Applied Acoustics 76 (2014) 113–118

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Application of the transmission line matrix method for outdoor sound propagation modelling – Part 1: Model presentation and evaluation

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ARTICLE INFO

Article history:
Received 13 November 2012
Received in revised form 9 July 2013
Accepted 18 July 2013
Available online 31 August 2013

Keywords:
Time-domain methods
Transmission line matrix model
Meteorological effects
Outdoor sound propagation

ABSTRACT

The present paper deals with an original time-domain approach applied to outdoor sound propagation under meteorological effects. The transmission line matrix method, based on the Huygens' principle, had already been validated over impedant grounds and complex topography. The presented formulation proposes to take into account meteorological effects (wind speed and temperature) through the relative sound speed. The necessary wavefront direction is determined through the calculation of the averaged intensity vector direction. A good agreement is found between simulations of both the transmission line matrix and parabolic equation methods. A relevant use of the method is shown in the framework of environmental acoustics and initial applications are proposed in Part 2.

1. Introduction

Many numerical models have been developed in order to simulate meteorological effects on outdoor sound propagation. One can cite analytical formulations such as geometrical methods (*e.g.* ray or gaussian beam tracing approaches) [1,2] or numerical models based on the resolution of the wave equation. Among these latter models, the Parabolic-Equation (PE) based method has been widely used for this purpose [2–5]. Over the last decade, with the increasing power of computational resources, time-domain methods have also been developed and applied successfully in environmental acoustics [6–9]. The most popular time-domain approach is undoubtedly the finite-difference in the time-domain (FDTD) method. Dragna has investigated for instance sound propagation over a 100 m distance within a realistic context in a frequency range between 100 Hz and 2 kHz [10]. An alternative time-domain method is the Transmission Line Matrix (TLM) approach [11]. This model seems very promising for describing complex outdoor sound propagation yet has not been used extensively. In order to incorporate the atmospheric effects, Hofmann has proposed an interesting formulation, which is however limited to temperature effects [12]. A first attempt to define a TLM scheme with unidirectional mean flow (*e.g.* wind field) into the TLM grid has been provided by Kagawa and his co-workers, but its method is only successful for single wind speed direction effects [13]. In this paper, the approach, inspired by a method proposed by Dutilleux [14], consists of modifying the sound speed at each point of the discretized domain as a function of the temperature and wind speed projection on the wave front direction.

This paper aims to present the integration of meteorological effects in the TLM model and then its comparison with a PE model in academic cases. The associated paper (part 2) addresses its validation by comparison with results stemming from Lannemezan's 2005 experimental campaign [15]. The wind and temperature fields are obtained from the meso-scale meteorological model Meso-NH [16,17].

The first section presents the TLM model. In Section 2 the formulation taking into account wind speed and temperature effects is described. The last section proposes evaluating the ability of the TLM to treat outdoor sound propagation problems through a comparison with PE results in two academic cases.

2. TLM modelling

The TLM method is based on the Huygens' principle, which states that a wavefront consists of a set of secondary sources radiating spherical wavelets whose envelopes can be broken down into a new generation of secondary sources as well. Hofmann has shown the equivalence of this approach with the resolution of the discretized wave equation [12]. Other authors have also derived the two-dimensional homogeneous cartesian formulation of TLM from a Lattice Boltzmann model by removing nonlinear

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0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.07.011

terms, in choosing a suitable viscosity and selecting a square grid [18].

The TLM statement allows describing sound propagation through both a spatial and temporal discretization of the medium as well as the propagation phenomena. This concept is numerically conveyed by replacing the propagation medium with a transmission lines network, through which sound propagates in the form of sound pulses. Thereby, as shown in Fig. 1, each junction, or node, links $N = 4$ or $N = 6$ transmission lines to each other in two dimensions (2D) or three dimensions (3D) respectively. Thereafter, the number of dimensions is called d such that $d = 2$ and $d = 3$ for creating a 2D and 3D model respectively. An additive branch, of index $N + 1$, is inserted at each node of the transmission line network, in order to consider the inhomogeneities of the propagation medium (*i.e.* branch 7 in Fig. 1). According to the TLM concept, sound propagates in the form of pulses. Thus, incident and scattered pulses are considered at each transmission lines junction and time increment. The propagation medium is discretized by means of a uniform cartesian meshing of mesh size $(\Delta l)^d$, with Δl being the spatial step such that:

$$\Delta l \leqslant \frac{\lambda\sqrt{d}}{10}, \tag{1}$$

with λ the minimal wavelength of the simulation.

The scattered pulses at time increment t and node of discrete coordinates $\mathbf{r}$ such that

$$\mathbf{r} = \begin{cases} (i,j) & \text{for } d = 2 \ (i.e. \text{ in 2D}), \\ (i,j,k) & \text{for } d = 3 \ (i.e. \text{ in 3D}), \end{cases} \tag{2}$$

are related with the incident pulses at this node at the same time iteration by the following matrix relation:

$$_t\mathbf{S}_\mathbf{r} = {_t\mathbf{D}_\mathbf{r}} \times {_t\mathbf{I}_\mathbf{r}}, \tag{3}$$

where $_t\mathbf{I}_\mathbf{r}$ and $_t\mathbf{S}_\mathbf{r}$ are the vectors composed of the incident pulses $_tI^n_\mathbf{r}$ and scattered pulses $_tS^n_\mathbf{r}$ through each transmission line n ($n = 1$ to $N + 1$) respectively. $_t\mathbf{D}_\mathbf{r}$ is a $(N + 1) \times (N + 1)$ scattering matrix given by:

$$_t\mathbf{D}_r = \frac{2}{_t\eta_\mathbf{r} + 2d} \begin{bmatrix} _ta_\mathbf{r} & 1 & . & 1 & _t\eta_\mathbf{r} \\ 1 & _ta_\mathbf{r} & . & 1 & _t\eta_\mathbf{r} \\ . & . & . & . & . \\ 1 & 1 & . & _ta_\mathbf{r} & \eta_\mathbf{r} \\ 1 & 1 & . & 1 & _tb_\mathbf{r} \end{bmatrix}, \tag{4}$$

with

$$_ta_\mathbf{r} = -\frac{_t\eta_\mathbf{r} + 2(d-1)}{2} \tag{5}$$

and

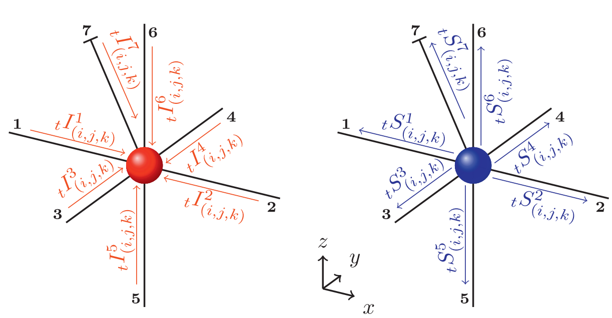

Fig. 1. Representation of the incident (left) and the scattered (right) pulses at node (i,j,k) in 3D.

$$_tb_\mathbf{r} = \frac{_t\eta_\mathbf{r} - 2d}{2}, \tag{6}$$

where $_t\eta_\mathbf{r}$ allows locally modifying, and if needed during the simulation, the sound speed in the propagation medium. In other words, this term is used in order to model an inhomogeneous atmosphere and is defined in Section 3.1.

Finally, the nodal pressure is written as a combination of all incident pulses, *i.e.*:

$$_tp_\mathbf{r} = \frac{2}{_t\eta_\mathbf{r} + 2d}\left(\sum_{n=1}^{N-1} {_tI^n_\mathbf{r}} + {_t\eta_\mathbf{r}}\,{_tI^N_\mathbf{r}}\right). \tag{7}$$

In addition, the scattered pulses from nodes adjacent to node (i,j,k) at time increment t become the incident pulses to this node at the next time iteration $t + \Delta t$, with Δt representing the time step defined by:

$$\Delta t = \frac{\Delta l}{\sqrt{d}\,c_0}, \tag{8}$$

with c_0 the adiabatic sound speed. This diffusion process is governed by connection laws depicted in Fig. 2 such as:

$$_{t+\Delta t}I^n_\mathbf{r} = {_tS^m_{\mathbf{r}^\pm_n}} \tag{9}$$

and

$$_{t+\Delta t}I^N_\mathbf{r} = {_tS^N_\mathbf{r}}, \tag{10}$$

with

$$\begin{Bmatrix} n \\ \mathbf{r}^\pm_n \end{Bmatrix} = \begin{cases} \begin{Bmatrix} m-1 \\ \mathbf{r}^- \end{Bmatrix} & \text{if } m \text{ is even}, \\ \begin{Bmatrix} m+1 \\ \mathbf{r}^+ \end{Bmatrix} & \text{if } m \text{ is odd}, \end{cases} \tag{11}$$

and

$$\mathbf{r}^\pm_n = \begin{cases} (i \pm 1, j, k), \text{for } n = 1 \text{ or } 2, \\ (i, j \pm 1, k), \text{for } n = 3 \text{ or } 4, \\ (i, j, k \pm 1), \text{for } n = 5 \text{ or } 6. \end{cases} \tag{12}$$

Boundaries are implemented in the TLM model at a distance $\Delta l/2$ from the nearest node in order to ensure the synchronism of sound pulses. They can be characterized by a reflection coefficient in pressure [11] or by an impedance boundary condition [19]. In addition, absorbing layers can be introduced in order to model an unbounded propagation medium as depicted in Ref. [20].

3. TLM formulation for acoustic propagation in a meteorological field

Regarding outdoor sound propagation, the temperature and wind fields combine to produce local variations of sound speed. The literature review above has shown that the implementation of thermal gradients is straightforward in TLM since sound speed is defined at the local level, whereas a suitable implementation for wind gradients is still underdeveloped. In order to address the general case of outdoor sound propagation, both thermal and wind effects must be taken into account simultaneously.

In order to allow for wind speed gradients in the TLM model, the approach developed in this section satisfies the previous requirement since it is based on the so-called effective sound speed. This approach requires knowledge of the local direction of the wavefront. A proof of concept of this approach for the TLM method has been proposed by one of the authors in Ref. [14].