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Acoustic performance of balconies having inhomogeneous ceiling surfaces on a roadside building facade

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ABSTRACT

Balconies provide noise screening effects in residential buildings even with the balcony door opened for natural ventilation. However, the screening effect of a balcony was found to be canceled due to the reflection from the ceiling. This paper describes a balcony whose ceiling is made from materials of inhomogeneous impedance which eliminates this drawback. The nonuniform impedance affects wave behavior by altering the direction of energy flux away from the region of a balcony as it reflects on the ceiling. A proposed realization of the balcony ceiling comprises a closely spaced array of progressively tuned hollow narrow tubes which create a phase gradient. The acoustic performance of a balcony with an inhomogeneous ceiling surface is examined theoretically by a ray-based model. All of the results predicted by the theory fit well with numerical simulations using a two-dimensional finite element method. Balconies with the proposed ceilings have the potential to be widely used in a roadside multi-residential building against the exterior traffic noise.

1. Introduction

Balconies are architectural features functioned as a buffer zone to provide a comfortable environment for residents, and recently regarded as one of the green and innovative features in residential building [1]. Due to the high density of population and the scarcity of building land in metropolis, it is common that multi-residential buildings are located close or even next to traffic roads and hence exposed to severe exterior noise. Existing sound protecting treatments, such as sound barriers, are limited in their ability to protect a roadside building, especially the upper stories, against the road traffic noise [2]. However, balconies were found to be effective in providing the noise screening effect in residential blocks even with the balcony door opened for natural ventilation [3]. Therefore, there have been a diversity of studies on investigating the screening effect of balconies. Mohsen and Oldham [4] investigated a closed balcony by computer simulation and measurements on a scale model, and derived an empirical equation to predict the performance of a closed balcony. May [5] observed a significant increase in sound level on high-rise balconies close to freeways by field measurement, and the sound absorption treatment of the ceiling was found to provide effective noise reduction. Boundary element method (BEM) was also used to study the performance of balconies in a tall building close to a road [6]. Kim et al. [7] investigated a special type of balcony, i.e. balconies fitted with windows, by using in-situ measurement. To predict the sound field inside balconies, which are partially covered by absorptive materials, Kropp and Berillon [8] developed a theoretical model by using the Green's function for rigid walls and replacing the non-rigid areas by monopole sources. Cheng et al. [9] carried out a theoretical study on windows with lintels, which are structures similar to balconies, by combining Macdonald's diffraction theory and the image receiver method. As a modification of the standard prediction scheme CRTN [10], a methodology based on the geometrical ray theory was developed for the prediction of sound field inside a balcony [11]. Furthermore, the form of balcony was also attracted much attention: A balcony opened to the street but enclosed on all other sides was investigated by means of scale models by Hammad et al. [12]. Hossam El-Dien and Woloszyn [13,14] tested the influence of balcony configurations, which include the ceiling inclined angle, balcony depth and parapet form, on the acoustic performance of building facades close to roadways using pyramid tracing simulations and scale model measurements. In addition, a study on the scattering effects of balconies has also been carried out using a scale model [15]. The studies mentioned above defined exterior noises solely as traffic noise and considered the balcony effect on a single

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building, Lee et al. [16] then investigated the noise reduction of balconies in an apartment complex and took other noises such as those produced from vehicles entering and exiting a parking lot or from nearby outdoor market into consideration.

When a multi-residential building is located near a road, the screening effect provided by a balcony declines for the occurrence of reflection from the ceiling [6,9]. In continuing efforts to improve the performance of balconies, a diversity of studies on various balcony forms have been conducted [12–15]. Nonetheless, the profiles of these types of balconies are relative complex. On the other hand, active noise control (ANC) has been used to reduce the amount of sound diffracted at the edge of balconies [17]. In particular, sound absorptive treatment was found to be very effective in counteracting the degradation due to the reflection from the ceiling [6]. However, because of the accumulation of dust and bacteria, the requirement of fireproof, as well as the irritation of human respiration system due to fibers from porous materials, the existing absorptive materials are not suitable for longterm use in practice. Moreover, using available absorptive materials leads to impractically thick balcony for low frequency absorption.

In the present study, we seek for a potential alternative solution—barriers whose ceilings having inhomogeneous surfaces—to improve the shielding effect of balconies in a road-side buildings. The balcony ceiling has a simple profile like that of a conventional rigid wall. By introducing an impedance inhomogeneity [18,19], the way the sound behaves as it reflects on the ceiling is altered. Balconies having ceilings with inhomogeneous surfaces successfully guide the sound energy flux away from the region of a balcony, and hence provide a better noise screening effect. In Sec. 2 of this paper, a balcony with a conventional rigid-wall ceiling is investigated theoretically and numerically. In Sec. 3, the behavior of sound interacting with an inhomogeneous impedance surface is evaluated; then the theoretical analysis and numerical simulations on the performance of a balcony having an inhomogeneous ceiling surface are carried out. Finally, a physical example of an inhomogeneous ceiling surface is demonstrated in Sec. 4.

2. Balconies with rigid-wall ceilings

2.1. Theoretical analysis

In this section, the first treatment—a balcony with a conventional ceiling (i.e. rigid-wall ceiling)—is considered, which is the most common case in practical use. Fig. 1 shows the cross sections (in the x–y plane) of a multi-residential building placed very close to a source on the ground; and the geometries are listed in the figure caption. This investigated model is equivalent to an infinite coherent line source parallel to a high building with a constant cross-section facade in three dimensions. Therefore, for the current analysis, the contributions of sound diffraction from the top edge of the facade and the vertical edges of the balconies are ignored. For clarity, the front parapet of each balcony is assumed to be acoustically transparent and will not be shown in the following figures. Notice that it is a critical circumstance since the source is placed very close to the building facade. Nonetheless, using the theoretical approach adopted in this paper, it is straightforward to study the performance of balconies with different source locations. For this conventional treatment, the ground, as well as the ceiling and back wall of each balcony are assumed to be rigid.

In this paper, a ray-based theory, which combines the image receiver method [9,11] and the theory of sound diffraction [20,21], is used to investigate the performance of a balcony. When a road-side multi-residential building is located close to a noise source, as shown in Fig. 1 with the given geometrical configuration, the receiver $\mathbf{R_0}$ is shielded from the source $\mathbf{S}$ by the balcony (i.e. is located in the shadow zone). Thus, the total sound pressure at $\mathbf{R_0}$ with the presence of the balcony can be obtained by combining contributions of the reflected ray and all diffracted rays, as

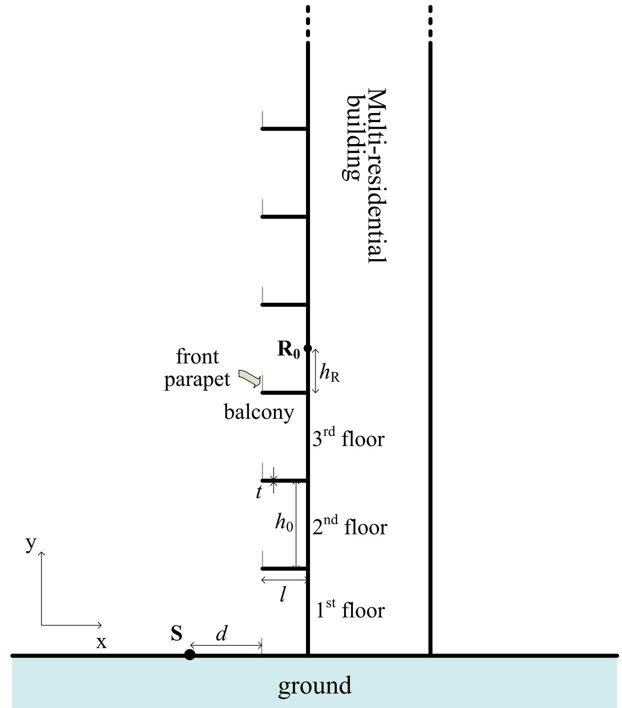

Fig. 1. Schematic representation of a multi-residential building located close to a source. $d = 2.5\ m$, $l = 1.5\ m$, $t = 0.1\ m$, $h_0 = 3\ m$, $h_R = 1.5\ m$.

$$p_w = p_{reflect} + p_{diffract} \tag{1}$$

where $p_{reflect}$ represents the contribution of the ray that is generated from the source $\mathbf{S}$, and then experiences multiple reflections from the ceiling and floor of the balcony on the 4th story before it reaches the receiver $\mathbf{R_0}$. The term, $p_{diffract}$, represents the overall contributions from the diffracted rays, which leave the source, diffract at the edge $\mathbf{E_1}$ or $\mathbf{E_2}$, and then experience reflections with different orders before reaching $\mathbf{R_0}$. For these diffracted rays, as illustrated in Fig. 2(a) and (b), the row of image receivers of the receiver $\mathbf{R_0}$ can be readily created by using a simple ray tracing technique. Then the ray path from the source to the corresponding image receiver is constructed by linking the source and receiver. For instance, an image receiver $\mathbf{R_1}$ is created for the ray that diffracts at $\mathbf{E_1}$ (the edge of the balcony floor) and then hits the balcony ceiling before it reaches $\mathbf{R_0}$. The image receiver $\mathbf{R_2}$ creates the ray that diffracts at $\mathbf{E_1}$, hits the ceiling, and then the balcony floor before it reaches $\mathbf{R_0}$. In an analogous manner, the ray paths traced by other image receivers, $\mathbf{R_3}$, $\mathbf{R_4}$, and so on, can be straightforwardly determined. These image receivers with positive subscripts correspond to the diffracted rays diffracted by the edge of the balcony floor, while other image receivers with negative subscripts are corresponding to the sound rays diffracted at the edge of the ceiling. For the reflected ray, the corresponding image receiver can be readily determined by using the same ray tracing technique. As illustrated in Fig. 2(a), the image receiver for the reflected ray is $\mathbf{R_2}$, which is the same virtual receiver for the diffracted ray of order 2 mentioned above. For the current investigated model, by setting the location of the actual receiver $\mathbf{R_0}$ as the origin, the vertical locations of these image receivers $\mathbf{R_n}$ ($n = \pm 1, 2, 3, \ldots$) are given by