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Technical Note

Experimental studies on the rain noise of lightweight roofs: Natural rains vs artificial rains

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ABSTRACT

Rain noise is often an unpleasant problem that disturbs people's activities significantly in buildings with lightweight roofs, however, the existing researches are all based on artificial rains in laboratory, while the characteristics of natural rain noise as well as the relationship between actual rain noise and laboratory measurements still need to be explored to fulfill practical demands. This paper first presents two experiments on natural rain noise, revealing that rain intensity is the decisive factor of natural rain noise for heavy rains, and the A-weighted sound pressure level of rain noise caused by heavy rains is proportional to the logarithm of rain intensity. Furthermore, three more experiments on the rain noise with artificial rains are carried out, indicating that differences in rain intensities, fall heights and raindrop size distributions are the factors that cause significant deviation between actual rain noise and laboratory measurements. This total deviation as well as the deviations caused by each factor are then quantified. Finally, a method to predict the actual rain noise of a certain roof using laboratory measurement results is provided, which can be useful in real projects as an effective substitute of experiments using uncontrollable real rains.

1. Introduction

1.1. Research background

When it rains, raindrops from the sky hit on the roof and make rain noise continuously. The lightweight roofs like metal panels and membrane structures vibrate more easily than heavy ones, thus severe rain noise is more likely to be caused. Because lightweight roofs nowadays are widely used in large-span buildings including theaters, gymnasiums, broadcast rooms, and factories, and the rain noise from these roofs significantly disturbs people's activities, communications and mental status in building spaces [1–3], many researches have been conducted regarding how to measure [4–7], analyze [8–11] and reduce [12–14] the rain noise from lightweight roofs. However, all these existing researches are based on artificial raindrops generated in the laboratory instead of natural rains, mostly following a standardized laboratory measurement scenario, *ISO 140-18: 2006* [15], or its successor *ISO 10140-5: 2010* [16]. Hence, the characteristics of rain noise caused by real natural rains, as well as the relationship between actual rain noise and laboratory measurements, still need to be explored. In real projects, however, we need to know the actual rain noise of a certain project under different rain conditions and judge whether the rain noise is acceptable according to the function, importance and location of the project. Taking two projects that we took charge of the rain noise problems as examples, the *National Aquatics Center of China* requires no more than 60 dB(A) under 120 mm/h rains, while the *National Performing Art Center of China* requires no more than 42 dB(A) under 60 mm/h rains (Fig. 1). Therefore, the knowledge conveyed by the existing researches is not sufficient enough to fulfill the demands of projects, because it neither reveals the relationship between natural rain noise and rain characters, nor provides a method to predict the natural rain noise using laboratory measurements. This paper presents a long-term experimental research aiming to improve these two problems above.

1.2. Related background of rains

In meteorology, *Rain Intensity* (I) is the most important parameter to describe a rain and is defined as the thickness of falling water within one hour. It can show how heavy a rain is, and usually uses millimeter/hour (mm/h) as its unit [17]. Rains are classified as

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Fig. 1. The National Aquatics Center of China and the National Performing Art Center of China.

slight, *moderate*, *heavy*, or *violent* for rain intensities of 0–2 mm/h, 2–10 mm/h, 10–50 mm/h, or greater than 50 mm/h, respectively [18].

Size distribution of raindrops is another significant character of a rain and is also highly related to *Rain Intensity*. Research shows that the diameters of raindrops in a rain follow an exponential distribution pattern [19], which is:

$$N(D) = N_0 * e^{-4.1 I^{-0.21} D} \tag{1}$$

where $N(D)$ (m^{-3} mm^{-1}) is the raindrop numbers at a certain diameter within 1 m^3 volume, N_0 is a constant equals to 8000 m^{-3} mm^{-1}, I is the rain intensity in mm/h, and D is the diameter of raindrops in mm. Although the distribution of raindrops is also influenced by the type of rains, heights of clouds, etc., Eq. (1) has been proved to be an effective predictor of the size distribution of raindrops, especially for heavy rains [20–23], which could cause louder rain noise than moderate rains and thus are what we care more about. The distribution can also be shown as Fig. 2, which indicates that the bigger the rain intensity is, the more large raindrops there will be.

The size of raindrop also determines its speed when hitting the ground, which is called the *Terminal Velocity* (m/s). Every raindrop starts to fall at an increasing speed after it leaves the sky because of gravity, however, after the force of air resistance equals to its gravity, its speed will stay constant until hitting the ground. Because the air resistance is proportional to the square of the drop diameter and the square of its speed, while the drop weight is proportional to the cube of its diameter, the terminal velocity of bigger drops is higher than that of smaller ones (Fig. 3). Also considering that the kinetic energy of a rain drop is proportional to its mass and the square of its velocity, the kinetic energy per mass of larger raindrops is bigger than that of smaller raindrops when hitting the ground. Besides the size of raindrops, wind is another influential factor of the terminal velocity of raindrops, which can not only affect the value of terminal velocity, but also change its direction. Therefore, raindrops with the same size could have different kinetic energy when hitting the ground in windy conditions. Since wind can change very quickly, the kinetic energy of raindrops when hitting the ground could have significant uncertainty. The smaller the raindrop is, the more influential wind could be comparing to gravity, and thus the kinetic energy of the raindrop has larger uncertainty and is less determined by its size [24,25].

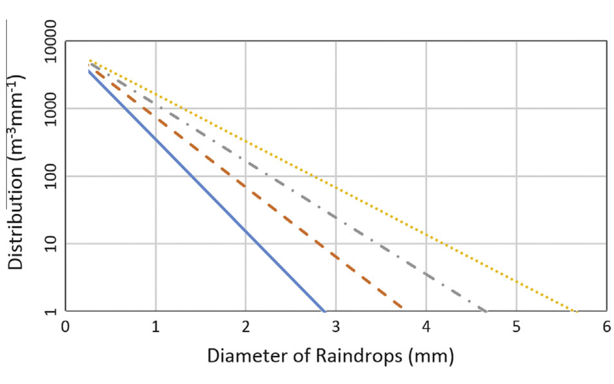

Fig. 2. Raindrop diameter distributions in different rain intensities.

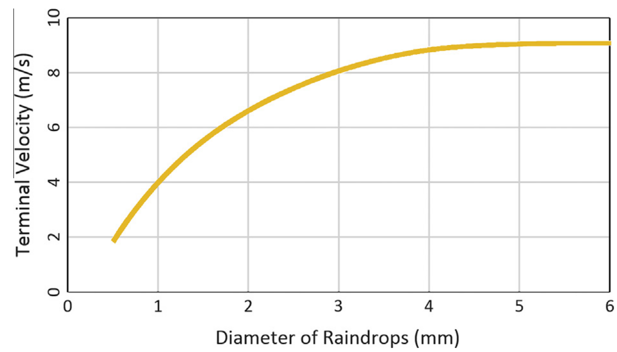

Fig. 3. Theoretical terminal velocity of raindrops of different diameters.

1.3. Laboratory measurement scenario of rain noise

As indicated in Section 1.1, artificial rains are commonly used to measure rain noise as a substitute of uncontrollable natural rains. ISO has published standards to standardize the laboratory method of producing artificial rains and measuring rain noise. In the commonly used *ISO 140-18: 2006* [15], which most existing researches comply with, artificial raindrops are required to be generated from a water tank with a perforated base (Fig. 4). The rainfall rate (rain intensity) is fixed to 40 mm/h while the diameter of raindrops is confined to 5 mm in order to simulate a heavy rain. (A light type of rain is also introduced in the standard, but it is rarely used and only recommended if lower rainfall rates are needed, therefore it is not included in this research.) The raindrops then hit the test specimen (roof) 3-meter below the tank and create rain noise into the test room. Then the sound pressure level of rain noise can be acquired by averaging 5 different positions in the test room (Fig. 5). For comparison between different test rooms, the sound pressure level can be converted to sound intensity level using Eq. (2), thus the deviations caused by different reverberation times and volumes of test rooms, as well as different areas of test specimens can be eliminated:

$$L_I = L_p - 10\lg\left(\frac{T}{T_0}\right) + 10\lg\left(\frac{V}{V_0}\right) - 10\lg\left(\frac{S}{S_0}\right) - 14 \tag{2}$$

where L_1 is the sound intensity level in dB; L_P is the sound pressure level in test room in dB; T is the reverberation time of the test room in s; T_0 is the reference time (=1 s); V is the volume of the test room in m^3; V_0 is the reference volume (=1 m^3); S is the area of the test specimen under impact in m^2; while S_0 is the reference area (=1 m^2) [15].