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Shape optimized inclined single and double wall wave barriers for ground vibration mitigation

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ABSTRACT

Stiff wave barriers are capable of reducing the transmission of ground vibrations. Most designs consist of a single vertical wall, although double walls are also being considered. This paper investigates the shape optimization (position, inclination, length and thickness) of these topologies in a two-dimensional setting, for a point source and a point receiver placed symmetrically with respect to the design domain. Three types of sources are studied: a single-frequency source, a broadband source and a harmonic source within a given frequency range. An economical constraint on the maximum material use is considered. A multi-region BEM methodology is used for evaluating the objective function and its gradient. Analytical expressions are presented for the sensitivities, providing a very effective simulation tool for this type of problem. It is found that significant improvement can be achieved by repositioning and inclining the walls when compared to the reference cases. It is also found that optimized double wall barriers outperform single wall barriers. The improvement is insignificant for sources which generate Rayleigh wavelengths similar to the design domain depth, but it greatly increases as frequency increases and the penetration depth decreases.

1. Introduction

Machinery and transportation systems are sources of vibrations that can travel through the soil to nearby constructions, where they can annoy people or cause equipment malfunctioning or even mechanical damage [1]. Whole-body vibrations are perceived in the frequency range 1–80 Hz [2], while higher frequency vibrations in the range 16–250 Hz lead to re-radiated noise inside buildings, which is also known as ground-borne noise [3]. In order to reduce these vibrations, a wave barrier can be installed along the transmission path as a passive attenuation system. For surface waves, open trenches are the best solutions to such problem since their stress-free boundaries act as perfect reflectors of elastic waves [4]. Their effectiveness greatly depends on the ratio between the Rayleigh wavelength and the trench depth. However, a pure open trench can not be excavated to any desired depth for soil stability reasons and the possible presence of ground water. Therefore, alternative systems such as open trenches reinforced with retaining sheet piles or concrete walls [5], in-filled trenches with soft [6] or stiff materials [7,8], or the installation of sheet piles [9] or rows of piles [10], are also used. Nowadays, the versatility of construction methods such as jet grouting opens up the door for more complex designs based on in-filled trenches with stiff materials. Recently, the use of manufactured structured media (metamaterials/metabarriers) [11] is also being considered for guiding of Rayleigh waves.

Van hoorickx et al. [12] explored novel stiff wave barriers designs obtained via topology optimization [13]. The designs emerging from topology optimization greatly improve the performance of any other conventional wave barrier. They are capable of producing a very high insertion loss at target frequencies, or a considerably improved insertion loss within a frequency range. They are, however, quite complex and thus require manual post-processing in order to define a viable design. In the present paper, we study the problem from a different perspective by exploring the possibilities of the shape optimization of simpler feasible designs: single and double wall barriers; where position, inclination, length and thickness of walls are taken as design variables. Single vertical walls have been extensively studied, while double wall barriers have been considered recently [14]. The effect of wall inclination has been considered by Andersen et al. [15,16], where it was observed that it is capable of improving barrier performance.

The Boundary Element Method (BEM) is probably one of the most

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used analysis tools for this type of wave propagation problems, and it is also used in this work. Open and in-filled trenches have extensively been studied through two-dimensional BEM models, see e.g. [17,18]. Three-dimensional open and in-filled trenches and piles have also been studied [19,20,10]. Coupled BEM–FEM models are often used in order to incorporate structural members in a more natural and efficient manner [6,8,9,21]. Three-dimensional and two-and-a-half-dimensional models offer more realistic results at the expense of more computational costs. However, as argued by Andersen et al. [22], two-dimensional models lead to similar wave patterns, and they offer a good trade-off for most typical long buried structures. Therefore, for long wave barriers, a two-dimensional methodology offers a good compromise between reproducing the actual physical problem and having a moderate computational cost. This is especially true for optimization problems, where a number of designs are evaluated in an iterative procedure.

In the present work, gradient-based shape optimization is used. The use of the BEM in the context of gradient-based design optimization began in the 1980s for two-dimensional heat conduction [23,24] and elastostatics [25,26] problems. More recently, Bonnet [27–30] covered a wide range of shape sensitivity analysis using the BEM and a rigorous mathematical treatment. In particular, Bonnet [31] proved that material differentiation formulas for regular integrals still hold for strongly singular and hypersingular integrals, which demonstrated that material differentiation can be applied to non-regularized as well as regularized BIEs. Gallego et al. [32–36] used the BEM for cavities and crack identification in potential and elastic problems, where geometric sensitivity BIEs derived from the Taylor's expansion of the shape perturbation are developed. In the present work, the latter technique is used to formulate the Geometric Sensitivity BEM, which is used in a direct approach rather than in an adjoint approach since a relatively small number of design variables is present in the studied problems.

The paper is organized as follows. In Section 2, the methodology and the formulation of the optimization problem are described. In particular, Sections 2.1 and 2.2 describe the use of the BEM for zero- and first-order geometric sensitivity analyses of time harmonic elastodynamics. Section 2.3 states the optimization problem and explains how it is solved. In Section 3, the methodology is validated, and then the obtained optimized wave barriers are described and results are interpreted from a physical point of view. Finally, conclusions are given in Section 4.

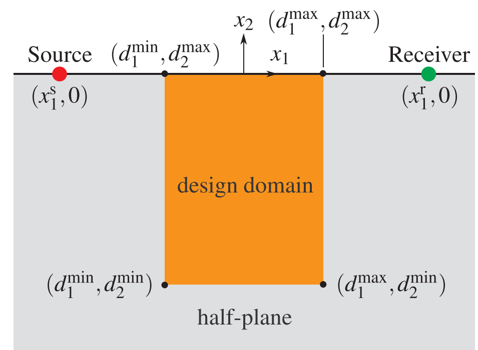
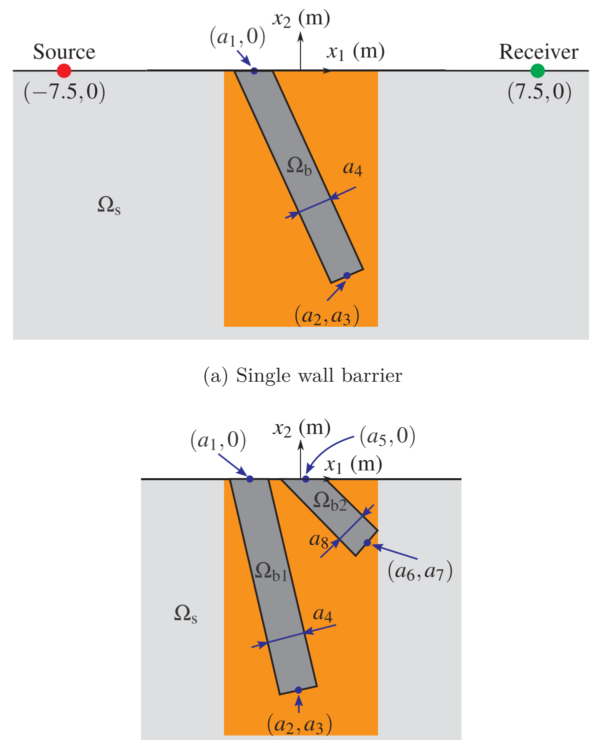


Fig. 1. Problem layout.



(a) Single wall barrier

(b) Double wall barrier

Fig. 2. Studied wave barrier topologies : (a) single wall barrier, and (b) double wall barrier; both located inside a design domain of 5 m × 8 m (in orange).

2. Methodology

2.1. Geometric Sensitivity BEM for elastodynamics

Let Ω be a region in $\mathbb{R}^2$ with boundary $\Gamma = \partial\Omega$ whose orientation is defined by the outward unit normal vector $\mathbf{n} = (n_1, n_2)^T$. Region Ω is an elastic solid under a plane strain state whose properties are: density ρ, Poisson's ratio ν, shear modulus μ, and Lamé's first parameter $\lambda = 2\mu\nu/(1-2\nu)$. A hysteretic damping ratio ξ can be considered by using complex elastic constants $\mu = \mathrm{Re}(\mu)(1 + i2\xi)$ and $\lambda = \mathrm{Re}(\lambda)(1 + i2\xi)$. Displacements are denoted as u_k, and tractions as $t_k = \sigma_{kj} n_j$, where the stress tensor is $\sigma_{kj} = \lambda u_{m,m}\delta_{kj} + \mu(u_{k,j} + u_{j,k})$, and $k, j, m = 1, 2$. For the time harmonic analysis at circular frequency $\omega = 2\pi f$, the Singular BIE (SBIE) for an interior or boundary collocation point $\mathbf{x}^{\mathrm{i}}$ can be written as [37]:

$$c_{lk}^{\mathrm{i}} u_k^{\mathrm{i}} + \fint_\Gamma t_{lk}^* u_k \, \mathrm{d}\Gamma = \int_\Gamma u_{lk}^* t_k \, \mathrm{d}\Gamma \tag{1}$$

where the body loads have been disregarded, $l = 1, 2$ is the live index related to the load direction, and $k = 1, 2$ is the dummy index related to the observation direction. In the present work, the superscript i is used to denote variables or parameters defined at the collocation point. Fundamental solutions in terms of displacements u_{lk}^* and tractions t_{lk}^* can be found elsewhere, e.g. [37]. The free-term c_{lk}^{i} for two-dimensional elastic problems can be found for example in [38]. The left hand side integral of Eq. (1) must be understood in the Cauchy Principal Value sense when $\mathbf{x}^{\mathrm{i}} \in \Gamma$. Assuming a discretization of Γ based on isoparametric Lagrange elements with shape functions $\phi_p^{(e)}$, each boundary element e introduces the following approximation:

$$x_k = \phi_p^{(e)} x_{kp}^{(e)}, \quad u_k = \phi_p^{(e)} u_{kp}^{(e)}, \quad t_k = \phi_p^{(e)} t_{kp}^{(e)} \tag{2}$$

where $p = 1, \ldots, N_{\mathrm{n}}^{(e)}$, and $N_{\mathrm{n}}^{(e)}$ is the number of nodes of boundary element e. An appropriate collocation of Eq. (1) once discretized leads to the well-known relationship:

$$\mathbf{Hu} = \mathbf{Gt} \tag{3}$$

and, after applying boundary conditions, can be written as:

$$\mathbf{Ax} = \mathbf{B}\check{\mathbf{x}} = \mathbf{b} \tag{4}$$

where $\mathbf{A}$ is composed of components of the influence matrices $\mathbf{H}$ and $\mathbf{G}$ related to the unknown components of $\mathbf{u}$ and $\mathbf{t}$ (gathered in $\mathbf{x}$), and $\mathbf{B}$ is