Journal of Sound and Vibration 389 (2017) 454–467

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

# A Transmission Line Matrix model for sound propagation in arrays of cylinders normal to an impedance plane

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ARTICLE INFO

*Article history:*
Received 26 February 2016
Received in revised form
2 November 2016
Accepted 4 November 2016
Handling Editor: R.E. Musafir
Available online 14 November 2016

*Keywords:*
Transmission Line Matrix
Time-domain method
Wave-based method
Multiple scattering
Outdoor sound propagation
Tree trunk

ABSTRACT

The present paper focuses on two of the acoustic phenomena involved in sound propagation through forested areas, namely multiple scattering caused by tree trunks at mid-frequencies and ground effect at low frequencies. The use of time domain methods can be of interest for the simulation of transient phenomena such as scattering. The study aims at evaluating the ability of an alternative time-domain approach, the Transmission Line Matrix (TLM) method, to model sound scattering by cylindrical scatterers. The TLM method is applied to the study of both single and multiple scattering coupled to ground effects, in two- and three-dimensional domains. Keeping in mind the initial purpose of this study, the size and the location of the scatterers (tree trunks), as well as the noise frequency range, are related to outdoor noise propagation in realistic forests. In order to validate the TLM method, numerical simulations are compared to analytical solutions as well as measurements on 1:10 scale-models. The most complete cases of cylinders arrays placed normal to impedance floors are in agreement with the measurement results.



## 1. Introduction

Noise annoyance remains a major concern for European countries. It is now well known that noise exposure has a significant impact on public health [1,2]. Concerning transportation noise, one of the options to protect the inhabitants is the alteration of the noise propagation path. Noise barriers are widely used to screen residential areas from high levels of traffic noise [3]. Nowadays, with the growing interest for sustainable development, ecological and natural existing materials are considered and investigated as promising solutions [4–12]. Several recent works agreed to state that forests can significantly impact sound propagation [13,14]. Among these green protections, forests appear to be an interesting alternative candidate for noise protection.

Among the acoustic phenomena encountered in forests, the ground effect specific to forest floors is predominant at low-frequencies [15–17]. Tree trunks are responsible for sound wave scattering that is predominant at mid-frequencies considering typical trunk diameters [18–20]. Smaller object such as branches, leaves or needles can be responsible for both scattering and viscothermal losses at high frequencies [21–23]. It is important to note that the effect of foliage should be

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http://dx.doi.org/10.1016/j.jsv.2016.11.005
0022-460X/

taken into account when considering dense and large forests. Finally, the forest canopy tends to modify the micro-meteorological properties of the propagation domain such as the wind velocity and the air temperature profiles [24]. Within the framework of road traffic noise studies, the acoustic phenomena of interest are mainly located at low- and mid-frequencies. Therefore, the following study focuses on the ground effect and tree trunks scattering, *i.e.* meteorological effects and scattering by foliage are not taken into account in the following simulations. Thus, the most complete cases of the following simulations reduce to sound propagation through different arrays of cylinders placed normal to an impedance plane.

The modeling of sound propagation in the time-domain presents the advantage of allowing to view the temporal dynamics of the scattering phenomenon using a large bandwidth source signal. In comparison with frequency-domain methods, a single time-domain simulation allows propagating a large frequency band. In forests, sound scattering by tree trunks is considered significant when the frequency of the acoustic waves is close to the apparent diameter of the trunks, whereas the ground effect is preponderant at low frequency [14]. In that sense, time-domain methods appear to be suitable for the study of such acoustic phenomena that occur in two distinct spectral ranges. Among the time-domain numerical methods already used for the modeling of sound propagation in arrays of cylinders, and looking at recent developments of the Transmission Line Matrix (TLM) method [25,26] for outdoor sound propagation, the TLM method appears to be an interesting alternative to the well-known finite difference methods. Its principle makes it easy to implement and custom for the simulation of acoustic wave propagation [27].

In order to ensure that the TLM method is able to provide reliable estimations of sound attenuation in arrays of cylinders, the code has to be both verified with analytical solutions and validated with measurements. This upstream verification and validation procedure rely on basic test cases that consider both single and multiple scattering by circular scatterers with and without grounds. Therefore, the present article starts from a single tree-trunk in 2D and goes up to the case of 3D arrays of trunks over an impedance ground. Section 2 reminds the general principle of the TLM method. The ability of the method for modeling scattering is presented in Section 3, in two-dimensions (2D). The most complete case of 3D multiple scattering by arrays of cylinders above an impedance plane is presented in Section 4. The TLM simulations for single and multiple scattering are compared to either analytical solutions and measurements. Keeping in mind that this study is mainly related to outdoor noise propagation, all physical parameters of interest, such as the scatterer radius (*i.e.* the trunk radius) and the frequency range of the acoustic emission (road transportation noise), are chosen so as to be realistic. In that sense, the following TLM simulations consider two scatterer radii of 0.10 m and 0.25 m (*i.e.* small to medium tree-trunk diameters) and source signals that extend over a frequency range of [100–1600] Hz, as this bandwidth includes the most energetic part of the road noise spectrum.

## 2. TLM method for acoustics

The TLM is a scattering-based numerical method that was introduced by Johns and Beurle [28] to solve electromagnetic problems. Its first application in acoustics was proposed by Saleh and Blanchfield [29] for the study of a transducer array radiation. The method was then extended to the simulation of acoustic propagation in heterogeneous media by Kagawa et al. [30] and applied latter to outdoor sound simulation [25,31–34].

A transmission-line network is made of scattering junctions, also referred as the nodes of a structured cubic grid in a Cartesian coordinate system. Each node is connected to the axial-adjacent nodes *via* transmission lines. Each line has the same length, which forms a regular rectilinear network. Heterogeneity and dissipation within the network are defined at each node by connecting additional artificial lines that enable to locally modify the acoustic impedance of the network. Similar to standard rectilinear finite-difference [35] or digital waveguide [36] methods, the TLM method must satisfy the Courant-Friedrichs-Lewy condition [35] that relates the physical wave propagation to the numerical properties of the network.

In the present work, TLM simulations are carried out using the scientific programming software scilab [37] for two-dimensional (2D) simulations. For larger three-dimensional (3D) domains, simulations are performed using the code described in [27].

## 3. Two-dimensional scattering

### *3.1. Single scattering by a circular scatterer*

This section aims at showing the ability of the TLM method for the simulation of 2D plane wave scattering by a single circular scatterer, compared to an analytical solution. In addition, the influence of the spatial discretization on the scattered field is addressed.

#### *3.1.1. Analytical solution for 2D single scattering*

The monochromatic incident pressure $p_i$, propagating in the vicinity of a circular scatterer with a radius $a$, can be written in a cylindrical coordinate system $(r, \varphi, z)$ as the sum of cylindrical waves as follows [38]: