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One-dimensional pressure transfer models for acoustic–electric transmission channels

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ABSTRACT

A method for modeling piezoelectric-based ultrasonic acoustic–electric power and data transmission channels is presented. These channels employ piezoelectric disk transducers to convey signals across a series of physical layers using ultrasonic waves. This model decomposes the mechanical pathway of the signal into individual ultrasonic propagation layers which are generally independent of the layer's adjacent domains. Each layer is represented by a two-by-two traveling pressure wave transfer matrix which relates the forward and reverse pressure waves on one side of the layer to the pressure waves on the opposite face, where each face is assumed to be in contact with a domain of arbitrary reference acoustic impedance. A rigorous implementation of ultrasonic beam spreading is introduced and implemented within applicable domains. Compatible pressure-wave models for piezoelectric transducers are given, which relate the electric voltage and current interface of the transducer to the pressure waves on one mechanical interface while also allowing for passive acoustic loading of the secondary mechanical interface. It is also shown that the piezoelectric model's electrical interface is compatible with transmission line parameters (ABCD-parameters), allowing for connection of electronic components and networks. The model is shown to be capable of reproducing the behavior of realistic physical channels.

1. Introduction

Traditionally, the transmission of electrical signals across a solid barrier, e.g., the wall of a pressure vessel, has required the addition of mechanical penetrations through the obstacle in order to pass physical electric connections through. In many cases, these feedthroughs are undesirable as they may reduce the structural integrity and environmental isolation provided by the barrier. Therefore, it would be beneficial to have an alternate means of transmission through the wall. Established radio frequency (RF) techniques are ineffective in these situations as conductive media greatly attenuate electromagnetic signals. Despite this limitation, the propagation of ultrasonic energy within the barrier is generally excellent. In taking advantage of this fact, acoustic–electric transmission systems have been of high interest; used for both power and data transmission solutions.

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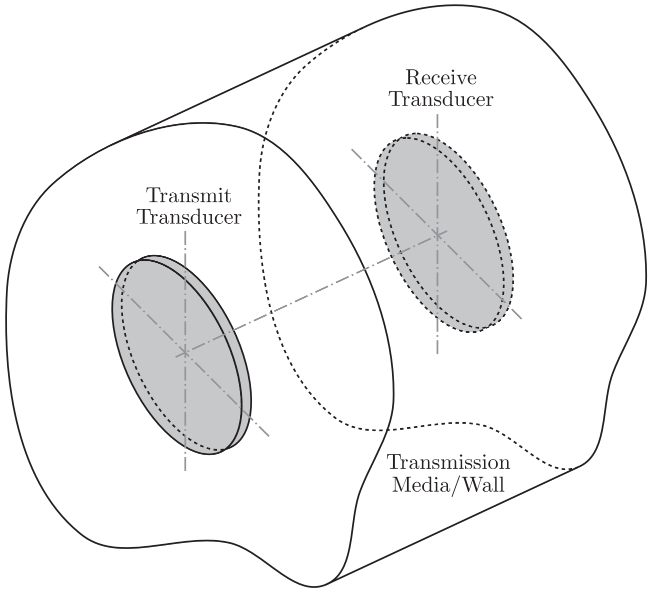

Fig. 1. Generic construction of an acoustic–electric channel.

The generation and reception of the ultrasonic waves may be accomplished through multiple means, though piezoelectric transducers are primarily employed. Physical demonstrations of such systems, or *channels*, have been discussed from multiple sources which show these types of systems capable of both high-power and high data-rate operation. In considering data transmission, several systems [1–3] have been shown to successfully transmit data at rates substantially less than 1 Mbps while simultaneously transmitting power in the opposite direction using the same mechanical channel. This type of system is useful in low-rate telemetry applications. Dedicated data implementations of these systems [4–6] have been shown to be capable of high data-rate communications, with both implementations employing multicarrier transmission techniques to achieve over 15 Mbps data-rates, with predictions of much higher rates being possible. Conversely, for strictly power transmission, a system [7] composed of disk transducers across a thick stainless steel barrier was shown to be capable of delivering at least 140 W with an approximate efficiency of 67 percent at 1.25 MHz; whereas Bao et al. [8] demonstrated delivery of over 1 kW at 24.5 kHz with an efficiency of 84 percent while using highly specialized piezoelectric transducer stacks operating on a thin titanium barrier.

Modeling of these types of systems has been performed using a variety of methods. A significant amount of modeling of such systems has been done using a coupled continuum equation approach. Both planar [9] and cylindrical [10,11] configurations of channels were considered, as well as nonlinear effects [12]. While these models are well developed, they are inherently coupled and therefore channels with many layers are bulky to construct and evaluate. Alternative to fully coupled modeling, equivalent circuit modeling techniques have been implemented which have been shown to be equally as valid [13] and easily assessed using time domain analysis [14,15]. Finite element analysis of such channels has been done [8,16,17] which is capable of a more comprehensive system model, allowing for complex geometries to be represented. While the finite element method is capable of producing a more complete model, it is severely hampered by the required evaluation time and computer resources, which becomes unacceptable for large degrees of freedom models (e.g., high-frequency and/or large geometry models).

A pressure-wave based layer model of generic layered acoustic–electric transmission channels is constructed in this work, where individual layers are represented by 2×2 matrices multiplied together to form a complete model of the structure. Specifically, the scientific objectives for the construction of this model were to design a simulation method which avoids the time and computational requirements of finite element models. Additionally, it was required to maintain the modularity provided by finite element software, where addition or subtraction of layers within a system model is relatively trivial as compared to the fully coupled mathematical models, which require a complete rederivation to achieve. This trait is shared by equivalent circuit models, where most layers may be implemented with transmission line elements; however, unlike the equivalent circuit models, this model resides completely within the mechanical domain, allowing for easier interpretation of elements within the full model.

A similar type of model has been described by Lawry et al. [18], which approached modeling of the channel's individual layers by isolating each layer and then modeling them using force–voltage mechanical analog ABCD-parameters, commonly known as acoustic transfer matrices, which map the pressure and particle velocities to adjacent interfaces. The modeling presented within this paper considers the independently traveling forward and reverse pressure waves as the mapped variables, which allows for a more intuitive understanding of the power flow characteristics of such systems. This paper expands on the means for modeling and reduction of the axisymmetric two-dimensional effects due to acoustic beam