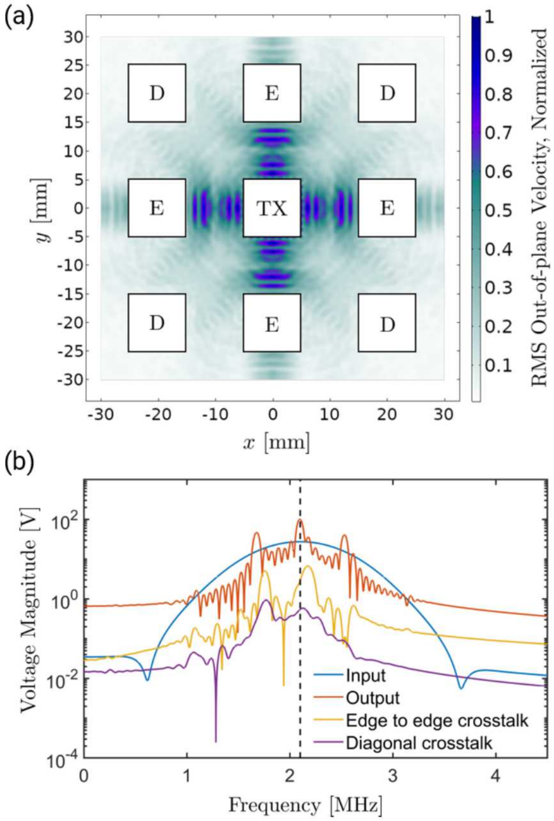

Fig. 1. (a) Out-of-plane velocity RMS for actuation of the center tile with a five-cycle Gaussian sine burst at 2.1 MHz and a simulation time of 16.2 µs. The square regions indicate separate communication tiles, labeled "TX" for the actuated channel, "E" for edge-adjacent channels, and "D" for diagonally-adjacent channels. (b) Magnitude spectrum comparing input, direct transmission, edge-adjacent crosstalk, and diagonally-adjacent crosstalk. Diagonal placement significantly reduces the crosstalk received by a tile.

communication channels on a 3 mm thick aluminum barrier, each comprising two 1 cm × 1 cm × 1 mm thick PZT-4 tiles, with 1 cm between tile edges. The center tile was actuated at its primary resonant frequency of 2.1 MHz, and the crosstalk voltage on the edge-adjacent tiles and diagonally adjacent tiles were compared. For a a five-cycle Gaussian sine burst at 2.1 MHz and a simulation time of 16.2 µs, the root mean square out-of-plane velocity field is shown in Fig. 1a. The spectrum (fast Fourier transform) of the input voltage, direct transmission voltage, and both crosstalk voltages are shown in Fig. 1b. From Fig. 1, it is clear that the guided waves propagate predominantly perpendicularly to the actuated tile edges. This is also indicated by the relative magnitude of the spectra in Fig. 1b, which shows that the crosstalk received by the diagonally adjacent tile is an order of magnitude less than the edge-adjacent tile. These results suggest that placing square tiles in a diagonal array will greatly reduce crosstalk between the tiles, and that edge-to-edge adjacency between tiles should be avoided.

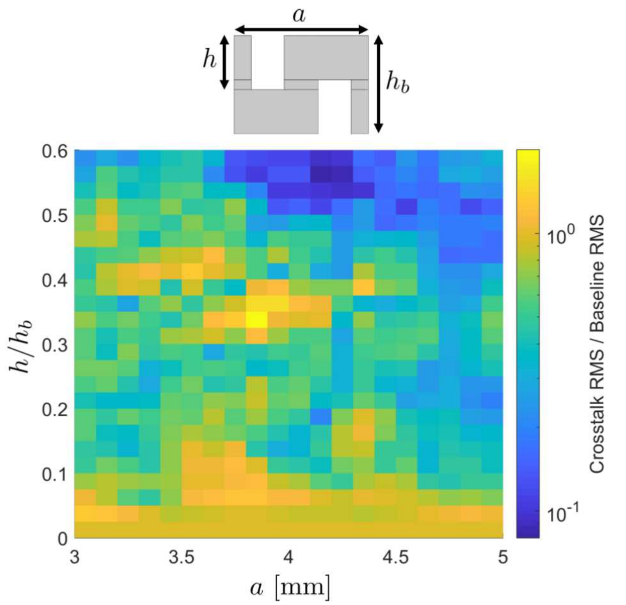

Fig. 2. Crosstalk voltage reduction vs. groove depth h normalized by barrier thickness h_b and unit cell size a.

III. MACHINED PHONONIC CRYSTAL

In many situations, the strategy of placing tiles to avoid crosstalk may not be feasible due to geometric constraints. For these situations, we propose to minimize crosstalk using periodic grooves machined into the metallic barrier, changing the guided wave modes that are able to propagate in the barrier. Again, the use of square tiles allow us to consider only waves propagating perpendicular to the tile edges; correspondingly, we consider 2D plane strain simulations of grooves that extend infinitely parallel to the tile edges. For this study, we consider only 1 mm wide rectangular grooves placed in a periodic fashion, alternating on the top and bottom surfaces of the barrier. The unit cell geometry is parameterized by the unit cell size a (i.e., the distance between periodic grooves on one side of the barrier) and the groove depth h (see Fig. 2). To characterize the performance of each unit cell design, we consider transient simulations using five unit cells between a pair of 1 mm thick tiles operating at 2.1 MHz and an adjacent channel comprising two 0.5 mm thick tiles. There is one region of interest near $a = 4$ mm and $h = 0.55h_b$ that offers significant crosstalk reduction (i.e., an order of magnitude or more) over a wide range of parameters, which is attractive for its reduced sensitivity to parameter variation. The crosstalk reduction performance in this case indicates the presence of a guided wave bandgap introduced in the barrier due to the periodic grooving into the barrier. These results indicate that this type of grooving can greatly reduce crosstalk while maintaining the structural integrity of the barrier.

To investigate the mechanism of crosstalk reduction, we consider the dispersion curves of the best-performing unit cell from Fig. 2. This design has grooves alternating on each surface of the barrier, with $h/h_b = 0.55$ and $a = 4.1$ mm.

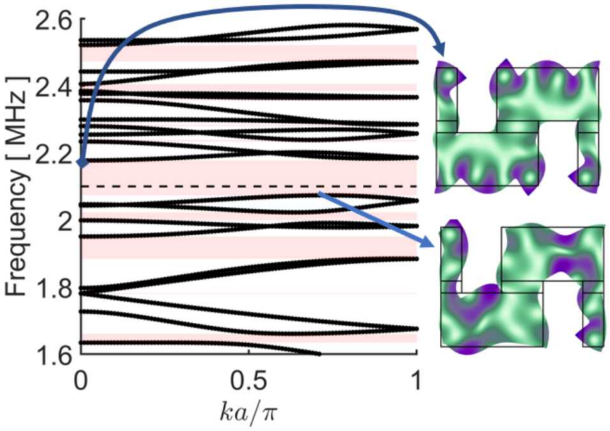

Fig. 3. Dispersion diagrams and selected mode shapes for the best-performing designs from Fig. 2 ($h/h_b = 0.55$, $a = 4.1$ mm). The dashed line indicates the center frequency of excitation for the transient studies, and the shaded regions indicate bandgaps.

To calculate the dispersion curves, we consider a 2D plane strain finite element model of single periodic unit cell with one groove on each surface, applying Floquet periodic boundaries to the edge faces. By sweeping the wavenumber k and calculating the eigenfrequencies of the unit cell, the dispersion curves can be obtained, as shown in Fig. 3.

IV. CONCLUSIONS

We present two strategies for minimizing the crosstalk between mechanical communication channels in a metallic barrier. Pairs of opposing piezoelectric transducers communicate through a metallic barrier by generating and receiving elastic waves in the barrier. This actuation results in guided wave propagation away from the transducers, generating unwanted signal crosstalk on other communication channels. This crosstalk can be reduced significantly by using square tiles that avoid edge-to-edge adjacency (e.g., placing tiles in a diagonal array), due to the highly directional nature of the short-wavelength guided wave modes in the barrier. Crosstalk can also be minimized at a fixed frequency by periodically machining grooves into the barrier, reducing the guided wave modes that are able to propagate in the barrier. Effective groove designs can be obtained through numerical transient simulations and band structure analysis.

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