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This article was originally published as: Wild, G., & Hinckley, S. (2010). Pspice simulation of an electro-acoustic communications channel. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 57(4), 981 - 985. Original article available here
This Journal Article is posted at Research Online.
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PSpice Simulation of an Electro-Acoustic Communications Channel

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***Abstract*—In this paper, we present results from a circuit simulation of a proposed electro-acoustic communications channel. The communications channel was modeled in PSpice using Redwood's version of Mason's equivalent circuit. The simulations used binary phase shift keyed communications signals with a carrier frequency of 1.12 MHz. Results obtained from the model are comparable with the results obtained experimentally. The frequency response of the model matched the measured frequency response, predicting lower frequency resonances obtained in the experimental data. The transient response of the model compares almost identically with the transient response observed experimentally. This is a significant characteristic as the acoustic communications are transient limited, which suggests that the model can be used with good confidence in the optimization of the transducers and algorithms used for acoustic communications.**

I. Introduction

The use of acoustic emission sensors in Aerospace Vehicle health monitoring has been established in the literature [1]. With the advent of smart materials and structures, in which sensors are interfaced with embedded distributed electronics, the information needs to be moved from the point of detection to the central processor or human interface. However, it has also been suggested that robots can be used to carry out autonomous inspection in non-destructive evaluation (NDE) [2]. In a complex system, the embedded sensors may not be able to detect all types of measurands. In this case, autonomous agents, robots, can be used to interrogate the structure together with the embedded sensors. The electro-acoustic communications channel is intended for use by autonomous robots in the structural health monitoring of aerospace vehicles with embedded distributed sensors.

The communications channel comprises several layers:

- a piezoelectric transducer used as the transmitter,
- a coupling medium,
- the material to be communicated through, specifically an aluminum panel, and
- a second piezoelectric transducer used as the receiver, which is bonded directly to the panel.

Manuscript received March 13, 2009; accepted December 14, 2009.
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Digital Object Identifier 10.1109/TUFFC.2010.1503

The aluminum panel represents the skin of an aerospace structure and the receiving transducer represents an embedded sensor in the skin of the aerospace structure. The final two layers, the transmitter and the coupling medium, are intended to be mounted on an autonomous inspection robot. The piezoelectric transducer used as the transmitter is also intended to be used in ultrasonic NDE; the use of electro-acoustic communications enables an existing structure intended to detect acoustic emissions to be able to interact with autonomous robots without the addition of wireless communications hardware, thus reducing the complexity and cost of implementing autonomous inspection agents.

In this paper, we present a model for the electro-acoustic communications channel. This model is intended to be used for two purposes. The first purpose is to characterize the performance of the communications channels, i.e., to aid in the selection of appropriate transducers. The second purpose is to perform research into the optimization of communications encoding methods and algorithms for working with resonant communications mediums.

II. Theory

A. Equivalent Circuit

The equivalent circuit used for the modeling of the electro-acoustic communications channel was Redwood's version [3] of Mason's equivalent circuit [4]. Redwood's version of Mason's equivalent circuit was chosen because of its ease of implementation in a circuit simulation program. The circuit was simulated in PSpice (Cadence Design Systems, San Jose, CA). The focus of previous SPICE implementations in the literature has been on the transducer [5]. However, work has previously been reported on modeling layered structures in which the transmitter and receiver are the same transducer [6], that is, a pulse-echo configuration. In this work, separate transducers are used for the transmitter and receiver in a pitch-catch configuration. The equivalent circuit simulated is shown in Fig. 1.

The piezoelectric transducers are modeled with [3]

- a bulk capacitance (C_0),
- a transformer,
- a negative capacitance ($-C_0$), and
- a lossy transmission line.

The transmission medium is modeled using an ideal transmission line. Here, the time delay in the electrical transmission line represents the acoustic time delay and the electrical impedance is related to the acoustic impedance. This relationship also applies to the backing materials, which because of their semi-infinite nature are simply represented by an electrical resistance.

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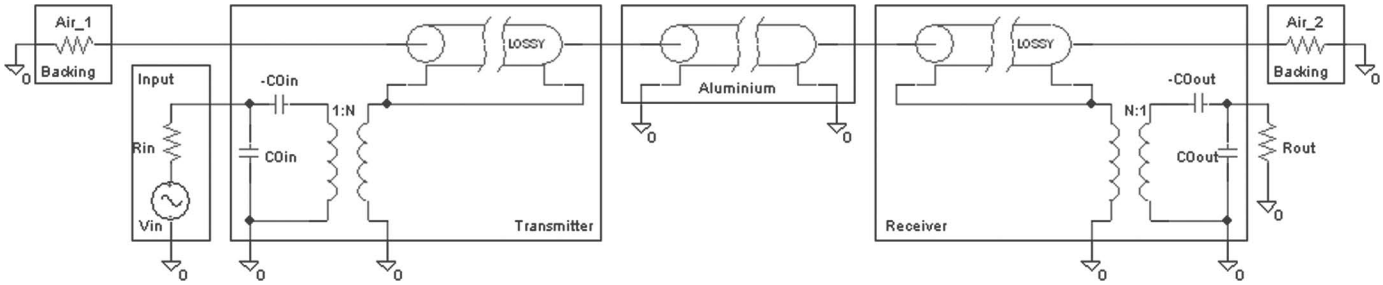

Fig. 1. Circuit model of electro-acoustic communications channel.

The relationship between the electrical resistance (R) and the acoustic impedance (Z) is given by [5],

$$R = AZ, \tag{1}$$

where A is the effective area of the system. For all elements, the area was taken as the area of the transducers.

The transformer used was a perfect transformer, the simplest transformer to implement in PSpice [7]. For a perfect transformer, the fact that the inductance (L) is proportional to the number of turns (N) squared gives

$$\frac{L_1}{L_2} = \left(\frac{N_1}{N_2}\right)^2. \tag{2}$$

With a primary inductance (L_1) of 1 Henry, the secondary inductance is given as N^2, where N is [3]

$$N = h_{33}C_0. \tag{3}$$

Here h_{33} is the piezoelectric deformation constant. The transformer also has a coupling coefficient of 1.

In the lossy transmission line, the length is the thickness of the transducer. The inductance per unit length, L_m, is then [8]

$$L_m = \rho A. \tag{4}$$

That is, the total inductance over the length d is equivalent to the mass. The resistance per unit length, R_m, is determined by the quality (Q) of the resonator, and is given as [5]

$$R_m = \frac{L_m}{Q}. \tag{5}$$

The capacitance per unit length, C_m, is given as [8]

$$C_m = \frac{1}{L_m v^2}. \tag{6}$$

The input and output impedances were 50 Ω and 1 MΩ, respectively, corresponding to the values of the devices used.

The model used is 1-D, using the assumption that the radius (r) of the transducer is much larger than the thickness (t), that is, $r \gg t$. This allows the electrical and acoustic phenomena to be approximated as 1-D.

B. Signal Processing

Phase Shift Keying (PSK) was chosen as the digital encoding method. Decoding the received PSK signal is done with some simple mathematics, which involves

1) multiplying the received signal by a synchronous sine and cosine (called I and Q, respectively),
2) low-pass filtering to remove the carrier, and then,
3) taking the arctangent of the filtered I on Q to recover the phase information.

The filter used was a raised cosine filter [9]. The decoding algorithm and the filtering were implemented in Matlab (the MathWorks, Natick, MA).

III. Experiments

The results of the model were compared with experimental results previously obtained [10]. The experimental setup is shown in Fig. 2. The piezoelectric transducers used were unbacked, and coupled to the aluminum panel using a thin film of acoustic coupling gel to ensure efficient coupling. The piezoelectric transducers used were Steiner and Martins SM111, a modified PZT-4 (Steiner and Martins, Inc., Miami, FL), a lead zirconate titanate (PZT) piezoceramic. Table I lists the manufacturer's specified parameters and physical properties.

The aluminum panel used was 1.5 mm thick. The acoustic velocity of the longitudinal pressure wave in aluminum is 6420 ms^{-1}. This gives a time delay of 234 ns in the aluminum transmission line.

IV. Results

A. Frequency Response

The frequency response was measured using an AC sweep. The frequency response curves from the simulation and experimentation are shown in Fig. 3. The overall shape of the simulated frequency response matches the

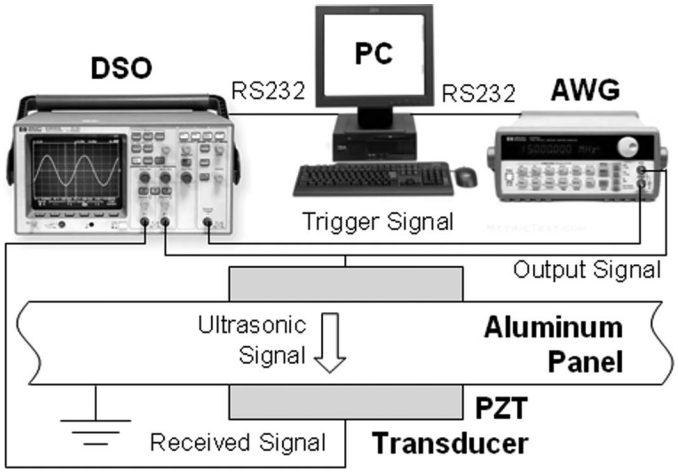

Fig. 2. Setup for experimental comparison. The arbitrary waveform generator (AWG) is an Agilent 33120A (Agilent Technologies, Santa Clara, CA), and the DSO is an Agilent 54600A.

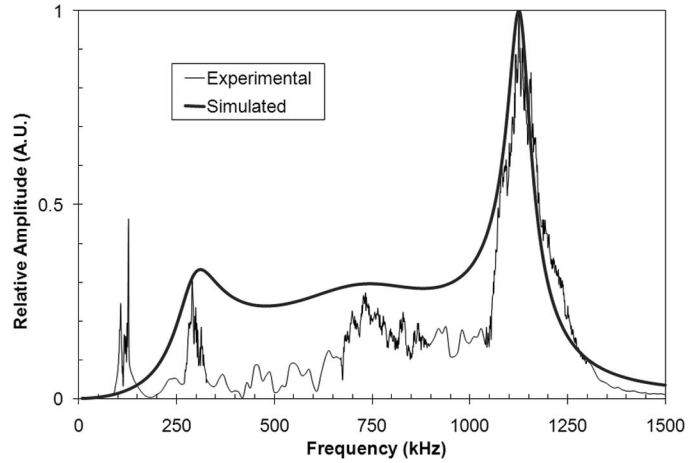

Fig. 3. The frequency response of the communications channel, comparing the experimental data (thin line) to the model (thick line).

TABLE I. Physical Parameters of Steiner and Martins PZT Transducer.

Property	Symbol	Value
Thickness, mm	t	2.08
Radius, mm	r	10.41
Dielectric constant	ε_k	1400
Density, kg/m^3	ρ	7900
Acoustic velocity, m/s	v	4500
Acoustic impedance, MRayl	Z	33
Coupling coefficient	k_t	0.45
Deformation constant, V/m	h_{33}	3.23×10^9
Quality	Q	1800

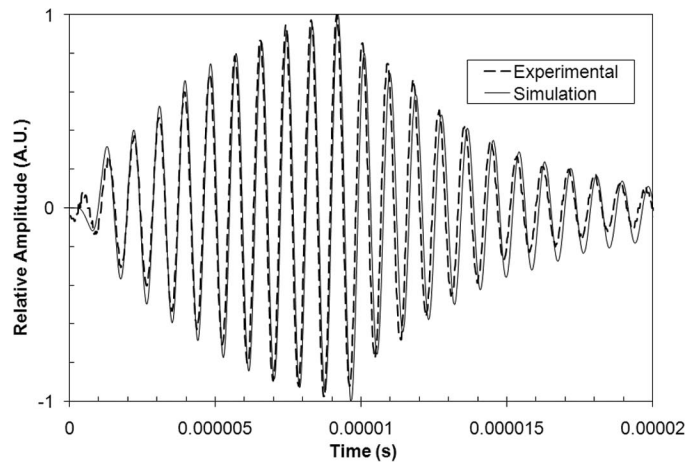

Fig. 4. The transient response of the model (light continuous line) compared with the transient response measured experimentally (heavy broken line).

shape of the experimental data. The only significant difference is the additional secondary peak in the experimental data located at 100 kHz. This has been calculated to correspond with a radial mode of the transducer. This radial mode peak is not in the simulated data because the model used was 1-D.

B. Transient Response

To determine how the model performed in the time domain, a transient response test was performed. A 15-cycle sine wave burst at 1.12 MHz was used to analyze the transient response. A tone burst was used to show the total response time at resonance and to determine the damping coefficient, and hence the quality of the communications channel as a whole.

The transient response is shown in Fig. 4. The transient response of the simulation is almost identical to the experimentally observed transient response. There is a slight difference in the ring down portion caused by the slight difference in the resonant frequency observed between the experiment and the model.

C. Communications Test

With the success of the frequency and transient comparisons, the final test was to transmit a communications signal through the model. The file used to program the arbitrary waveform generator was modified for use in PSpice. The signal had a data rate of 1/20 of the carrier frequency. With a carrier of 1.12 MHz, this gave a data rate of 56 kbps. Fig. 5(a) shows the received PSK signal from the experimental results and Fig. 5(b) shows the received PSK signal from the simulation. Fig. 6 shows the results of the communications test. The decoded PSK signals are shown in Fig. 6, with both the simulated and experimental results.

The simulated and experimental communications signals show similar transitional and steady periods. As expected, the switching times for both (as shown in Fig. 6) are almost identical except for the phase wrapping. The model appears to give a very good qualitative comparison of the channel performance, and can be used confidently

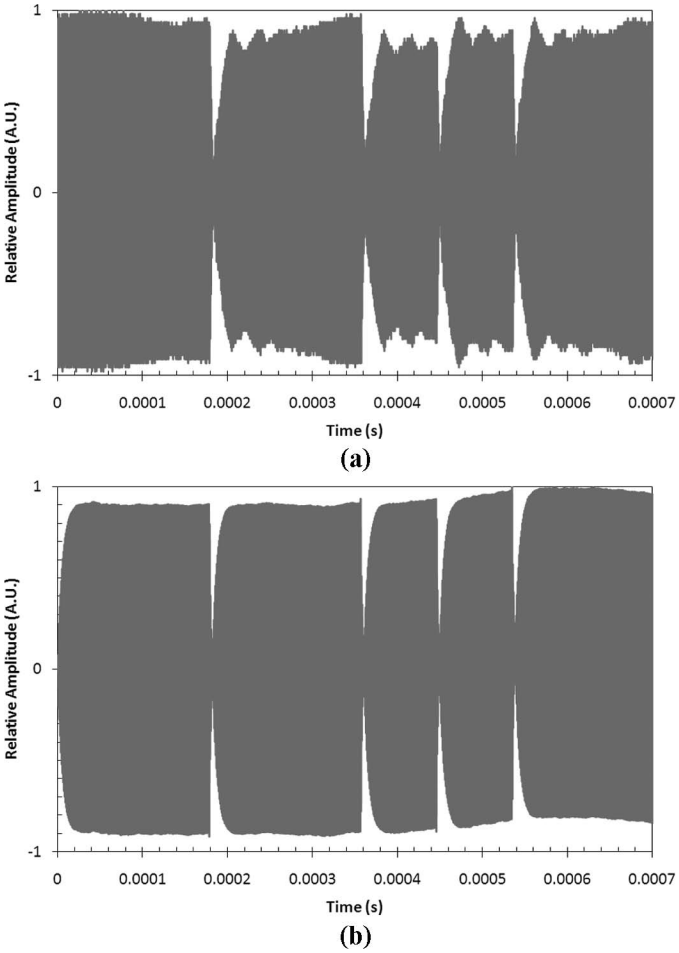

Fig. 5. Received acoustic communications signals, showing both the experimental result (a) and the simulated result (b).

to theoretically investigate the performance of the communications channel.

V. Discussion

A small amount of optimization was performed using the acoustic velocity of the PZT. This was required to better match the simulated resonant frequency to the measured resonant frequency. This also resulted in the matching of secondary and tertiary peaks, because when using the manufacturers specified value of 4200 m/s, only one secondary peak occurred in the simulation result, which was located between the two lower peaks, at approximately 400 kHz.

The fact that the equivalent circuit model is a 1-D approximation means the model can only be used when the transmitter and receiver are directly opposite each other. This leads to a relatively small source of experimental uncertainty when comparing to the results of the simulation. This fact can be directly seen in Fig. 5(a) in which there is ripple in the received signal, likely caused by reflections from the edge of the aluminum panel, which measured 170 × 200 × 1.5 mm.

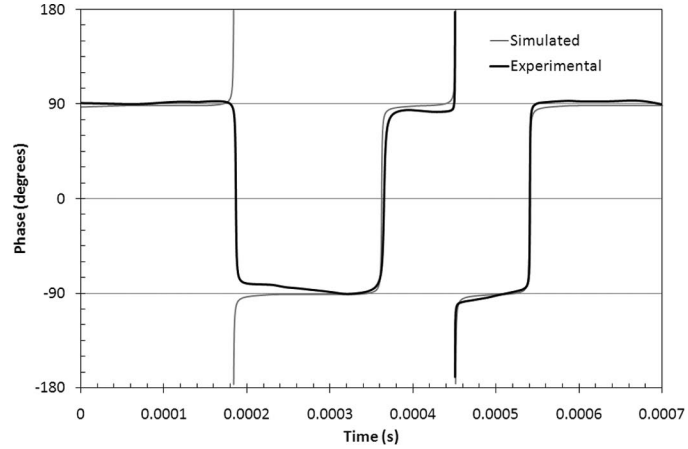

Fig. 6. The recovered phase information from the Phase Shift Keying acoustic communications signals.

The model used is limited to high-frequency signals, because of the implementation of a perfect transformer which is made up of two coupled inductors. This may cause distortion when waveforms contain a dc component. This distortion is seen as the low-frequency ripple in the received signal, Fig. 5(b). The use of the perfect transformer may also account for the small skew in the major resonant frequency, see Fig. 4. However, as with previous implementations using a perfect transformer [6], this is not a problem for the relatively high frequencies associated with communications signals. This may also be solved by optimizing the inductor values, while maintaining condition (2). Alternatively, an ideal transformer could be implemented [5].

Future work will focus on utilizing the model as a theoretical representation of the communications channel, however, some additional work may be performed to further optimize the model to try to incorporate the radial modes. Future utilization of the model will involve using it to compare digital encoding methods, such as amplitude shift keying (ASK) and frequency shift keying (FSK). It will also be used to optimize the problems encountered with PSK: specifically, the high quality of the transducers causing long transient times between switching, which limits the data rate of PSK. More advanced methods of PSK using more than two phases can also be investigated, as can quadrature and amplitude modulation (QAM) methods which combine PSK and ASK.

VI. Conclusion

In conclusion, Redwood's version of Mason's equivalent circuit has been used to model an electro-acoustic communications channel. The model gave results comparable to experimental results in both frequency and transient characteristics. The model can be used to optimize the transducers and other layers used in the system. The model will also be used to investigate other encoding methods, i.e., FSK, and more complex PSK methods such as QAM.

Acknowledgment

The experimental work referred to in this article was initiated in a joint honors project between the Optical Research Laboratory at Edith Cowan University and the Intelligent Systems Group at The Commonwealth Science and Industrial Research Organization. The group, lead by D. Price and including A. Scott, G. Edwards, C. Lewis, and M. Headley, deserves specific acknowledgment for its work on the honors project and for inspiring this and future work. The authors also thank E. Maione for his helpful discussion.

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