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Wideband Acoustic Data Transmission Through Staircase Piezoelectric Transducers

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***Abstract*—Ultrasounds have been investigated for data communication to transmit data across enclosed metallic structures affected by Faraday shielding. A typical channel consists in two piezoelectric transducers bonded across the structure, communicating through elastic mechanical waves. The rate of data communication is proportional to the transmission bandwidth, which can be widened by reducing the thickness of the transducers. However, thin transducers become brittle, difficult to bond and have a high capacitance that would draw a high electric current from function generators. This work focuses on investigating novel transducer shapes that would allow to provide a constant transmission across a large bandwidth while maintaining large-enough thickness to avoid brittleness and electrical impedance constraints. The transducers are shaped according to a staircase thickness distribution, whose geometry has been designed through an analytical model describing its electro-mechanical behavior formulated for this purpose.**

***Index Terms*—piezoelectric transduction, acoustic transmission, through-wall data transmission, bandwidth enhancement**

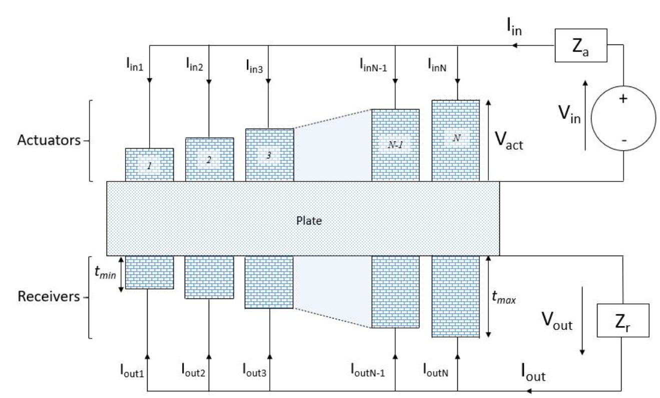

Fig. 1: Structure for piezoelectric data transmission across multiple parallel channels

I. Introduction

While methods based on electromagnetic waves such as capacitive coupling [1], inductive coupling [2] or magnetic resonance coupling [3] constitute a traditional approach to transmit data across a barrier, they become highly inefficient in an enclosed metallic structure due to the Faraday shielding. A possible solution consists of using mechanical waves generated through piezoelectric transduction [4]. A piezoelectric actuator bonded to the barrier is then actuated by an input signal, therefore generating elastic waves traveling towards a piezoelectric receiver on the other side of the structure. Different results have shown the possibility of experimentally communicating across a metallic plate [5], [6]. While the rate of data transmission is proportional to the usable bandwidth in

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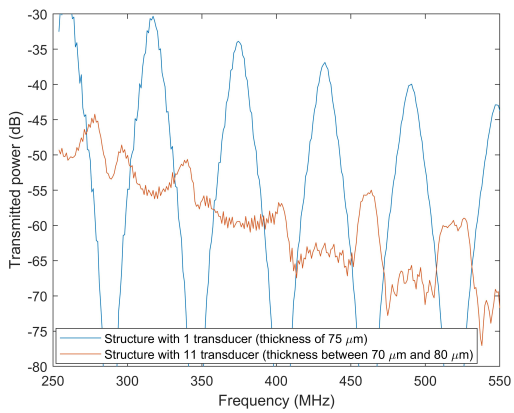


Fig. 2: Finite element comparison of a structure made of a single channel (transducer thickness of 75 μm) with a structure of 11 channels (transducer thickness between 70 μm and 80 μm)

the frequency domain, the fidelity between the input and the output can be improved by reducing the amplitude variations within this bandwidth. Methods such as a shunted electrical impedance [7] have then been introduced to decrease the fluctuations of the transmission magnitudes. However, for high frequencies the usable bandwidth is limited by the presence of anti-resonances. The objective of this research is to introduce a transducer design with a varying thickness to overcome the anti-resonances and allow the possibility of transmitting data across a larger bandwidth.

II. Structure of the communication channel

A regular piezoelectric communication channel is made of two piezoelectric transducers bonded to a plate and driven around their fundamental resonance frequency. In this paper, we explore the possibility of driving these piezoelectric patches at high frequencies (in the range of hundreds of MHz). The objective is to define a configuration with a bandwidth above 100 MHz, within which the amplitude variations are limited to 3 dB (also called bandwidth at -3 dB). Communications at such frequencies would require a decrease in the transducer thickness to a range of a few micrometers. However, when piezoelectric tiles are too thin, they become extremely brittle. In addition, they are characterized by a large capacitance that would draw a high current from the generator. Conversely, when thicker transducers are used, the usable bandwidth is limited by the presence of numerous anti-resonances.

A structure of N communication channels connected in parallel and transmitting a signal across a plate is therefore introduced (Fig. 1). Each channel is composed of an actuating transducer, a metal plate, and a receiving transducer. Each of the actuators are connected to one generator (voltage V_{in}) and are in series with an electrical impedance Z_a. The receivers are connected to a measurement device through the electric impedance Z_r. The thicknesses of the transducers in each channel increase regularly from t_{min} to t_{max}, therefore giving the structure a staircase shape. While the bandwidth associated with each separate channel is limited by the presence of anti-resonances, they are now compensated by the presence of other channels. In Fig. 2 the transmitted power ($20 * log_{10}(V_{out}/V_{in})$) of a structure with 11 channels that have transducer thicknesses increasing from 70 μm to 80 μm and are without electrical impedances is compared to a single channel with a transducer thickness of 75 μm. The figures were generated using the Finite Element software COMSOL.

III. Extension of the Mason model for N communication channels

The Mason model is a one-dimensional analytical approach that describes both the electrical and mechanical behavior of a single piezoelectric communication channel. It relates the voltage and current across the receiving transducer (V_{out} and I_{out}) with the voltage and current across the actuator (V_{act} and I_{in}) through a 2X2 transmission matrix $[T]$:

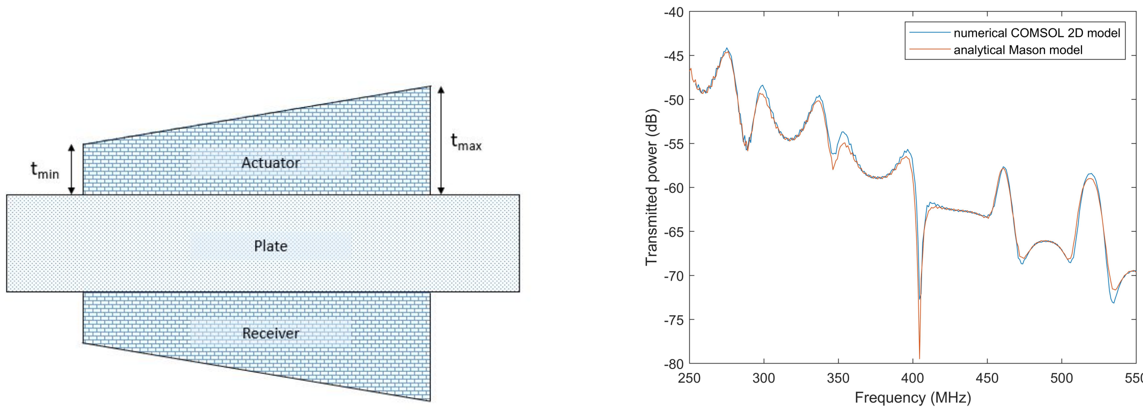
$$\begin{bmatrix} V_{out} \\ I_{out} \end{bmatrix} = [T]. \begin{bmatrix} V_{act} \\ I_{in} \end{bmatrix} \tag{1}$$

The Mason model is extended to a system of N channels to characterize the data transmission for the structure introduced previously. The i-th channel is characterized by a transmission matrix $[T_i]$. $I_{in(i)}$ represents the current across the i-th actuator while $I_{out(i)}$ is the current across the i-th receiver. The voltage across all the actuators is identical and defined by V_{act}. The voltage across all the receivers is identical and defined by V_{out}. Each channel is considered to be mechanically independent, which means that there is no mechanical crosstalk between them. However, they are electrically connected to the same generator and measurement tool. The electrical and mechanical behavior of the full system is therefore described by the following equations (for i=1,...,N):

$$\begin{gathered} \begin{bmatrix} V_{out} \\ I_{out(i)} \end{bmatrix} = [T_i]. \begin{bmatrix} V_{act} \\ I_{in(i)} \end{bmatrix} = \begin{bmatrix} T_{11(i)} & T_{12(i)} \\ T_{21(i)} & T_{22(i)} \end{bmatrix} . \begin{bmatrix} V_{act} \\ I_{in(i)} \end{bmatrix} \\ V_{out} = -Z_r \sum_{i=1}^{N} I_{out(i)} \\ V_{in} = V_{act} + Z_a \sum_{i=1}^{N} I_{in(i)} \end{gathered} \tag{2}$$

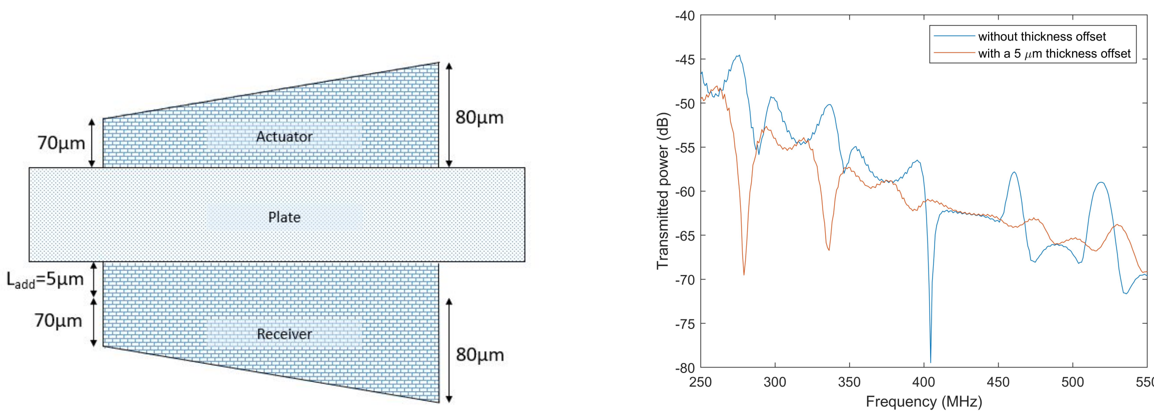
The system of equations (2) can be solved to provide the ratio V_{out}/V_{in}:

$$V_{out}/V_{in} = \frac{N_1 - N_2}{1 + D_1 Z_r - D_2 Z_a - D_3 Z_r Z_a} \tag{3}$$



(a) (b)

Fig. 3: a) Geometry of the slanted transducer, b) Comparison of the transmitted power between a numerical 2D COMSOL model for a slanted transducer and an analytical Mason model decomposed into 100 channels



(a) (b)

Fig. 4: a) Geometry of the slanted transducer with thickness offset at the receiver, b) Comparison of the transmitted power between a channel without thickness offset and a channel with a 5 μm thickness offset

where

$$\begin{aligned} N_1 &= \sum_{i=1}^{N} T_{21(i)},\ N_2 = \sum_{i=1}^{N} \frac{T_{11(i)}T_{22(i)}}{T_{12(i)}} \\ D_1 &= \sum_{i=1}^{N} \frac{T_{22(i)}}{T_{12(i)}},\ D_2 = \sum_{i=1}^{N} \frac{T_{11(i)}}{T_{12(i)}} \\ D_3 &= \sum_{i=1}^{N} T_{12(i)} \sum_{i=1}^{N} \frac{1}{T_{12(i)}} - \frac{T_{11(i)}T_{22(i)}}{T_{12(i)}} \sum_{i=1}^{N} \frac{1}{T_{12(i)}} \\ &\quad + \sum_{i=1}^{N} \frac{T_{22(i)}}{T_{12(i)}} \sum_{i=1}^{N} \frac{T_{11(i)}}{T_{12(i)}} \end{aligned} \tag{4}$$

IV. Introduction of the Slanted Transducer Design

A major drawback of the structure with N channels is the amount of space required for the setup on the plate. Consequently, a more compact structure that utilizes the shape of a slanted transducer is introduced (Fig. 3a). It consists of a single actuator with a varying thickness increasing linearly between t_{min} and t_{max} that faces a similar receiver across the plate. The analytical approach based on the Mason model is used to describe the behavior of the slanted transducer by breaking it down into multiple parallel channels of increasing thicknesses. This approach is compared with numerical results for a slanted transducer from a COMSOL 2D model in Fig. 3b. In the analytical extended Mason model, the transducers are decomposed into 100 parallel channels. The thickness of the transducers ranges between $t_{min} = 70\mu m$ and $t_{max} = 80\mu m$ and have no electrical impedances connected. The results offer a validation of the Mason extended model to describe the behavior of the slanted transducer when the structure is decomposed into a sufficient number of parallel channels.

V. Strategies for Bandwidth Enhancement

A. Thickness offset between the actuator and the receiver

While the slanted transducer design decreases the amplitude variation when compared to a flat transducer, its finite thickness dimensions still generate abrupt amplitude changes. However, these variations can be partly cancelled if the actuator and the receiver have different thicknesses, such that a section of the actuator working at its resonance faces a section of the receiver working at its anti-resonance. Therefore, a new design is introduced where an additional thickness L_{add} is added uniformly to the receiver while the actuator remains unchanged. L_{add} equals to half of the wavelength in the transducers at the targeted frequency.

For an actuator with a thickness varying between $70\mu m$ and $80\mu m$, an additional receiver thickness of $5\mu m$ (for a total thickness between $75\mu m$ and $85\mu m$) corresponds to a half-wavelength at the frequency 430 MHz (Fig. 4a). The transmitted power between the structures with and without the thickness offset are computed through the analytical extended Mason model and compared in Fig. 4b.

B. Structure with electric impedances

For growing frequencies, the impedance associated with the capacitance of the piezoelectric transducers decreases. This generates a transmission loss and results in a negative slope that needs to be compensated to obtain a large bandwidth at -3 dB. This issue is solved by introducing electrical impedances Z_a and Z_r connected respectively to the actuator and to the receiver. Each electrical impedance is comprised of a resistance (R_a for the actuator, R_r for the receiver) in series with an inductance (L_a for the actuator, L_r for the receiver). The resulting electrical impedances are then given by:

$$\begin{aligned} Z_a &= R_a + jL_a * (2\pi f) \\ Z_r &= R_r + jL_r * (2\pi f) \end{aligned} \tag{5}$$

where f is the driving frequency.

The transmitted power of the system is computed through the extended Mason model while varying the parameters R_a, R_r, L_a and L_r across an array of values in order to find numerically the largest bandwidth at -3dB possible. The structure with a thickness offset introduced in the previous subsection is again used while considering a transducer cross-section of 1 cm^2. The largest bandwidth at -3 dB is found for $R_a = 35m\Omega$, $L_a = 20pH$, $R_r = 9m\Omega$, $L_r = 9pH$. It equals to 185 MHz for a carrier frequency of 430 MHz (Fig. 5).

VI. Conclusions

The design of a slanted piezoelectric transducer is introduced as an approach to transmit data across a Faraday cage at high frequencies (in the range of hundreds of MHz) while limiting the amplitude variations over the largest bandwidth possible. This design succeeds in overcoming the presence of anti-resonances found in structures with flat transducers. Configuration enhancements such as a thickness offset between the actuator and the receiver as well as the presence of electrical impedances in the circuits connected to both transducers are also introduced. With these improvements, a bandwidth at -3dB of 185MHz is derived for a carrier frequency of 430MHz.

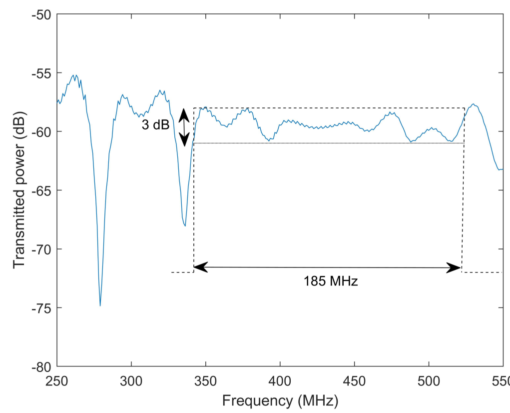


Fig. 5: Transmitted power for a structure with slanted transducers connected to electrical impedances

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