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Acoustic scattering characteristics of Penrose-tiling-type diffusers

Hyojin Lee [a,b,*], Yuzo Tsuchiya [c], Tetsuya Sakuma [b]

[a] Department of Architectural Engineering, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 54896, Republic of Korea
[b] Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan
[c] Institute of Construction Technology, Toda Corporation, 315 Kaname, Tsukuba, Ibaraki 300-2622, Japan

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ABSTRACT

Periodic surfaces involve strong dependence of incidence angle and frequency on scattering directivity, which can be harmful to auditory tonal impressions in room acoustics, while non-periodic surfaces have potential in yielding uniform directivity and moderate frequency characteristics. This paper aims to develop a new type of aperiodic diffuser based on the Penrose tiling of the plane, and furthermore incorporating a fractal expansion for broadening the effective frequency range. In numerical calculation and scale model experiment, the effects of shape, height and arrangement of Penrose tiles on random- and normal-incidence scattering coefficients are examined. In addition, the uniformity of scattering directivity is evaluated in the calculation of directional diffusion coefficients.

1. Introduction

In room acoustics design, diffusers are a proficient treatment for promoting spaciousness, preventing echoes and improving speech intelligibility in a variety of architectural spaces [1]. Since scattering coefficient, which is defined as a ratio of non-specularly reflected sound energy to total reflected energy [2,3], was proposed as an index to evaluate scattering capability of the diffusers, it has been widely utilized for geometrical room modeling programs, and also required for theoretical estimation of reverberation time in rectangular rooms [4].

There exist three kinds of methods for scattering coefficient determination: (1) the standard method of ISO 17497-1 [5] for measuring random-incidence values in a reverberation room; (2) a laboratory method for measuring normal-incidence values in a rectangular room [6]; (3) a BEM-based numerical method for directional values in a free field [7,8]. Up to now, using the above methods, parametrical studies have been conducted to quantify scattering characteristics of several typical surfaces. For hemispheric and cubic diffusers [9], one- and two-dimensional grooves [10], rib and block structures [11] and so on, 1/10- and 1/4-scale model measurements were performed in accordance with the ISO method. Furthermore, the authors numerically characterized random- and normal-incidence scattering coefficients of one-dimensional periodic surfaces with sinusoids, triangles and rectangles [12].

As introduced above, most researches on diffuser design have been focused on periodic profiles because of easy implementation, while the periodicity involves strong dependence of incidence angle and frequency on scattering directivity, which can be harmful to auditory tonal impressions. On the other hand, non-periodic or random profiles have potential in yielding uniform directivity and moderate frequency characteristics. Among them, one of the most innovative appearances is the quadratic residue diffuser as a kind of phase grating diffuser proposed by Schroeder [13]. However, it was revealed later that the Schroeder diffuser has high absorption at low frequencies due to the resonance in the well system [14].

In this paper, a new type of aperiodic diffuser is developed based on the Penrose tiling of the plane, and furthermore incorporating a fractal expansion for broadening the effective frequency range. In numerical calculation and scale model experiment, the effects of shape, height and arrangement of Penrose tiles on random- and normal-incidence scattering coefficients are examined using the above three kinds of methods. In addition, the uniformity of scattering directivity is numerically evaluated in the calculation of directional diffusion coefficients, which is defined as the average of directional autocorrelation coefficients in reflection directivity [15,16].

Penrose tiling is a non-periodic covering of the plane by two prototiles with no overlaps or gaps, discovered by Roger Penrose

* Corresponding author at: Department of Architectural Engineering, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 54896, Republic of Korea.
E-mail address: hyojinlee@jbnu.ac.kr (H. Lee).

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in 1970s [17,18]. The tiling uses a pair of rhombuses with equal sides but different angles, where the interior angles of the thick rhomb are 72° and 108° and those of the thin rhomb are 36° and 144°, respectively. These angles are multiples of one tenth of 2π, hence involving the golden ratio $\varphi = (1+\sqrt{5})/2$ (approximately 1.618) in the rhombuses. In a special case as illustrated in Fig. 1, a Penrose tiling has fivefold rotational symmetry as a quasi-periodic structure. Furthermore, a Penrose tiling has a self-similarity, so that the same patterns occur at larger scales as a fractal expansion. In view of these unique properties, it is expected that an aperiodic diffuser based on the Penrose tiling will have a capability for high uniformity of scattering directivity.

2. Experimental and numerical setups for scattering characterization

2.1. Measurement of random-incidence scattering coefficient

In accordance with ISO 17497-1, measurements for random-incidence scattering coefficients are performed in a 1/4-scale reverberation room of dimensions of 1.5 m × 1.2 m × 0.9 m. A turntable is made of an acrylic circular base plate with a diameter of 0.75 m, and it is surrounded with a plastic border with a height of 50 mm to suppress scattering from the perimeter of a test sample [19]. Room impulse responses are measured in six combinations of two loudspeakers and three microphones, where the period of swept sine signals is 0.68 s, the revolution period of the turntable is 72 s/rev, and the number of signals is 105. The random-incidence scattering coefficients are determined from the reverberation times under the four conditions with and without a sample on the still or rotating turntable.

2.2. Measurement of normal-incidence scattering coefficient

Based on the laboratory method developed by the authors [6], measurements for normal-incidence scattering coefficients are performed in the same room as used for the random-incidence measurement, but installing absorbing materials on all the sidewalls as illustrated in Fig. 2. The absorbing materials are polyurethane foams with a density of 25 kg/m^3 and a thickness of 150 mm, and the circular floor and ceiling are reflective. The test samples used for the random-incidence measurement are placed on the floor. In the one-dimensional sound field, room impulse response measurements are done using swept sine signals in six

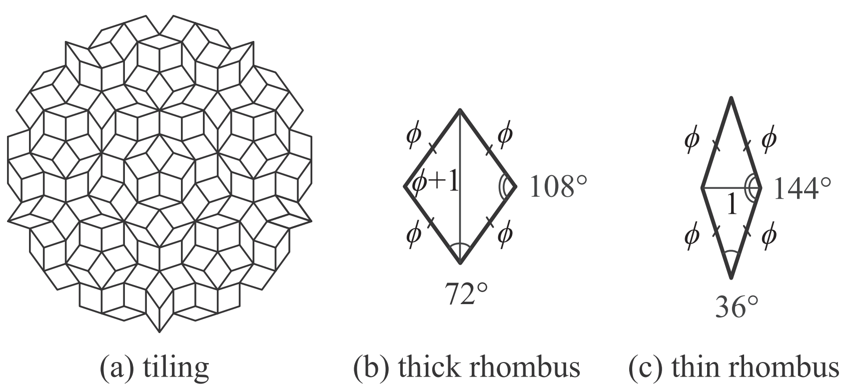

Fig. 1. Penrose tiling with a pair of rhombuses involving the golden ratio φ.

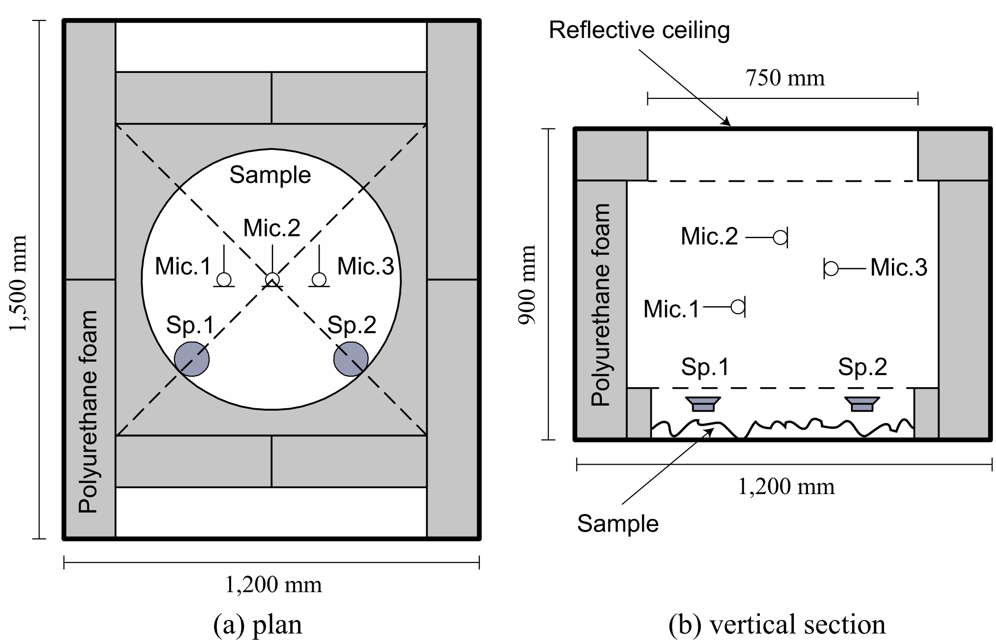

Fig. 2. 1/4-scale test room with a circular sample, a reflective ceiling and absorptive sidewalls.