CHARACTERIZATION OF AN ULTRASONIC NONDESTRUCTIVE MEASUREMENT SYSTEM

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Abstract: The Electroacoustic Measurement Model (EAM model) is an explicit model of an ultrasonic measurement system. This model is used to quantitatively examine the combined effect of the pulser/receiver, cabling, and transducers by grouping them in a single term called system transfer function. It is shown that the system function obtained in this fashion agrees with the same function as measured in a calibration setup. It is demonstrated that by using the EAM model one can accurately simulate the output signal in an ultrasonic measurement system.

1. INTRODUCTION

An ultrasonic measurement system is a collection of elements, each one contributing to the signals that are measured in a nondestructive evaluation (NDE) studies. Recently a complete model of an ultrasonic measurement system, called an *electroacoustic measurement model* (EAM) was developed [1-3]. In this model the electrical and electromechanical components of a measurement system are modeled in terms of parameters that can be obtained with electrical measurements. The acoustic/elastic wave propagation and scattering processes present are also modeled through general reciprocity conditions [1]. In the EAM model a commercial (single element) ultrasonic transducer is modeled by electrical impedance and sensitivity parameters. The sensitivity is a parameter that is challenging to determine experimentally since by definition it involves both electrical and mechanical quantities. Dang *et al.* [3] determine the sensitivity of a single ultrasonic immersion transducer by applying a modified reciprocity-based approach adapted from the acoustics literature that involves the use of three transducers in various pitch-catch setups. Recently, Lopez [4] replaced this cumbersome reciprocity method with a much simpler model-based pulse-echo method for determining the transducer electrical impedance and sensitivity. This new method produces a new and highly effective way to implement the EAM model.

Here the transducer impedance and sensitivity determined with the new pulse-echo method [4] are used in conjunction with experimentally determined parameters for all the other electrical elements in an ultrasonic measurement system to determine a system transfer function that characterizes the combined effect of the pulser/receiver, cabling, and transducers. The system transfer function obtained in this fashion is shown to agree with the same function as measured directly in a reference setup.

It is shown that the measured signals of the entire measurement system can be accurately simulated when the system transfer function is combined with models of the acoustic/elastics processes present in a measurement system.

2. ULTRASONIC NDE MEASUREMENT SYSTEM

A general ultrasonic immersion measurement system is shown schematically in Fig. 1(a) and the corresponding electroacoustic measurement model that gives a complete model of an ultrasonic measurement system in terms of lumped parameters is shown in Fig. 1(b). All of these parameters are defined in the frequency domain and so are functions of frequency ω.

In the electroacoustic measurement model the pulser is modeled by an equivalent voltage source,

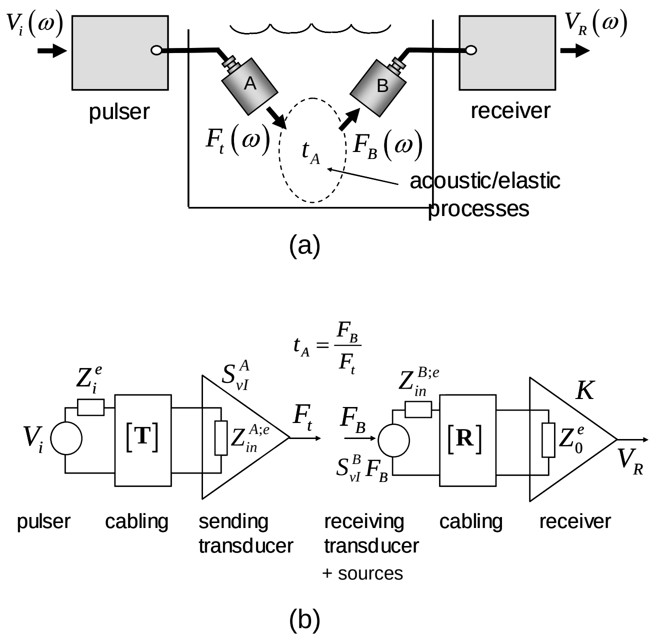

***Fig. 1** a) General ultrasonic immersion measurement system, b) models of the components of measurement system in a) in the electroacoustic measurement model.*

$V_i(\omega)$, and an equivalent electrical impedance, $Z_i^e(\omega)$. The equivalent voltage source and impedance are both functions of the pulser settings and can be determined experimentally through simple electrical measurements [2].

At frequencies normally used in an NDE testing, the cabling used in an ultrasonic measurement system affects the signals transmitted to/received from the transducer. In the measurement model the cabling is modeled as a two-port electrical system [2], and a corresponding 2x2 transfer matrix, ($[\mathbf{T}]$ and $[\mathbf{R}]$ in Fig. 1(b)). The elements of the cable transfer matrix are determined by measuring voltage and current at both ends of the cabling under different termination conditions as described in detail in [3]. In an immersion setup it is common practice to use not only flexible cables but also fixture supports and connectors to position the transducer; since all those elements contribute to the measured cable compensations it is important that these measurements be done in situ, treating the entire cabling system as a whole.

The receiver section of a pulser/receiver can be modeled as an electrical impedance, $Z_0^e(\omega)$, and an amplification factor, $K(\omega)$, as shown in Fig. 1(b). These parameters can be obtained by driving the receiver with a particular source and measuring voltages and currents at the input and output terminals of the receiver, as described in [2]. The receiver's filtering characteristics are not modeled here but any filter operation can be applied later to the receiver output signal.

The transducer X (where X=*A* for the sending transducer and X=*B* for the receiving transducer) is modeled as an electrical impedance, $Z_{in}^{X;e}(\omega)$, and a sensitivity, $S_{vI}^{X}(\omega)$. These parameters can be found by the new pulse-echo method [4] where only voltage and current measurements are made when the transducer is operating in a pulse-echo setup.

The output force, $F_t(\omega)$, at the sending transducer's acoustic port is related to the output velocity by $F_t = Z_r^{A;a} v_t$, where $Z_r^{A;a}$ is the acoustic radiation impedance. For a piston immersion transducer operating at the high frequencies found in most NDE tests, it can be shown that $Z_r^{A;a} = \rho c S_A$, where ρ is the density of the fluid the transducer is radiating into, *c* is the wave speed of the fluid, and S_A is the active area of the transducer's acoustic port. The motion of the sending transducer's face generates waves in the surrounding fluid which then can be transmitted into other components, interact with flaws (if any), and ultimately reach a receiving transducer. These complex wave propagation and scattering processes can be characterized by an acoustic/elastic transfer function, $t_A(\omega) = F_B(\omega)/F_t(\omega)$, where $F_B(\omega)$ is a compressive force on the face of the receiving transducer generated by those waves reaching the receiving transducer face.

It can be shown [2] that the acoustic waves at the receiving transducer B and the acoustic-to-electrical conversion properties of that transducer can be modeled by a voltage source of strength $F_B(\omega) S_{vI}^{B}(\omega)$ in series with the receiving transducer electrical impedance, $Z_{in}^{B;e}(\omega)$.

Once the receiving transducer converts the received acoustic waves into electrical signals, they are passed to the receiver through the receiving cable and amplified to generate a measured output voltage whose frequency components are $V_R(\omega)$.

The acoustic/elastic transfer function, $t_A(\omega)$, is inherently a quantity that cannot be measured directly since it involves complex wave field parameters and wave interactions inside of components. However, for a general flaw measurement setup it is possible to determine $t_A(\omega)$ using reciprocity relations [5] and sufficiently general beam propagation and flaw scattering models. For some simple reference setups one can obtain an explicit model for $t_A(\omega)$. An example of this type will be given shortly for a pitch-catch setup.

It can be shown [2, 4] that it is possible to combine all the models of the electrical and electromechanical components of the measurement system into a single factor, $s(\omega)$, called the system function, given explicitly by

$$s(\omega) = \frac{S_{vI}^{A} Z_r^{A;a}}{\left(T_{11} Z_{in}^{A;e} + T_{12}\right) + Z_i^e \left(T_{21} Z_{in}^{A;e} + T_{22}\right)} \cdot \frac{K Z_0^e S_{vI}^B}{\left(R_{11} Z_0^e + R_{12}\right) + Z_{in}^{B;e}\left(R_{21} Z_0^e + R_{22}\right)} \cdot V_i \tag{1}$$

Equation (1) shows the contribution that any of the electrical and electromechanical components in an ultrasonic measurement system make to the system function.

The output voltage $V_R(\omega)$ can be expressed as

$$V_R(\omega) = s(\omega) t_A(\omega) \tag{2}$$

Since all the explicit parameters appearing in Eq. (1) can be obtained experimentally and the acoustic/elastic transfer function, $t_A(\omega)$, can be modeled [1,2,4], Eq. (2) gives the complete EAM model of an ultrasonic measurement system. The output voltage of the system versus time, $v_R(t)$, can then be obtained by inverting $V_R(\omega)$ with an inverse Fast Fourier transform.

The introduction of the system function is important since there is also a way of obtaining this function without measuring all the individual components contained in Eq. (1). Equation (2) shows that for any reference setup where we can model the transfer function $t_A(\omega)$ explicitly and where the frequency components of the received voltage, $V_R(\omega)$, can be obtained experimentally, the system transfer function can be obtained directly since

$$s(\omega) = \frac{V_R(\omega)}{t_A(\omega)} \tag{3}$$

Because division in the frequency domain is a noise-sensitive deconvolution process Eq. (3) is normally implemented in practice with a Wiener filter [5]. Of course one should obtain the same system function by either measuring all the components in Eq. (1) or performing the deconvolution of Eq. (3). We will show below that this is indeed the case.

Determining the system transfer function by deconvolution in a reference setup allows us to characterize in one measurement the effect of all the electrical and electromechanical components in an ultrasonic measurement system. However, the system function of Eq. (1) is a powerful engineering tool for explicitly analyzing the contributions that all the components of an ultrasonic measurement system make to this transfer function.

3.ULTRASONIC SYSTEM CHARACTERIZATION

We have described all the elements contained in an ultrasonic measurement system and methods and/or models that can be used to obtain those elements. To illustrate how one can combine these elements to determine the system function and simulate a measured output voltage, consider the simple pitch-catch immersion setup shown in Fig. 2 where two 5 MHz, 6.35 mm diameter planar ultrasonic

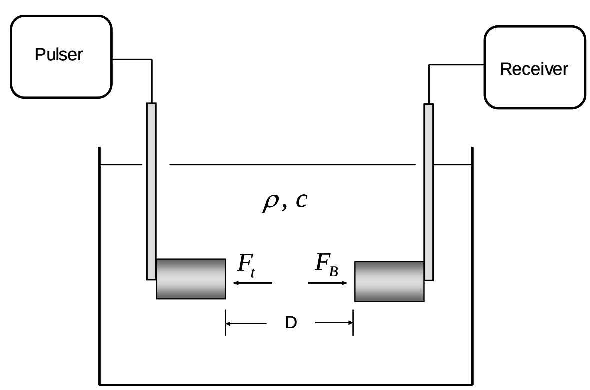

Fig. 2 *An ultrasonic pitch-catch measurement setup, where the axes of two planar transducer of the same radius are aligned and separated a distance D.*

transducers were placed in an immersion tank with their axes aligned in a pitch-catch configuration separated a distance of $D = 0.067$ m.

A Panametrics 5052PR pulser/receiver was used to drive the transmitting transducer and receive the signal from the receiving transducer in a pitch-catch mode. The cablings used to connect each transducer to the pulser/receiver consisted of a flexible 50 Ω coaxial cable of 1.83 m, a fixture rod (with 0.61 m length for the transmitting transducer and 0.76 m for the receiving transducer) and a right angle adaptor.

The measurement protocol for making all the measurements needed for the EAM model is described in detail in [4]. Combining all the experimentally determined characteristics of the components in the measurement system we determine the corresponding system function, see Fig. 3. However, we can compare this synthesized system function with the one obtained by deconvolution using the actual measured output voltage and modeling the acoustic transfer function. For the setup shown in Fig. 2, it can be shown that $t_A(\omega)$ is given explicitly by [5]

$$t_A(\omega) = 2\exp[-\alpha(\omega)D]\{1 - \\ -\exp(ika^2/D)[J_0(ika^2/D) - iJ_1(ika^2/D)]\} \quad (4)$$

where $\alpha(\omega)$ is the frequency dependent attenuation

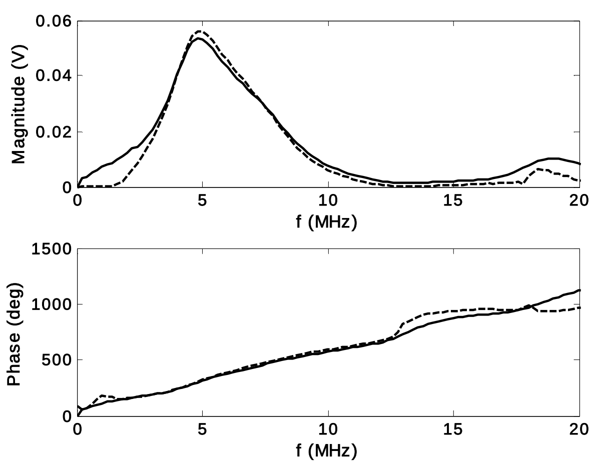

Fig. 3 *The synthesized (dashed-dotted line) and deconvolved (solid line) system function (amplitude and phase) versus frequency, for a pulser energy setting of 1 and damping setting of 7.*

of the fluid, a is the radius of the transducer (assumed to act here as a circular, piston source), and $k = \omega / c$ is the wave number for the fluid, and J_0 and J_1 are Bessel functions of the first kind of order zero and one, respectively

The attenuation coefficient for (degassed) water at room temperature is given by [4]

$$\alpha(\omega) = 25.3 \times 10^{-15} f^2 \quad (5)$$

where the attenuation is measured in Np/m, and the frequency, $f = \omega / 2\pi$, is given in Hertz.

Figure 3 compares the system function synthesized from Eq. (1) with the same function obtained by deconvolution of Eq. (3) for the pitch-catch setup shown in Fig. 2. It can be seen that there is excellent agreement between both results.

To determine the frequency components of the output voltage, $V_R(\omega)$, for the two transducer pitch-catch setup of Fig. 2, we use the synthesize system function and the acoustic transfer function given in Eq. (4). The received time domain voltage signal was obtained by performing an inverse FFT on $V_R(\omega)$ [6]. This synthesized output voltage was then compared with the actual voltage measured at the receiver output on an oscilloscope, see Fig. 4.

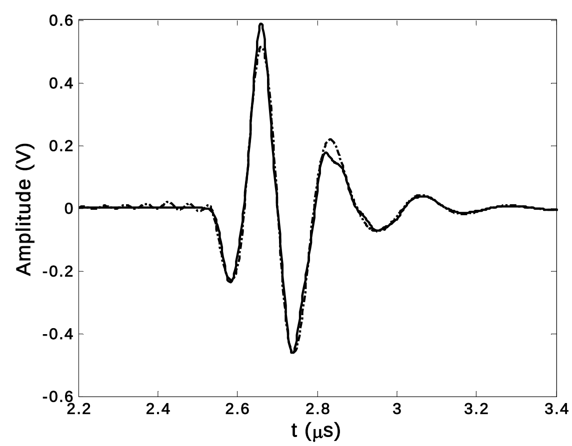

Fig. 4 *The synthesized (dashed-dotted line) and directly measured (solid line) output voltage signal of the ultrasonic pitch-catch measurement system of Fig. 2, for a pulser energy setting of 1 and damping setting of 7.*

A difference of only -0.6 dB was observed between the peak-to-peak voltage response of the synthesized signal to that of the measured signal, showing that the agreement between the EAM model and measurements was excellent [7].

Since experimental errors of 1 dB or more are often observed in even very carefully controlled ultrasonic studies, it can be concluded that the EAM model is indeed a good model to predict the output voltage response, as well as an effective engineering tool determine the contributions of each element to the entire measurement chain.

Very good agreement was also observed in similar studies conducted using transducers pairs of 2.25 MHz and 10 MHz [4, 7], however, for limitations in space those results are not presented here.

4. SUMMARY

A very practical way to characterize ultrasonic measurement systems was described. The method involves primarily a series of standard electrical measurements coupled with appropriate wave propagation and/or scattering models. This capability has been illustrated here for pitch-catch immersion systems, but the approach is equally applicable to pulse-echo setups and to contact testing setups. The value of having a complete system model of this type is that one can then examine in detail how individual components affect system performance and can make estimates of the effects of system changes without necessarily going through costly experimental validation studies.

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