Sound Insulation Provided by a Single Wall Separating Dwellings Via BEM

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Summary

The Boundary Element Method (BEM) is used to compute the airborne sound insulation conferred by a single wall when a harmonic line load excites the system at low frequencies. Two models are used in the computations: in the first model the acoustic spaces are modelled assuming that they are buried in an elastic medium (tunnels), while in the second model the acoustic spaces are modelled with the thickness of the surrounding elastic structure (slabs and exterior walls) being specifically taken into account. In both models, the solid elastic material ascribed to the separating wall can be different from the one comprising the surrounding medium.

Introduction

Airborne wall sound insulation is a classic problem in acoustics. The first publications on it appeared at the beginning of the twentieth century [1]. It is not easy to measure the sound insulation provided by a partition construction element separating two compartments, for low frequencies (below 400 Hz), given the many intervening parameters [2]. Different researchers have proposed a range of numerical techniques to study this issue, which include: simplified methods [3], Finite Element Method [4], Boundary Element Method ([5]-[7]), and others. Well-established numerical techniques, such as the finite element and finite difference methods, have certain drawbacks; the domain being analysed has to be fully discretized, and very fine meshes are needed to solve excitations at high frequencies.

There are many variables that may affect the acoustic insulation provided by a separation element, among these are the: wall mass, sound frequency, angle of incidence of the incident sound waves, the presence of weaker areas in the insulation, and the element's rigidity and damping. The connections between the surrounding walls and the sound propagation within the two rooms are also important, with the vibration eigenmodes of the excited rooms being a determining factor for the latter ([3], [8]).

Numerical and experimental methods have shown that, at low frequencies, the sound reduction index is highly dependent on parameters such as the size of the testing chambers, sound source location and the rooms' surface absorption conditions ([9]-[11]), which makes it difficult to extrapolate test results to real-world situations.

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This work presents two BEM models that have been formulated to compute and compare the responses obtained for the sound level pressure differences, referred to in this work as sound insulation, conferred by a single wall, at low frequencies ($< 300\,\text{Hz}$). In the first model, the acoustic spaces are modelled assuming that they are buried in an elastic medium (tunnels) and separated by a single wall, modelled with an elastic solid material that could be different from the tunnels' surrounding medium. The second model is more concerned with the specific thickness of the room's slabs and walls. The results for the two models are compared, in the knowledge that the second one exhibits responses closer to the real life situations in a dwelling room.

BEM Formulation

The BEM only requires the discretization of the acoustic spaces' surface and the boundary defined by the frontier between the two solid media, in this case, the separating wall and surrounding solid medium (see Figure 1). *Model 2* also requires the discretization of the exterior slabs and wall surfaces. Along the boundary of the interior and exterior acoustic spaces, the system of equations required for the solution is arranged so as to impose the continuity of the normal displacements and normal stresses, and null shear stresses. The equations that need to be integrated to obtain this system of equations are known and can be found in Santos *at al.* [5].

Along the boundary that separates the two solid elastic media, the system of equations required is arranged so that the continuity of both displacements and stresses is imposed. This two-dimensional system of equations requires the computation of the following integrals along the appropriately discretized boundary,

$$H_{ij}^{(s_m)kl} = \int_{C_l} H_{ij}^{(s_m)}(x_k, x_l, n_l)\,dC_l$$

$$G_{ij}^{(s_m)kl} = \int_{C_l} G_{ij}^{(s_m)}(x_k, x_l)\,dC_l \qquad i, j = 1, 2 \;; \quad m = 1, 2 \tag{1}$$

in which $H_{ij}^{(s_m)}(x_k, x_l, n_l)$ and $G_{ij}^{(s_m)}(x_k, x_l)$ are respectively the Green's tensor for traction and displacement components in the solid medium S_m, at point x_l in direction j caused by a concentrated load acting at the source point x_k in direction i; n_l is the unit outward normal for the l^{th} boundary segment C_l; the subscripts $i, j = 1,2$ denote the normal and tangential directions, respectively, and the subscripts $S_m = 1, 2$ denote the solid elastic media 1 and 2. These equations are conveniently transformed from the x, y Cartesian coordinate system by means of standard vector transformation operators. The required two-dimensional fundamental solution (Green's functions) and stress functions in Cartesian co-ordinates, for the elastic medium, can be found in Tadeu and Kausel [12].

The integrations in Equation (1) are performed analytically for the loaded element ([13], [14]). A Gaussian quadrature scheme is used when the element to be integrated is not the loaded element.

Numerical Applications

Figure 1 shows the geometry of the two models used in the numerical applications. This figure also indicates the position of the source and the grid of receivers used to compute the response. In the first model the acoustic spaces are modelled assuming that they are buried in an elastic medium (tunnels), while the second model accounts for the thickness of the elastic structure (slabs and exterior walls) surrounding the acoustic spaces. In both models the thickness ($0.20\,\mathrm{m}$) and the height ($3.00\,\mathrm{m}$) of the separating wall are constant. The thickness of the slabs (St) in *model 2* is $0.30\,\mathrm{m}$, while the thickness of the exterior walls (Wt) is $0.20\,\mathrm{m}$. The mechanical properties of the solid and fluid media used in the computations are listed in Table 1. The calculations are performed for a frequency range from 1 to $300\,\mathrm{Hz}$ with a frequency increment of $1\,\mathrm{Hz}$. The responses

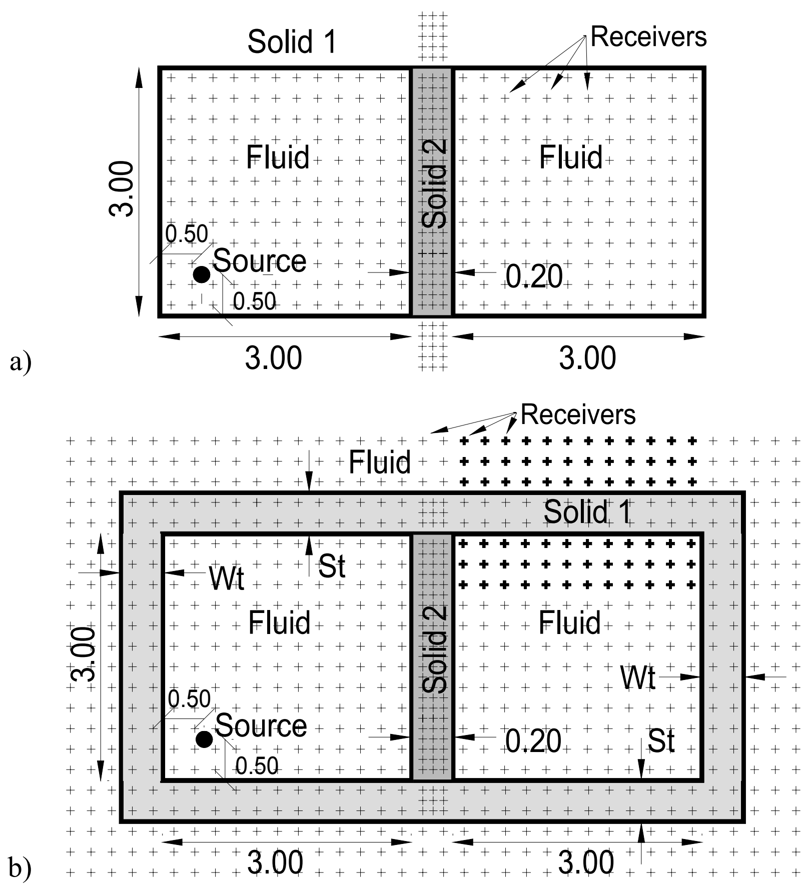

Figure 1: Geometry of the problem: a) *model 1*; b) *model 2*.

were recorded along a grid of receivers placed in the two rooms, equally spaced at a distance of $0.25\,\mathrm{m}$ along the vertical and horizontal directions, as illustrated in Figure 1. Receivers were also placed in the solid medium, in order to record the displacements of the separating wall and surrounding medium.

Table 1: Mechanical properties of the solid and fluid media: α - the compressional wave velocity; β - the shear wave velocity; ρ - the density; η - the loss factor.

Medium	Solid			Fluid
Material	Ceramic	Concrete	Steel	Air
$\alpha\,[\mathrm{m/s}]$	2182	3499	6010	340
$\beta\,[\mathrm{m/s}]$	1336	2245	3212	-----
$\rho\,[kg/m^3]$	1400	2500	7850	1.22
η	2×10^{-2}	4×10^{-3}	3×10^{-4}	-----

Figure 2 gives the average sound insulation conferred by a ceramic separating wall ($0.20\,\mathrm{m}$ thick) using *model 1* and *model 2*. In order to study the importance of a structure's stiffness to sound insulation, *model 2* was also used when the material ascribed to the surrounding medium is steel instead of concrete.

As expected [5], the localized dips in the sound insulation originated by the creation of a stationary pressure wave field inside the tunnels, are visible in all curves. These dips are smoother for higher frequencies. Additionally, there are other sound insulation dips that are related to the separating wall's natural modes of vibration. In this frequency range ($1-300\,\mathrm{Hz}$) it is possible to identify the dips associated with the first three eigenmodes, labelled in Figure 2 as F1, F2 and F3.

Besides the sound insulation dips (separating wall vibration modes and stationary pressure wave field) mentioned about, additional dips in the sound insulation curves are found for *model 2*, and these are related to the eigenmodes of the surrounding structure. As expected, when the surrounding structure has greater stiffness (steel instead of concrete), the sound insulation curves approach to those provided by *model 1*, that is, the additional dips are less important. The first significant sound insulation dip for the case of concrete (*model 2*), occurs at $24\,\mathrm{Hz}$, and when steel is used, the eigenfrequency increases to $29\,\mathrm{Hz}$ (Figure 2). Besides this increase of the eigenfrequency with increasing structure stiffness, the dip in the sound insulation becomes less pronounced, as mentioned earlier. This was also expected, given the lower flanking sound transmission in the stiffer structure, due to lower displacement amplitudes. However, certain dips in the sound insulation become more accentuated, namely for $128\,\mathrm{Hz}$ and $207\,\mathrm{Hz}$. The physical explanation for this could be in the overlapping of the eigenfrequencies related to the vibration of the steel structure and the ones related to the vibration modes of the air inside the rooms. This would lead to an increase in the sound level pressure inside the steel structure.

The additional dips that are more visible for *model 2* than for *model 1* are in the frequency range around 200 Hz (see Figure 2). As mentioned above, these additional dips are related to the vibration eigenmodes of the surrounding structure (slabs and walls). The vibration of slabs and walls results in increased flanking sound transmission, and a consequent drop in the sound insulation conferred by the separating wall in the vicinity of these frequencies.

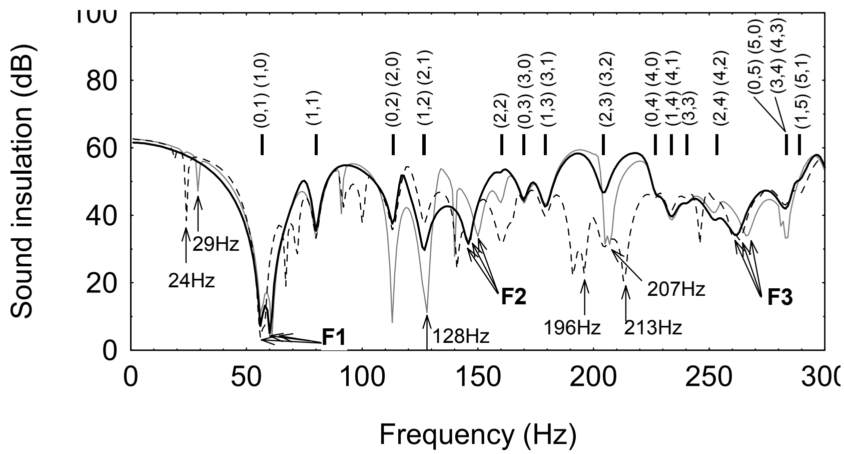

Figure 2: Average sound insulation conferred by a ceramic separating wall when the material ascribed surrounding medium is: ——— concrete (*model 1*), - - - - - - concrete (*model 2*) or ——— steel (*model 2*).

Conclusions

The Boundary Elements Method was used to compute the low frequency sound insulation provided by a single wall separating tunnels (*model 1*) or dwellings (*model 2*), when the system is excited by a pressure line source placed inside one of the acoustic spaces. The sound insulation dips related to the eigenmodes of the separating wall and to the creation of a stationary wave field inside the acoustic spaces were identified and still present in the numerical applications computed for both models.

When, instead of two tunnels (*model 1*), the separating wall divides two dwellings (*model 2*), besides the above-mentioned sound insulation dips (separating wall vibration modes and stationary pressure wave field), there are extra dips in the sound insulation curves, and these are related to the surrounding structure's eigenmodes (slabs and exterior walls). As expected, when the stiffness of the surrounding structure is greater (steel instead of concrete), the sound insulation curve approaches those provided by *model 1*. However, some dips in the sound insulation become more accentuated. This happens when there is an overlapping of eigenfrequencies related to the vibration of the steel structure and the ones related to the vibration modes of the air inside the rooms.

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