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2.5D BEM modeling of underwater sound scattering in the presence of a slippage interface separating two flat layered regions

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ABSTRACT

This paper describes the use of a boundary element formulation in the frequency domain to investigate the 2.5D acoustic wave propagation in an underwater configuration with a bottom irregularity, simulating the effect of a possible slippage between two flat parts of a waveguide. Each part is delimited by a free surface and a flat bottom, which may be built as multilayered fluid structure.

The problem is solved using a model which incorporates Green's functions that take into account the presence of flat layers of different thicknesses, computed using the definition of pressure potentials at each flat interface. With this procedure only the bottom irregularity and the slippage interface need to be discretized.

The mathematical formulation is presented for the general case in which two multilayered structures are connected via an interface, and then verified and applied to the computation of 3D frequency and time domain pressure responses for the benchmark problem of a rigid bottom with step or slope irregularities. These simulations are used to identify wave propagation features that may help to assess the presence and shape of the bottom irregularities.

1. Introduction

Acoustic wave propagation in the open ocean has been a topic of interest for researchers for many years. Traditional approaches to the problem include computationally efficient methods based on acoustic ray theory, normal modes or parabolic equations. The now classic book by Jensen et al. [1] contains an extensive review of those techniques, describing in detail their formulation and applications. However, in the context of this work it is important to note that each has specific shortcomings.

Ray theory is known to be suitable for deep-water wave propagation, in particular for high excitation frequencies, but it fails to provide accurate estimations at the lower frequencies and in configurations with strong bottom interaction. Normal mode theory is efficient for the analysis of range-independent problems but its application is not straightforward when the propagation domain is range-dependent. For range-dependent problems the coupled-mode model developed by Evans [2], which assumes that the waveguide is subdivided into a finite number of adjacent columns, has been widely used [e.g. 3,4], through the associated code COUPLE [5]. This model considers the full coupling between the modes and is able to handle the backscattering effects. However, the model has to approximate the various continuous surfaces of the problem by making use of piecewise constant sections, forming a sequence of small steps. A large number of sections are usually needed, with a corresponding increase in the computational requirements of the model.

Parabolic equation methods were initially introduced in underwater acoustics by Hardin and Tappert [6]. They have also been extensively applied in deep-water long-range sound propagation. Because they can easily cope with range-dependent propagation

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and are extremely computationally efficient these methods are preferred for long-range ocean acoustic analysis. However, since the parabolic equation is a simplified version of the full-wave equation for the case of a pure one-way propagation it neglects the backscattering effects which are essential in shallow waters containing topographic features. Several authors have nonetheless been investigating the applicability of parabolic equation methods for the analysis of range-dependent shallow water problems, testing those methods against well known test cases such as an upslope wedge or upslope–downslope seamount [3,7–9].

Thanks to the advent of high-speed computers and to recent developments in numerical physics, sound propagation in the shallow ocean margins can be studied and quantitatively described in greater detail with the more exact wave theory. Many models have been developed based on the well-established finite difference, finite element and boundary element numerical methods. An overview of the most common numerical methods used in underwater acoustics can be found in the paper by Buckingham [10]. As mentioned, researchers have been investigating the accuracy of the existing models by comparing their results with exact solutions for benchmark problems like an ideal wedge with pressure release boundaries, described in Buckingham et al. [11].

An important early work on acoustic scattering in the open ocean by Dawson and Fawcett [12] takes the waveguide surfaces to be flat, except for a compact area of deformation where the acoustic scattering takes place. An application of the boundary element method (BEM) using a hybrid model which combines the standard method in an inner region with varying bathymetry and an eigenfunction expansion in an outer region of constant depth was subsequently presented by Grilli et al. [13].

Santiago and Wrobel [14] applied the sub-region technique in boundary element formulation for two-dimensional acoustic wave propagation in shallow water to solve general propagation problems with irregular seabed topography, considering the following boundary conditions: velocity potential null at the free surface and its normal derivative null at the bottom. The BEM model makes use of two modified Green's functions, one of which satisfies the free surface boundary condition while the other directly satisfies the boundary conditions on the free surface and the horizontal part of the bottom boundary. Alternatively, a Green's function in the form of eigenfunction expansions is employed in order to improve the convergence characteristics of the latter [1,15].

In many practical applications the propagation in shallow regions of the ocean can be considered to occur in areas where the geometry is constant in one direction, which is a very common configuration near continental margins. However, even in these situations the acoustic excitation is usually 3D, and thus the wave propagation phenomenon is three-dimensional. These are usually called 2.5D systems, and the 3D acoustic wave equation can be mathematically manipulated to obtain the frequency domain solution in such systems as a summation of simpler 2D problems (Bouchon [16]). Branco et al. [17] and Godinho et al. [18] used this approach for a boundary element formulation in the frequency domain to study the pressure field generated by point sources placed inside a fluid channel with a rigid deformation on its floor. This model used Green's functions based on the superposition of virtual sources to simulate the boundary conditions of the free surface, the rigid flat floor and the lateral walls confining the channel. António et al. [19] and Tadeu et al. [20] subsequently developed BEM formulations integrating Green's functions for the case of a waveguide with an elastic bottom, and used them to study the scattering of waves by a buried or submerged object. Those Green's functions were expressed as discrete summations of the effects of plane waves, following the technique first applied by Lamb [21].

This paper describes a BEM model developed to compute the three-dimensional wave propagation in a system defined by two separate regions; each corresponds to a waveguide with a multilayered fluid bottom and a free surface which are connected by a bottom irregularity to simulate the effect of a slippage of the seabed. The model assumes two-dimensional geometry to simulate regions which have little variation along the shoreline, excited by a point pressure source. The two waveguides with flat interfaces (constant thickness layers) are modeled using Green's functions to avoid the discretization of the surface and flat interfaces, which means that only the bottom irregularity and the slippage interface need to be discretized. The formulation used provides time series and may be suitable to solve shallow water wave propagation problems. For the particular case of a rigid bottom the model is verified by comparing the results with other BEM models and with a coupled normal modes code, "COUPLE" (Evans [5]). The applicability of the formulation is also shown by computing the wave propagation for the benchmark problem of a flat rigid bottom and a free surface in the vicinity of a step- or a slope-shaped irregularity possibly caused by a slippage. Time domain signatures computed for the cases of a rigid bottom containing a step or a slope are displayed by applying Inverse Fast Fourier Transforms and the main features of wave propagation in the near field are identified. Energy responses are also displayed in order to analyze the possibility of clearly identifying the presence and shape of the irregularity.

The 2.5D problem formulation is presented next, in Section 2. The boundary element method and the Green's functions used are then described, followed by the verification of the model. The procedure used to obtain time domain signatures is also described. Finally the proposed model is applied to compute frequency and time domain signatures for several configurations in order to identify wave propagation features that may allow assessment of the presence and shape of the bottom irregularities.

2. 2.5D problem formulation

Consider the problem of acoustic wave propagation in a water waveguide with a bottom that has undergone a slippage. The resulting system is composed of two flat waveguides of different depths, connected by a localized irregular bottom and a slippage interface. For this problem, consider that each flat waveguide consists of a region of infinite extent in the x and z directions, with a free surface and a bottom modeled as a sequence of acoustic layers ($j=2,\ldots,n$ identifies the number of layers below the bottom), as depicted in Fig. 1. In each medium, the pressure must be null at the free surface, and at each fluid/fluid interface continuity of normal particle velocity and pressure must be enforced.