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Technical Note

Accuracy and efficiency of a moving-zone method in the time-domain simulation

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ABSTRACT

A moving zone approach is developed to overcome the barrier of the computing power required for a large, single-domain time-domain simulation for possible long-range acoustic propagation. This concept uses a moving computational domain that follows an acoustic wave. The size and interval of motion of the domain are problem dependent. In this study, an Euler-type moving domain in a stationary coordinate frame is investigated. Size effects, resolution requirement, moving-domain intervals, and boundary conditions for the moving domain are considered. The results are compared and verified with both analytical solutions and results from the single large-domain simulation. Perfectly-matched layers are employed at the free-space boundary in the moving domain.

1. Introduction

It is well known that the primary advantage of the time-domain (TD) simulation over the frequency-domain simulation is its ability to accommodate a wide variety of physical effects on broadband acoustic propagation, including boundary-medium effects, scattering by turbulence, refraction by shear and temperature gradients, and diffraction over terrain [1–7]. However, most of the conventional time-domain schemes have limited capability in modeling long-range acoustic propagation because of the vast computer resources needed to cover the entire region of interest with a single computational domain. Therefore, improvements using TD simulation to understand long distance acoustic propagation in realistic terrain and atmospheric environments are a great challenge. Many of the long-range acoustic propagation problems need to consider propagation distances of hundreds or thousands of meters. It is thus very difficult to maintain adequate grid resolution for such a large computational domain, even with the state-of-the-art capacity in computer memory and computing speed. Typical resolution requires at least tens of spatial points to resolve one wavelength. Therefore it is almost impossible to properly resolve waves at the range above 10 Hz if the sound propagation simulation needs to be covered in a single large domain of several kilometers.

In order to overcome this barrier, we present a moving zonal-domain approach. This concept is to move the computational domain that follows an acoustic wave. The zonal domain size and the time intervals of the moving zonal domain are problem dependent. On one hand, the size of the domain needs to be small enough so that the computational efficiency can be achieved. On the other hand, the domain has to be sufficiently large to contain all the wave contents that are of interest to the analysis. The time interval of moving the domain depends on the sizes of the domain and the grid, as well as the size of the time step. An additional requirement is that the frequency of the domain motion be away from the interested frequency range to avoid interference. More importantly, the construction of the moving zonal-domain should not distort the original wave field, at least not in the specifically interested frequency and spatial range of the problem.

Fidel et al. [8] proposed a moving-domain method to simulate propagations of electromagnetic pulses. Akleman and Sevgi [9] used the moving zonal-domain approach in a wave propagator with a finite-difference, time-domain (FDTD) algorithm. Salomons et al. [1] applied moving domains to sound propagation in TD simulation. More recently, Lee et al. [10] developed a finite-element, moving window technique to simulate the propagation of electromagnetic waves inside large and long structures.

In this paper, we present a FDTD simulation of a linearized Eulerian model for acoustic propagation with moving zonal domain. The type of the moving domain is considered the Euler-type moving domain in a fixed frame of reference [8]. In order to eliminate the influence of unwanted reflection from the top free-space boundary, perfectly-matched layers (PML) with highly efficient absorbing ability are employed in the moving domain. We will provide examples on using the moving zonal-domain approach for cases with and without background shear flow. By comparing with the results from

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the corresponding non-moving, large domain simulation, we address the accuracy of the moving zonal domain method. We also test long-range acoustic propagations and compare the results with the literature data to demonstrate the efficiency and effectiveness of the moving zonal-domain approach in simulating long-range acoustic propagations.

2. Model problem and equations

We select the same test problem as in Zheng and Li [5], which is shown in Fig. 1. In the z-direction, $z \in [z_g, 0]$ m is the ground porous medium; $z \in [0, z_{\max}]$ m is the air; and $z \in [z_{\max}, z_e]$ m is the PML absorbing boundary condition region to represent the non-reflective free-space boundary. When there is wind shear in the background, V_{av} is the non-uniform shear velocity.

The Eulerian linearized governing equations of acoustic propagations are [1,5–7,11]:

$$\frac{\partial \mathbf{u}}{\partial t} = \begin{cases} -(\mathbf{u}_{av}\cdot\nabla)\mathbf{u} - (\mathbf{u}\cdot\nabla)\mathbf{u}_{av} - \alpha_{av}\nabla p - \alpha\nabla p_{av}, & \text{in air} \\ -\frac{\Omega}{c_s}\alpha_{av}(\nabla p + \sigma\mathbf{u}), & \text{in the ground porous medium} \end{cases} \tag{1}$$

$$\frac{\partial p}{\partial t} = \begin{cases} -(\mathbf{u}_{av}\cdot\nabla)p - (\mathbf{u}\cdot\nabla)p_{av} - \gamma p\nabla\cdot\mathbf{u}_{av} - \gamma p_{av}(\nabla\cdot\mathbf{u}), & \text{in air} \\ -\frac{\gamma p_{av}}{\Omega}(\nabla\cdot\mathbf{u}), & \text{in the ground porous medium} \end{cases} \tag{2}$$

where $\mathbf{u}_{av}$, p_{av} and α_{av} are the time averaged velocity, pressure, and specific volume, respectively; and $\mathbf{u}$, p and α are their acoustic fluctuations. We have:

$$\alpha = -\frac{p}{\gamma p_{av}\rho_{av}} \tag{3}$$

where γ is the specific-heat ratio, and the time averaged density ρ_{av} is $1/\alpha_{av}$. For the cases in this paper, we use the values $p_{av} = 100$ kPa, $\gamma = 1.4$, the speed of sound in the air $c = 340$ m/s, the porosity $\Omega = 0.3$, the porous medium structure factor $c_s = 3$, and the flow resistivity $\sigma = 100$ kPa s m^{-2} for the porous ground. For typical absorbing ground materials the flow resistivity approximately ranges from 10 kPa s m^{-2} to 100 kPa s m^{-2} [1].

Berenger [12] first proposed the concept of PML, and used it for absorbing electromagnetic waves. Here, we implement a version of PML by Hu [13,14] for the linearized Euler equations with non-uniform background flow, which is able to efficiently absorb the outgoing waves. According to the coordinate system as shown in Fig. 1, the equations of the top-boundary PML are derived as:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}_{av}\cdot\nabla)\mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u}_{av} + \alpha_{av}\nabla p = -\zeta_z\left[V_{av}\frac{\partial \mathbf{q}}{\partial y} + (\mathbf{q}\cdot\nabla)\mathbf{u}_{av} + \mathbf{u} + \alpha_{av}\nabla q_p\right] \tag{4}$$

$$\frac{\partial p}{\partial t} + (\mathbf{u}_{av}\cdot\nabla)p + (\mathbf{u}\cdot\nabla)p_{av} + \gamma p_{av}\nabla\cdot\mathbf{u} = -\zeta_z\left[\gamma p_{av}\frac{\partial q_v}{\partial y} + V_{av}\frac{\partial q_p}{\partial y} + p\right] \tag{5}$$

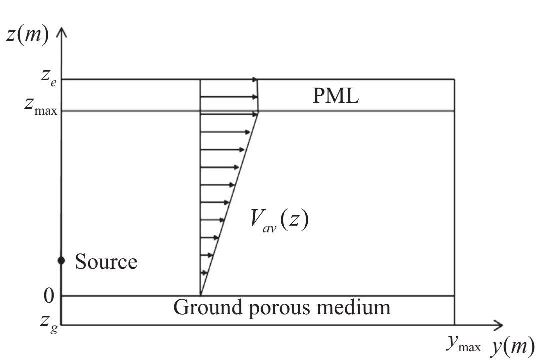

Fig. 1. Description of the test problem and coordinate system.

where $\mathbf{q}(q_v, q_w)$ and q_p are auxiliary variables:

$$\frac{\partial \mathbf{q}}{\partial t} = \mathbf{u} \tag{6}$$

$$\frac{\partial q_p}{\partial t} = p \tag{7}$$

and ζ_z is the absorption coefficient:

$$\zeta_z = \zeta_{\max}\left|\frac{z - z_{\max}}{D}\right| \tag{8}$$

where D is the height of the PML domain. It should be noted that the average velocity is uniform in the PML here,

$$\mathbf{u}_{av} = V_{av}(z)\mathrm{j} \tag{9}$$

For an effective PML domain, a grid stretching is also introduced [14]:

$$\frac{\partial}{\partial z} \to \frac{1}{\beta(z)}\frac{\partial}{\partial z} \tag{10}$$

where $\beta(z) \geqslant 1$ represents the smooth function, and we choose:

$$\beta(z) = 1 + A\left|\frac{z - z_{\max}}{D}\right|^s \tag{11}$$

where $A = 25$, and $s = 2$, and different values of $\zeta_{\max}$ are used in different cases. A similar implementation of the PML with a uniform background flow is in [15].

3. Moving zonal-domain approach: the domain-size effect and computational efficiency improvement

This method requires the computational domain of the moving zone to move with a propagating pulse. If the moving zonal domain is large enough, it is able to contain a dispersing pulse and the energy is essentially confined within the computational domain. On the other hand, the size is small enough so that the computational efficiency can be achieved. Consequently, it should not degrade the computational accuracy.

Fig. 2 is an illustration of the moving-zonal approach. Each domain consists of a moving zone including a top boundary of absorbing layer, the air, and the ground porous medium. The wave, with the initial pressure distribution, propagates until arriving at a distance from the right boundary, preferably near the center of the moving domain to minimize the boundary effect. Then the moving zonal domain moves a certain distance towards the right, with the equations for all of the three media (air, porous medium, and absorbing layer) properly included in the moving domain. Since the moving domain procedure is case dependent, we will explain the procedure in details in the next section for each of the cases.

In this study, the boundary conditions are set as $w = 0$ m/s at the upper and lower boundaries, and $v = 0$ m/s at the left and right

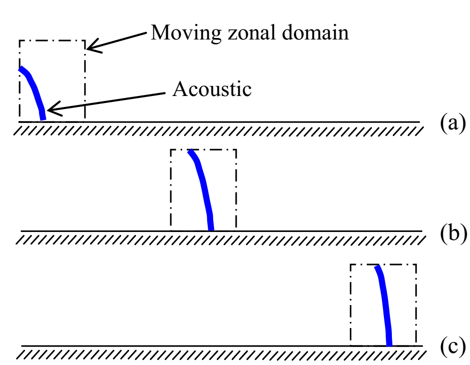

Fig. 2. Illustration of the moving-zonal approach.