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Reflection at a liquid–solid interface of a transient ultrasonic field radiated by a linear phased array transducer

Nadir Maghlaoui [a,*], Djema Belgroune [a], Mohamed Ourak [b], Hakim Djelouah [a]

[a] Université des Sciences et de la Technologie Houari Boumediene, Faculté de Physique, Laboratoire de Physique des Matériaux, BP 32 El Alia 16111, Algiers, Algeria
[b] Département d'Opto Acousto Electronique, IEMN, Université de Valenciennes et Hainaut Cambrésis, BP 311, 59304 Valenciennes, France

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ABSTRACT

In order to put in evidence the specular reflection and the non-specular reflection in the transient case, we have used a model for the study of the transient ultrasonic waves radiated by a linear phased array transducer in a liquid and reflected by a solid plane interface. This method is an extension of the angular spectrum method to the transient case where the reflection at the plane interface is taken into account by using the reflection coefficient for harmonic plane waves.

The results obtained highlighted the different components of the ultrasonic field: the direct and edge waves as well as the longitudinal head waves or leaky Rayleigh waves. The transient representation of these waves have been carefully analyzed and discussed by the rays model. Instantaneous cartographies allowed a clear description of all the waves which appear at the liquid–solid interface.

The obtained results have been compared to those obtained with a finite element method package.

1. Introduction

This paper is devoted to the theoretical study of the transient ultrasonic field emitted by a linear array transducer in a liquid and reflected by a plane liquid–solid interface, in order to highlight the leaky Rayleigh wave and the longitudinal head wave the analysis of which is essential, particularly when the immersed plane solid is in the near field of the transmitting transducer.

Measurements of phase velocity and propagation attenuation of leaky surface acoustic waves are widely used for material characterization by ultrasound. In most of these quantitative ultrasonic material characterization systems, the amplitude of the monochromatic output signal is recorded as a function of the relative position of the transducers and the specimen immersed in a liquid. Typically, the phase velocity and propagation attenuation of the leaky guided waves, such as leaky Rayleigh, Lamb and skimming longitudinal waves, as well as a reflectance function for the specimen–water interface can be obtained from the recorded data. In another approach the leaky surface wave and the specular reflection are separated in the time domain and the velocity is determined from the time of flight. It has been applied by Yamanaka [1] to measure the surface acoustic wave velocity. Separation in time reflection for the different types of waves from the structures located below the sample surface provides additional information about these structures and also allows their location to be determined [2,3]. The disadvantages of these methods are obvious: the mechanical scanning of the transducer is associated with slowness of the data acquisition, and the accuracy of the measurements depends on the precision of the mechanical movement.

The measurements can be improved by using a method based on transmitting and recording the ultrasonic field distribution of the scattered wave with a phased array transducer [4]. Phased array transducers are multi-element transducers, where different elements are activated with different time delays. The advantage of these transducers is that no mechanical movement of the transducer is needed to scan an object. One phased array transducer can scan an object relatively quickly because it can inspect a wide range by emitting acoustic energy in controlled directions [5]. Thus efficient scanning is possible by phased-array transducers. The parameters of the leaky waves can be obtained by processing the set of the output waveforms [4].

For realistic prediction of ultrasound imaging, pulsed ultrasound fields should be simulated. Among the various calculation methods developed for the simulation of the propagation of ultrasonic waves, we first distinguish those which are totally numeric. This concerns in particular the finite difference method [8–10], the boundary element method (BEM) [11] or the finite element method (FEM) [12–14]. All of these methods calculate the pressure

* Corresponding author.
E-mail address: maghlaoui.n79@gmail.com (N. Maghlaoui).

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at each grid point; therefore, the simulation time is proportional to the number of array elements multiplied by the size of the computational grid. These simulations are relatively slow due to the large number of calculations involved. A difficulty in FE analysis appears when solving ultrasonic problems in an infinite or semi-infinite medium because of the unbounded geometry of the problem. Reflections from the artificial boundaries are avoided by surrounding the problem geometry with artificial absorbing layers having a gradually varying attenuation. Nevertheless, the main drawback of FE analysis is the requirement of a large number of finite elements, since to obtain reliable results, the dimensions of individual finite elements must be only a fraction of the wavelength. For high frequencies the number of elements needed to solve an ultrasonic problem becomes very large.

On the other hand, in the semi-analytic methods, pressure fields generated by ultrasound transducers are typically calculated by superposing the fields produced by individual transducer sources. Traditionally, these sources are modelled with point source superposition applied to the Rayleigh–Sommerfeld integral, the spatial impulse response method, and other analytically equivalent integral approaches.

The transient pressure field in front of a planar transducer in homogeneous isotropic materials has been computed both in the time domain [15–17] and in the frequency domain [18,19]. In the time domain Stepanishen [15] introduced the concept of the impulse response function which results in the expression of the transient ultrasonic field under the form of a convolution in time. In the liquid solid interface case, Zhang and Baboux compute the impulse response of a broadband large-aperture spherical transducer [20]. The impulse response is obtained by performing an analytical inverse Fourier transform of the harmonic results. The weight and the arrival time of each discontinuity of the impulse response is analytically evaluated and the physical meaning of each of them is clearly established with the help of a ray model [20].

Another method called Pencil method [21], which deals with radiation through a fluid coupling into a solid medium, is based on a decomposition of the radiating surface of the transmitter in a set of point sources radiating spherical waves which can be regarded as plane waves if the considered field point is enough far from the source. The amplitude of these plane waves decrease during the propagation. This decreasing is characterized by a pencil represented by a set of slowly diverging rays emanating from the point source. This method has been extended to take into account surface waves and head waves [22]. The main advantage of this method is an easy numerical implementation and a good computation speed.

Another method which also allows very fast calculations of the harmonic ultrasonic field in homogeneous media was initially developed by Wen and Breazeale [23], where the total field is calculated by superimposing a number of gaussian beam solutions. Schmerr [24] and Schmerr et al. [25] studied the ultrasonic field near a fluid–solid curved interface using multi-gaussian beam modelling technique. This model is based on a paraxial approximation and has a number of limitations. For example, it cannot correctly model the critical reflection phenomenon.

In the DPSM technique, the active part of the transducer surface is discretized into a finite number of small hemispherical surface areas. Point sources are placed at the centres of these hemispheres. Each point source acts as an active source of energy. The total ultrasonic field is computed by superimposing the solutions of all point sources. Conventional DPSM solves acoustic problems in steady-state frequency domain [26]. It has been extended to the time domain by replacing the harmonic point sources by time-dependent point sources. This modified method is denoted t-DPSM [27]. The interaction between ultrasonic waves and fluid–solid interfaces was studied in. The generation of the leaky Rayleigh wave when finite size transducers are inclined at Rayleigh critical angles has been correctly modelled by the technique [26–28].

Another efficient semi-analytic method is the elastodynamic finite integration technique (EFIT). This method is a grid based numerical time-domain method, using velocity–stress formalism, and easily treats with different boundary conditions which are essential to model ultrasonic wave propagation [29]. It allows time-domain simulations of elastic wave propagation in both, fluids and solids, and includes focusing of the incident wave field as well as scattering at defects and the fluid–solid interface taking mode converted echoes and leaky Rayleigh waves into account. The simulations can be performed for different frequencies and materials and can be used for the continuous and time-resolved mode as well as for transmission and reflection microscopy; the results can be represented by time-domain signals and wave front snapshots [29–31]. Detailed descriptions of leaky Rayleigh and Scholte wave solutions are presented [31].

The angular spectrum approach has been utilized by a number of investigators in a variety of applications [5–7]. The angular spectrum method is a powerful technique for modelling the propagation of acoustic fields. The technique can predict an acoustic pressure field distribution over a plane, based upon knowledge of the pressure field distribution at a parallel plane. Predictions in both the forward and backward propagation directions are possible. In addition to predicting the effects of diffraction, the model also includes the effects of attenuation, refraction, dispersion, phase distortion, and the effects of finite amplitude acoustic propagation. It can predict the propagation of wideband acoustic fields produced by sources of arbitrary geometry including all of the above propagation effects [32].

This approach decomposes the diffracted wave into plane waves via the two dimensional 2D Fourier transform, propagates these components in the spatial frequency domain, and recovers the pressure field in planes parallel to the input plane through the 2D inverse Fourier transform. Application of the angular spectrum approach ASA to the calculation of acoustical fields has become an increasingly interesting topic, because the ASA is easy to be numerically implemented upon the basis of the discrete Fourier transform DFT and can be used to effectively solve a variety of complex problems, especially those involved with boundaries and multilayer media. Particularly in the case of a fluid–solid interface the expression of the reflection coefficient for harmonic plane waves is used. This method has the advantage of being valid in both near-field and far-field domains and to implicitly take into account all the phenomena involved (evanescent waves, surface waves, etc.). The use of the Fast Fourier Transform algorithm (FFT) algorithm performs the calculation globally on a large number of points, and has the advantage of allowing a real time-saving, but it imposes some requirements, including having a constant discretization step. This model based upon a decomposition into monochromatic plane waves has been extended to transient domain [7,33].

In this paper the angular spectrum approach has been used to study the ultrasonic field emitted in a liquid by a linear arrays transducer and reflected by a plane liquid–solid interface as well in focussing or steering beam. The results obtained highlighted the different components of the ultrasonic field: the direct and edge waves as well as the longitudinal head waves or leaky Rayleigh waves. The transient representation of these waves have been carefully analyzed and discussed by the rays model. Instantaneous cartographies (snapshots) allowed a clear description of all the waves which appear at the liquid–solid interface. The obtained results have been compared to those obtained with a finite element method package [34].