ISSN 1063-7710, Acoustical Physics, 2018, Vol. 64, No. 1, pp. 10–17. © Pleiades Publishing, Ltd., 2018.

CLASSICAL PROBLEMS OF LINEAR ACOUSTICS AND WAVE THEORY

Application of Discrete Huygens Method for Diffraction of Transient Ultrasonic Field[1]

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Received December 27, 2016

Abstract—Several time-domain methods have been widely used to predict impulse response in acoustics. Despite its great potential, Discrete Huygens Method (DHM) has not been as widely used in the domain of ultrasonic diffraction as in other fields. In fact, little can be found in literature about the application of the DHM to diffraction phenomenon that can be described in terms of direct and edge waves, a concept suggested by Young since 1802. In this paper, a simple axisymmetric DHM-model has been used to simulate the transient ultrasonic field radiation of a baffled transducer and its diffraction by a target located on axis. The results are validated by impulse response based calculations. They indicate the capability of DHM to simulate diffraction occurring at transducer and target edges and to predict the complicated transient field in pulse mode.

Keywords: transient ultrasound diffraction, transmit–receive mode, discrete Huygens method

DOI: 10.1134/S1063771018010013

1. INTRODUCTION

The classic problem of determining reflected and diffracted sound fields is of considerable importance in many domains such as underwater acoustics, nondestructive testing (NDT) and medical ultrasound [1, 2]. For objects of simple shapes, several analytical solutions have been used successfully. However, when applied to practical configurations, these solutions can be slow to achieve convergence or even impossible to be calculated. With the continuous improvement of computers, various calculation methods for obtaining approximate solutions of wave scattering and diffraction problems are available.

The numerical time-domain solution of acoustic equations has been initiated by the Finite Difference Method (FDM) in the mid-1960s [3, 4]. This method starts from differential equations governing the problem and uses finite difference stencil in space and time. A different approach based on the integral form of the full set of Maxwell's equations in electromagnetic was introduced in the mid-1960s. This technique, commonly called today Finite Integration Technique (FIT), is a grid based numerical time-domain method. It was adapted to elastodynamic problems [5] and it is currently used to simulate ultrasonic wave propagation [6].

Probably, the most common calculation methods are based on boundary integral formulation. It consists of expressing the acoustic quantities within the acoustic volume as a surface integral over the domain boundary. The latter is based on acoustic boundary pressure and velocity as well as Green's function. In case of semi-infinite free field, this formulation is called Rayleigh integral. A simple approach to evaluate this integral for time-dependent sound pressure generated by an impulse particle velocity excitation (pulsed mode) of a baffled transducer is based on the evaluation of the corresponding Impulse Response Function (IRF). It has been adopted by Stepanishen [7], Harris [8] and many other authors [9–11] to assess the transient ultrasonic field radiated from a baffled transducer with different profiles [12] and scattered by a rigid parallel target with various dimensions [13]. However this IRF-based method is useful only in relatively uncomplicated situations defined for simple shapes. For more general configurations with arbitrary shapes, reliance has to be made on computers to evaluate the boundary integral equation numerically.

Among the other widely used methods for the calculation of ultrasonic fields, DPSM technique (Distributed Point Source Method) can be cited [14]. It is based on a physical principle since the active part of the transducer surface is discretized into a finite number of small hemispherical surface areas. The total

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ultrasonic field is computed by superimposing the solutions of all point sources. 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 and is due to Rahani and Kundu [15]. They have applied it to simulate the acoustic diffraction from flat and focus transducer.

Another powerful method for the description of ultrasonic diffraction in solid and fluid media is the angular spectrum approach [16, 17]. It has been developed to deal with harmonic fields as well as more general pulsed fields. It is a convolution-based technique to describe the acoustic field. In fact, by using Fourier transform the field is decomposed as summation of propagating and evanescent waves. The acoustic field is expressed as a superposition of plane waves with variable amplitudes and propagation directions whereas the evanescent waves are usually ignored. This technique has been used to the study of the diffracted field in liquid and solid as well as in presence of liquid/solid interface under normal and oblique incidence [18, 19].

Among time-domain methods, a numerical adaptation of Huygens principle usually called Discrete Huygens Method (DHM) is available. According to Huygens principle, the wave front can be represented by an infinite number of secondary sources which radiate spherical waves. In its turn, each generated wavelet can be broken down into a new set of secondary sources. By breaking down the continuous propagation medium into discrete domains, Johns and Beurle [20] have proposed a first numerical version of this physical principle in case of electromagnetic problems. Thereafter, because of its well-proven efficiency, DHM was also adopted for acoustic propagation problems.

Despite its great potential and emergence in many acoustic applications, few works have been devoted to study ultrasonic diffraction using DHM. In references [21, 22], the authors have been interested by medical ultrasound applications in 3D problems and harmonic mode case such as scattering by objects, wave propagation with steering and Doppler effect. However, in many domains, new applications of ultrasound tend to use the pulsed mode. In fact, compared to harmonic one, the detected ultrasonic field in transient mode contains complicated waves in accordance with diffraction phenomena because of the limited size of both transducer and target.

The aim of this paper is to demonstrate the ability of DHM to detect the characteristics of ultrasonic transient field such as membrane, edge, and diffracted waves that the amplitudes are usually small compared to the incident wave. To this end, the numerical simulations using DHM are performed to predict the transient field radiated by a circular transducer and scattered by a rigid circular target for different profiles of vibration (Subsection 4.1). To study its efficiency, performance of DHM has been compared to the FDM and the IRF-based methods (Subsection 4.2).

2. DISCRETE HUYGENS METHOD

This section briefly presents the basic concepts of the DHM. A detailed derivation of its governing equations is described in a step by step manner in Carvalho et al. work [23].

This technique consists of discretizing the propagation domain into interconnected control volumes through acoustic tubes or branches that insure wave propagation at discrete times. Hence, these shared regions between branches, also called nodes, play the role of secondary sources. When the control volumes are regularly spaced by a space step Δl (square mesh), a same time step Δt represents the required time for all pulses to travel branches of Δl length [24].

In the DHM, acoustic waves propagate in pulses form. Thus, at each time increment, an arriving pulse from one branch at a given node is partially reflected back through that incident branch. The remaining part is transmitted through the other branches linked to the concerned node. To calculate the acoustic field, connection laws are required to make a relationship between incident pulses (I) on a node and scattered waves (S) at the adjacent nodes. The way that scattering occurs is defined by the scattering matrix that can be obtained by applying both mass conservation and pressure continuity laws to the control volume [23].

In the DHM, the wave propagation velocity depends on the direction. In fact, the time taken by the wave to travel the apparent distance between the nodes (i, j) and $(i+1, j+1)$, namely $\sqrt{2}\Delta l$, is $2\Delta t$. In fact, a scattered wave $S_k^{i,j}$ by node (i, j) at time $k\Delta t$ propagates towards the node $(i, j+1)$ as an incident wave $I_{k+1}^{i,j+1}$ and arrives there at time increment $(k+1)\Delta t$ after traveling a distance of Δl within Δt. At the next time increment, the impulse reaches the node $(i+1, j+1)$ at $(k+2)\Delta t$ [25]. Hence, the wave velocity in the DHM-network is less than its speed in the fluid ($c_{\mathrm{DHM}} = c_0/\sqrt{2}$). In order to have a perfect equivalence between propagation of waves in the network (c) and the fluid (c_0), it is appropriate to correct the propagation speed in branches by taking $c = \sqrt{2}c_0$.

3. PROBLEM STATEMENT

The present work concerns the application of discrete Huygens method to the radiation and the diffraction of pulsed ultrasonic field in case of circular transducer without and with a target located on axis. The