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Short Communication

Numerical comparison of acoustic wedge models, with application to ultrasonic telemetry

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ABSTRACT

Ultrasonic telemetry imaging systems are used to monitor such immersed structures as main vessels of nuclear reactors. The interaction between acoustic beams and targets involves scattering phenomena, mainly specular reflection and tip diffraction. In order to assist in the design of imaging systems, a simulation tool is required for the accurate modeling of such phenomena. Relevant high-frequency scattering models have been developed in electromagnetic applications, in particular, the geometrical optics (GO), Geometrical Theory of Diffraction (GTD) and its uniform corrections (UAT and UTD), Kirchhoff approximation (KA) and Physical Theory of Diffraction (PTD). Before adopting any of them for simulation of scattering of acoustic waves by edged immersed rigid bodies, it is important to realize that in acoustics the characteristic dimension to the wave length ratio is usually considerably smaller than in electromagnetics and a further study is required to identify models' advantages, disadvantages and regions of applicability. In this paper their numerical comparison is carried out. As the result, the most suitable algorithm is identified for simulating ultrasonic telemetry of immersed rigid structures.

1. Introduction

An ultrasonic telemetry imaging system reported in [1] allows its operators to monitor position of structures immersed in opaque liquids, ensuring continual safe operation of such structures. One of its possible applications is in monitoring the core of a sodium-cooled fast-neutron reactor, a Generation IV nuclear plant design [2]. Deploying the system in conjunction with this design is particularly attractive, because sodium's opacity makes ultrasound a more effective monitoring agent than light. No significant impediments to its adoption are envisaged, since ultrasonic techniques are already widely used in industry for Non-Destructive Evaluation (NDE) of structural integrity of solid components [3].

Telemetry is the process of determining the distance between the surface of a probe emitting an acoustic beam and a bright spot on the target. This is achieved by measuring the time of flight of the echo backscattered from the target. Many parameters influence the received signal: the incident angle, signal frequency, target geometry and size, material properties of the medium carrying the beam (such as velocity fluctuations) [1,4], etc. Therefore a simulation tool [1,5] is required to allow designers to investigate and optimize the performance of the proposed system.

When an acoustic beam interacts with targets of different geometries (large planar structures or edged bodies), the most widely known scattering phenomena that take place are high-frequency effects of specular reflection and edge diffraction. Several high-frequency scattering approximations mainly developed in electromagnetism [6–11] can be used to model the high-frequency acoustic wave scattering by immersed rigid targets. Some of them are based on ray theories and others on integral formulations.

To start with the specular phenomena, when an acoustic beam impinges on a smooth (locally plane) surface its reflection/refraction can be described by the simplest ray theory known as Geometrical Optics (GO) [6,11] using Snell–Descartes law and energy conservation. When the surface has a complicated shape but can still be considered locally plane it is convenient to employ the so-called Kirchhoff approximation (KA) based on the Green's integral formalism and referred to in electromagnetism as Physical Optics (PO) [11–13].

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Diffraction phenomena arise in presence of such surface irregularities as edges. Their quantitative description is provided by the Geometrical Theory of Diffraction (GTD) originally proposed by Keller [7]. This is another ray theory, with the directions of diffracted rays governed by the Snell–Descartes law of diffraction. The GTD [13] states that the amplitudes carried by these rays can be computed using the stationary phase asymptotics of the solution of the relevant canonical problem, that is, the problem that reproduces the main features of the local geometry. The most widely used canonical problems [12] are diffraction of a plane wave by a planar wedge and by a rigid half-plane (the 360° wedge).

GO and classical GTD provide good description of reflected/refracted and diffracted fields, respectively, but fail in transition zones. For example, if a GTD recipe is applied in a transition zone (known as penumbra) surrounding the shadow boundary (SB) between an irradiated and shadow regions the resulting diffraction coefficients possess non-physical singularities. One approach to remedying the situation is to develop a generalization of GTD as is done in the Uniform Geometrical Theory of Diffraction (UTD) [8]. This offers asymptotics of the diffracted field which are valid not only in irradiated and shadow regions but inside the penumbras as well. Another approach is to develop uniform asymptotics of the total field. One such solution is offered by the Uniform Asymptotic Theory (UAT) [9] and another, by the Physical Theory of Diffraction (PTD) [10].

In this paper the numerical comparison of the above physical theories is carried out in two-dimensional configurations using typical parameters encountered in ultrasonic NDE in order to identify the one best suited for the purpose at hand. Scattering by both a rigid half-plane and a rigid wedge is considered. Preliminary works done for the half plane are shown in Proceeding [14]. The present paper focuses on the wedge scattering problem providing new results obtained using validated UTD and PTD wedge models so that five different analytical approximations are compared in an acoustic case: GTD, UAT, UTD, KA and PTD. For instance, PTD is shown to surpass KA for the scattering near a wedge surface or in shadow zones.

2. Approximate solutions to the wedge scattering problem

Consider first a two-dimensional space filled with a homogeneous fluid supporting an acoustic speed c and containing a perfect rigid wedge of angle Φ irradiated by an acoustic plane wave incident at an angle θ_0 with one of the wedge faces (see Fig. 1). Introduce the Cartesian system with the origin at the wedge tip $\mathbf{x}_0 = (0, 0)$ and the x_1-axis running along the irradiated face. Then any observation point $\mathbf{x} = (x_1, x_2)$ can also be described in terms of the corresponding polar coordinates (r, θ) (Fig. 1).

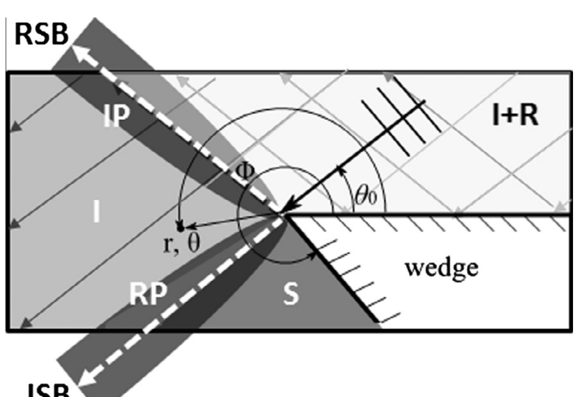

Fig. 1. Scatter of a plane wave incident at an angle θ_0 by a wedge of angle Φ. Description of illuminated and shadow areas, transition zones (penumbras) and shadow boundaries (white dashed arrows).

In ray theory, the resulting total field φ^t comprises the incident field φ^i, reflected field φ^r and field φ^d diffracted from the edge. Fig. 1 details – for the field incident on the upper wedge face – the illuminated and shadow zones of the incident and GO reflected fields, which are separated by straight light/shadow boundaries. Transition zones (also called penumbras) are areas surrounding shadow boundaries. Area I + R lies inside both incident, reflected and diffracted fields, $\varphi^t = \varphi^i + \varphi^r + \varphi^d$ for $0 < \theta < \pi - \theta_0$ and outside penumbra IP. Area I lies inside both incident and diffracted fields, $\varphi^t = \varphi^i + \varphi^d$ for $\pi - \theta_0 < \theta < \pi + \theta_0$ and outside penumbras IP and RP. Area S is the total shadow zone of GO; only diffracted rays penetrate it, $\varphi^t = \varphi^d$ for $\pi + \theta_0 < \theta < \Phi$ and outside penumbra RP. ISB (RSB) is the light/shadow boundary of the incident (reflected) field and separates the area illuminated by incident (reflected) rays from its corresponding shadow zone. Outside transition zones (designated "incident IP" and "reflected RP" in Fig. 1), the total field can be represented as the sum of the GO fields and the edge diffracted waves. Penumbra is the neighborhood of the shadow boundary where such a representation of the total field is inapplicable and the field exhibits a transient behavior.

We start with the edge diffracted field. It is best described by the classical GTD, which represents it as decreasing as the square root of both the distance to the edge and wave frequency and involves the so-called GTD edge diffraction coefficients D_{GTD} [7]. GTD can be obtained as the leading order term in the non-uniform asymptotic series, which apply in geometrical (illuminated and shadow) regions but not in the transition zones, such as penumbras. In particular, the GTD diffraction coefficients D_{GTD} are often infinite at SB of the incident field as well as SBs of the fields reflected from both wedge faces. By way of an example, Fig. 2 shows the diffraction coefficient of a wedge of angle $\Phi = 270°$ for the incidence angle $\theta_0 = 50°$. In this configuration, only the horizontal wedge face is illuminated and reflects the incident field, and the GTD singularities are located at $\theta = 180° - \theta_0 = 130°$ (the reflected SB) and $\theta = 180° + \theta_0 = 230°$ (the incident SB).

As mentioned in the Introduction, several uniform theories can extend the validity of GTD to penumbras.

It has been shown in [15] that to leading order, UAT and UTD give the identical description of the field scattered from a planar wedge illuminated by a plane wave. However these theories are uniform only in the absence of other transition zones outside penumbras. In particular, both are invalid in caustic regions. In the case studied here of plane wave scattering from a wedge with planar faces, the only caustic region is the edge of the wedge. Other caustics in the edge diffracted field can occur if the edge is curved

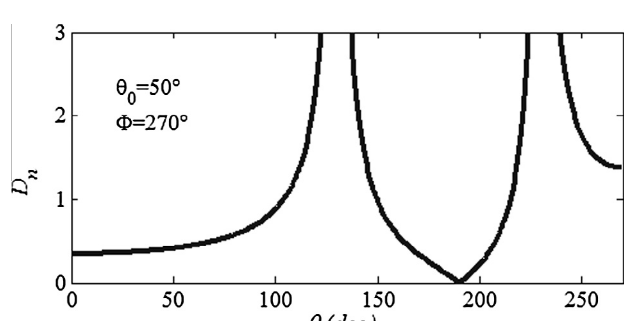

Fig. 2. GTD diffraction coefficient for $\Phi = 270°$ and $\theta_0 = 50°$. $\omega = 2\pi^*$ 1 MHz and $c = 2472$ m/s.