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A time-domain model and experimental validation of the acoustic field radiated by air-coupled transducers

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ABSTRACT

This paper presents a time-domain model for the prediction of an acoustic field in an air-coupled, non-contact, ultrasonic setup, which includes an air-coupled **E**mitter, the **P**ropagation space and an air-coupled **R**eceiver (EPR). The model takes into account the finite size of the aperture receiver, attenuation in air, and the electric response of the emitter-receiver set h_e. The attenuation is characterized by a causal time-domain Green's function, allowing the wideband attenuation of a lossy medium obeying the power law $\alpha(\omega) = \alpha_0\omega^\eta, 1 \leqslant \eta \leqslant 2$ to be included. The electrical response is recovered experimentally using a procedure which includes the deconvolution of air absorption effects. The model is implemented numerically using a discrete representation approach. In order to study the influence of receiver size and attenuation, five different computational approaches are proposed; each of these is evaluated quantitatively, by comparing the predicted acoustic field with the experimentally measured signal. The prediction error is studied in both the near and far fields, for three typical field features: the system's impulse response, the on-axis field distribution, and the directivity pattern, for the case of air-coupled transducers operating at two different central frequencies, namely 50 kHz and 350 kHz, with a 10 mm diameter wideband receiver. It is shown that when the attenuation in air, the receiver size, and the accurately recovered electric response h_e, are correctly taken into account, the model allows the system's impulse response to be accurately predicted, with on-axis errors ranging between 0.2% in the far field and 1% in the near field. In the near-field area and within the far field −3 dB beam spread width, the error is generally greater than on the axis, but globally remains smaller than 1%. Inclusion of the size of the receiver dimension in the model appears to be crucial to the accuracy of the near field predictions, and an approximate criterion is proposed for the evaluation of the influence of receiver. The procedure used to recover the electric response h_e is also presented in detail. The results obtained from this study are used to formulate various recommendations related to EPR modelling.

1. Introduction

In recent decades, considerable efforts have been made to develop air-coupled ultrasonic transducers for the purposes of radiating/receiving ultrasonic signals directly into/from air. This enables the development of so called *non-contact* ultrasonic testing methods which do not require any physical contact with the tested object (i.e. using air as a coupling medium). They are of particular interest for fast scanning applications, where coupling (physical contact) between the ultrasonic transducers and tested materials must be avoided. As a consequence of its straightforward and efficient implementation, non-contact techniques have been applied to automatic, fast non-destructive testing in different engineering disciplines e.g. for the testing of paper, composites, food, wooden materials, metal plate, for evaluating surface roughness, for the inspection of concrete. A complete review of various air-coupled, non-destructive testing approaches and applications is provided in two recent papers [1,2]. Further examples are also provided in [3–11].

In an air-coupled *non-contact* ultrasonic testing system, the ultrasonic waves propagating through a characterized medium are radiated and received by a pair of air-coupled ultrasonic transducers. A crucial requirement for appropriate understanding and optimisation of such a system is the accurate characterization of the basic setup, including the air-coupled **E**mitter, the **P**ropagation space, and the air-coupled **R**eceiver (EPR).

Previous research into the characterization of EPR has shown that strong attenuation in air, which follows a power law of the

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type $\alpha(\omega) = \alpha_0\omega^2$, as well as the finite size of the receiver, are very important factors in a system model. Gachagn et al. [12] modelled the radiation of an air-coupled transducer, and used a simplified attenuation model with a low-pass filter. Bashford et al. [13] modelled attenuation effects using spectral correction of the signal. Although a generally good agreement was found between prediction and experiment (using a small point-like receiver), the observed differences were not quantitatively analyzed. This study noted that the decay in amplitude caused by attenuation could not be neglected, and suggested that attenuation-induced dispersion phase shifting could also be a factor leading to distortion of the modelled field. Kong et al. [14] and Hutchins et al. [15] modelled and measured the acoustic field radiated by a capacitance emitter. They concluded that neglecting the receiver size could lead to differences between the predicted and experimental fields, and that the receiver size should be included in the computational model. Neild et al. [16] developed an analytical model adapted to the case of a rectangular emitter and receiver, but neglected the effects of attenuation. In all of the cited references, the radiated fields were modelled using the time-domain Rayleigh integral and the spatial impulse response concept [17,18].

All previous studies have revealed the highly significant influence of air attenuation, and have shown that the attenuation-induced phase shift (which remained unclarified) should be included in modelling of air-coupled systems. Although the size of the receiver is found to influence the experimental measurements, it is not taken into account in the models including the effects of attenuation. The goal and originality of this paper lies in the fact that it presents a new EPR model, which simultaneously takes the attenuation in air, as well as the size of the planar receiver, into account, thus providing an answer to the above unsolved questions. Additionally, the accuracy of the model is improved by including the effects of the electric response of the emitter-receiver set [19].

The aim of this study is not to develop an alternative modelling tool (such as FEM), but to further develop and improve previous studies. For this reason, the same computational principle is used, i.e. modelling the field radiated by a planar or quasi-planar emitter of any shape using the time-domain Rayleigh integral and the spatial impulse response technique. This approach is considered to be well adapted to the EPR solution. Consequently, the attenuation and induced velocity dispersion are accurately modelled using a time-domain solution for the causal Green's function in a lossy medium. In order to accurately represent the typical operation of non-contact systems, which use coded signals, and to improve the signal-to-noise ratio (required during the experiments), the so-called chirp technique is used in our experiments.

The EPR prediction model developed in this study represents the first step towards future research efforts, with the aim of developing an accurate model of a fully contactless system, including the characterization of an elastic medium. This paper is organized as follows. Section 2 presents the mathematical model of the EPR. The model is established in the time domain and includes the finite size of the receiver. It is expressed in the form of convolutions between the excitation signal, the electro-acoustic response of the air-coupled emitter-receiver pair, and the response describing propagation in absorbing air between emitter and receiver. Section 3 presents the experimental emitter-receiver setup, and compares the measured acoustic field characteristics with those predicted by the model. The conclusions of our study are presented in Section 4. Various technical details are derived and explained in Appendices A–C. A special procedure is proposed, allowing the experimental recovery of the electric response of the EPR (Appendix B). These responses were, in return, used for the computational prediction.

2. Theory: time domain model of the EPR system

The modelled EPR system is illustrated in Fig. 1, where the first block represents the common electric response of the emitter and receiver $h_e(t)$ and the second block, characterized by a pressure impulse response $h_{pr}(\mathbf{M}_o, t)$, represents the combined effects of acoustic radiation from a perfect emitter, propagation, and reception by a receiver of finite size. In this study, the receiver is centered at point $\mathbf{M}_o(x_o, y_o, z_o)$. In accordance with linear system theory, for any excitation signal $s(t)$ observed at the receiver output, the pressure can be computed in the form of a convolution:

$$p(\mathbf{M}_o,\ t) = s(t) * h_e(t) * h_{pr}(\mathbf{M}_o,\ t) \tag{1}$$

The pressure p can thus be correctly predicted if an accurate solution is found for $h_{pr}(\mathbf{M}_o,\ t)$, and if $h_e(t)$ is accurately characterized. Different solutions for $h_{pr}(\mathbf{M}_o,\ t)$ are presented in the following, whereas an experimental approach for the retrieval of h_e is proposed in Appendix B.

2.1. Radiation and reception: case of a lossless medium

The most commonly used method for determining the transient acoustic field produced by an ultrasonic transducer in a lossless medium is that introduced by Stepanishen [18], based on the transducer's spatial impulse response. The velocity potential impulse response $h_\psi(\mathbf{M}_o,\ t)$ of the radiating surface S is defined as the acoustic potential radiated from S, excited by a normal component velocity in the form of a Dirac function $v_n(\mathbf{M},\ t) = v_n(\mathbf{M})\delta(t)$ (assumption of piston mode displacements of the emitter) and observed at an observation point $\mathbf{M}_o$ (Fig. 1). Under these conditions, assuming the surface S to be planar, rigid and placed in a rigid planar baffle, h_ψ can be derived from the Rayleigh integral as:

$$h_\psi(\mathbf{M}_o,\ t) = \int_S v_n(\mathbf{M})\, g(\mathbf{M},\ \mathbf{M}_o,\ t)\ \mathrm{d}S \tag{2}$$

where

$$g(\mathbf{M},\ \mathbf{M}_o,\ t) = \frac{1}{2\pi R}\delta\left(t - \frac{R}{c}\right) \tag{2a}$$

denotes the Green's function for the half (baffled) space in a lossless medium, and $R = |\mathbf{M} - \mathbf{M}_o|$, and c is propagation velocity. The function $g(\mathbf{M},\ \mathbf{M}_o,\ t)$ and its frequency domain counterpart

$$G(\mathbf{M},\ \mathbf{M}_o,\ \omega) = \frac{e^{j(kR-\omega t)}}{2\pi R} \tag{2b}$$

are related by the Fourier transform:

$$g(\mathbf{M},\ \mathbf{M}_o,\ t) = \mathcal{F}^{-1}[G(\mathbf{M},\ \mathbf{M}_o,\ \omega)] = \mathcal{F}^{-1}\left[\frac{e^{j(kR-\omega t)}}{2\pi R}\right] \tag{3}$$

where $k = \omega/c$ is the wavenumber and the symbol $\mathcal{F}$ denotes the Fourier transform.

The conditions of a rigid infinite baffle assumed when using the Rayleigh integral are often assumed "automatically" in studies of planar or quasi planar transducers, whereas the hypothesis of an infinite baffle is totally realistic in practical situations. In practice, the rigid housing of all common emitters (which prevents radiation from the back plate from interfering with the direct wave), successfully plays the role of the baffle. Although the absence of a baffle also modifies the edge waves, this effect is negligible in the near-axis region [20], which is normally the region of interest. In addition, it is generally assumed that the surface S radiates in perfect piston mode. This means that other parasite modes of vibration arising in typical emitters, such as spurious or radial modes, etc. are neglected. This explains why integral (2) is largely and