STUDY OF SIMULATED RAINFALL NOISE ON ROOFS AND GLAZINGS

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ABSTRACT

In this paper, a theoretical model and a laboratory set-up for the evaluation of rainfall noise on complex systems such as roofs and glazings are discussed. First, the impact force associated to a raindrop size and a statistical model for the distribution of natural raindrop size allowing the determination of the structural rainfall power spectrum injected to the test structure are presented. Several 3-dimensional theoretical models describing the vibrational response and transmitted acoustic field for a planar complex (multi-layered) system are then briefly developed. The laboratory set-up for measuring rainfall noise is under construction; preliminary experimental and theoretical results will soon be compared.

INTRODUCTION

In modern buildings, the use of light weight elements (generally made of steel sheets) or the use of large skylight type glazings on roofs has become more extensive. The noise produced inside buildings by rainfall impacting on these roof surfaces is raising significant concern. Indeed, in spaces with such roof surfaces, rainfall increases the interior background noise levels, inducing a decrease of speech intelligibility.

A new international standard prescribing a laboratory method for the measurement of sound generated by rainfall on buildings elements using artificial raindrops under controlled conditions is being discussed. Other mechanical simulation methods (impact hammer) have been investigated but have not been able to adequately simulate real rain both in terms of sound levels and spectra generated. The rain can be described in terms of rainfall rate, drop diameters and fall velocities. The characteristic parameters for the artificial raindrops have been chosen to be 15 mm/h rainfall rate, 2 mm drop diameter and 4 m/s fall velocity for an intense rain and up to 40 mm/h rainfall rate, 5 mm drop diameter and 7 m/s fall velocity for a heavy rain. Artificial raindrops can be generated by hydraulic spray nozzle generating water drops of uniform diameter.

In this context, the CSTB has decided to implement a laboratory set-up for artificial rainfall noise measurement as well as to develop the associated analytical tools to help achieving design improvement with respect to rainfall noise of roof elements.

In this paper, the impact force associated to a raindrop size and a statistical model for the distribution of natural raindrop size allowing the determination of the structural rainfall power spectrum injected to the test structure are presented. Three 3-dimensional theoretical models describing the vibrational response and transmitted acoustic field for a planar complex (multi-layered) system are then introduced and their results are compared. At the time this paper is being written, the laboratory set-up for measuring rainfall noise is still under construction. Experimental results should be soon available.

ANALYTICAL MODEL

Rainfall Excitation Spectrum

The impact force F(t) caused by a drop can be expressed by [1]

$$F(t) = \rho\, \pi r^2\, V_t^2 \left\{1 - \frac{3V_t}{8r} t\right\} \text{ for } 0 \le t \le 8r/3V_t \tag{1}$$

where ρ is the water density, r the water drop radius, and V_t the drop terminal velocity.

The excitation force of natural rainfall can be evaluated by adopting a statistical model for the distribution of natural rainfall proposed by [2]. This distribution N(D) in $mm^{-1}m^{-3}$ is

$$N(D) = 8000\, \exp\left\{-4.1R^{-0.21}D\right\} \tag{2}$$

where R is the rainfall rate in mm/h and D the water drop diameter in mm.

The terminal velocity of a raindrop (in m/s) is given by an empirical formula [3]

$$V_t(D) = 9.58\, \left\{1 - \exp\left[-(D/1.77)^{1.147}\right]\right\} \tag{3}$$

Consequently, the number n of raindrops having a diameter between D and D+δD impacting a unit area (1 m^2) of roof per unit time (1 s) is

$$n(D) = N(D)\ \delta D\ V_t(D) \tag{4}$$

The power spectrum of the excitation force associated with a raindrop of diameter D is then expressed

$$P_{exc}(D,\omega) = n(D) \left|\tilde{F}(D,\omega)\right|^2 T_0 \tag{5}$$

where T_0 is the reference time (T_0=1 s), and $\tilde{F}(D,\omega)$ is the impact force spectrum, i.e., the Fourier transform of the impact force given in Equation (1).

For artificial rainfall, all drops are assumed to have the same diameter D_a and the same terminal velocity V_{ta} (usually obtained by measurement); the number n_a of drops impacting a unit area of roof per unit time is then for a fall rate R_a

$$n_a = \frac{10^{-3} R_a}{3600} \frac{6}{\pi D_a} \tag{6}$$

For a flexible structure excited by rainfall, it is necessary to take into account the point impedance of the structure Z_{struc} and the flow impedance of the water drop Z_{drop}. The impact force spectrum is then changed to

$$\tilde{F}_{flex}(D,\omega) = \frac{Z_{struc}}{Z_{struc} + Z_{flow}} \tilde{F}(D,\omega) \quad \text{with } Z_{flow} = \rho\, \pi r^2\, V(D) \tag{7}$$

Figure 1 shows the impact force spectrum for drop diameters from 0.5 mm to 5.0 mm. It can be observed that with increasing raindrop diameter, the impact force spectrum level increases and the frequency at which the impact force spectrum is maximum decreases. This is due to the fact that larger sized raindrops have more mass, a higher terminal velocity and a longer impact duration.

Table 1 shows some typical characteristics of different natural and artificial (Intense 1 and Heavy 1) rainfall types as given in [4]. Figure 2 presents in third octave band the power spectrum associated with the natural as well as the artificial rainfalls described in Table 1 (for the natural rainfall, δD=0.1 mm was considered). For natural rainfall, even if the number of drops per m^3 decreases sharply with drop diameter (see Equation (2)), the larger sized raindrops contributes the most to the power spectrum because they are associated with higher impact force spectrum as explained previously. It can be seen that the power spectra corresponding the artificial rainfall Intense 1 and Heavy 1 recommended by [4] do not well represent those of their associated natural intense and heavy rainfall. The power spectra for the artificial rainfall Intense 2 and Heavy 2 provide a better agreement with their associated natural rainfall over the entire frequency range.

Table 1 : Characteristics of different rainfall types.

Rainfall type	Rainfall rate (mm/h)	Drop diameter (mm)	Fall velocity (m/s)
Natural Moderate	Up to 4	0.5 – 1.0	1 – 2
Natural Intense	Up to 15	1.0 – 2.0	2 – 4
Natural Heavy	Up to 40	2.0 – 5.0	5 – 7
Artificial Intense 1	15	2.0	4.0
Artificial Heavy 1	40	5.0	7.0
Artificial Intense 2	15	1.5	5.0
Artificial Heavy 2	25	3.5	7.5

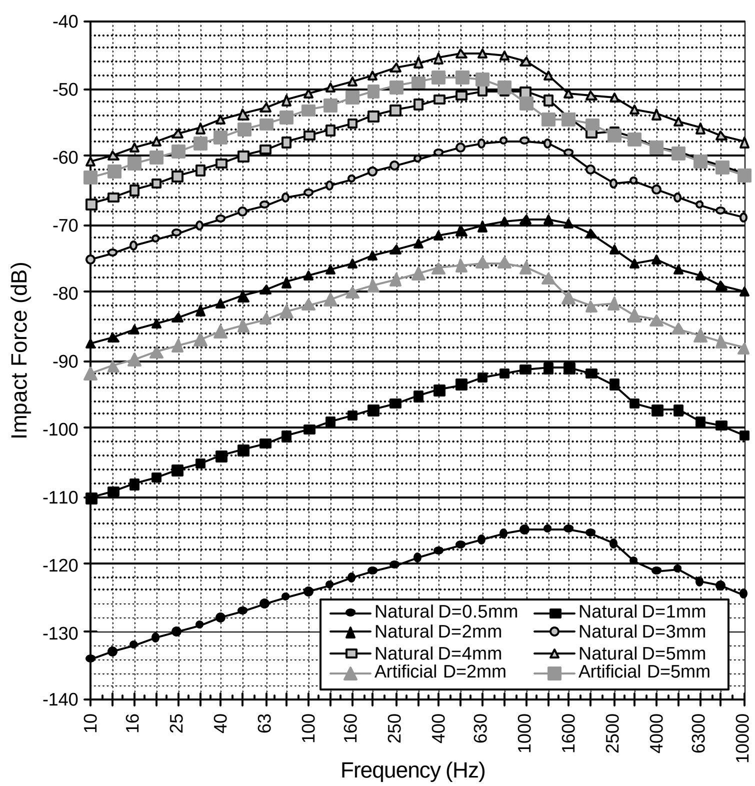

Figure 1: Impact force spectrum for different drop diameters.

<u>Infinite Multi-layered Structure Model</u>

The model for infinite multi-layered structures is based on a transfer matrix approach (see [5] for example). The different layers of constant thickness, constituting the structure can be either solid, fluid, or porous (following Biot's theory) elements. Furthermore, the layers can be bounded or unbounded with each others. The computer program CASC based on this approach is already used at CSTB to predict sound transmission, sound absorption and impact noise, to obtain propagation constants. It was then modified to include rainfall type excitation as described in the previous section and to calculated the associated sound power radiation. It should also be noted that a spatial windowing technique can be used to take into account the effect of the finite size structure as presented in [6].

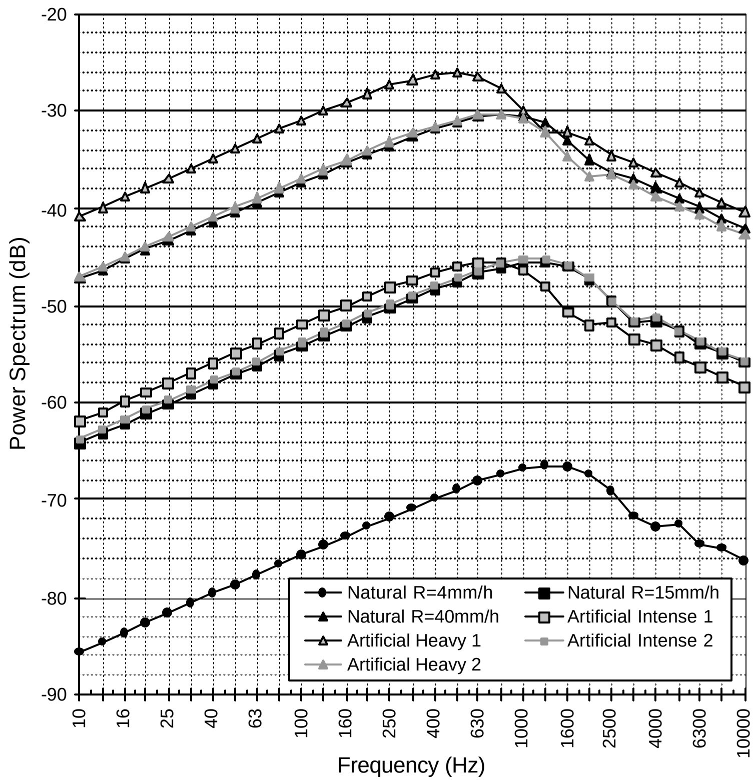

Figure 2: Power spectrum for different rainfall types.

Modal Model

The modal model allows the consideration of a single plate, or two plates coupled by an air cavity. The model is based on a superposition of a simply supported thin plate solution for the structural component and duct type solutions with rigid boundary conditions for the coupling cavity if present. Such a model is described in [7]. An average of 100 forces randomly distributed on the structure surface was used for the prediction of sound power radiation under rainfall type excitation.

SEA Model

A SEA model for a single component was also implemented. The derivations follow those presented in [8], allowing to write the radiated sound power as

$$\Pi_{SEA} = \frac{\rho_0 c_0}{m_s\, \omega\eta}\, \sigma\, \Pi_{in} \tag{8}$$

where $\rho_0 c_0$ is the characteristic acoustic impedance of air, m_s the structure density per unit area, η the structure loss factor, σ the radiation efficiency (given by Leppington, see in [8]) and Π_{in} the injected power. For rainfall type excitation, the injected power can be expressed as

$$\Pi_{in} = \frac{1}{2} P_{exc}(\omega)\, \mathrm{Real}\{Y_s\} \text{ with } Y_s = 1\Big/\left(8\sqrt{D_s\, m_s}\right) \tag{9}$$

where D_s is the structure bending stiffness and $P_{exc}(\omega)$ the power spectrum associated with the rainfall (deduced from Equation (5)).

RESULTS

Results are presented for a single glazing (10 mm thick glass) and a double glazing (composed of 10 mm thick glass / 6 mm thick air / 4 mm thick glass). The characteristics of the glass component are given in Table 2. The considered glazings have a surface area of 1.48x1.23 m^2. The calculations presented below are conducted for the artificial heavy rainfall noted Heavy 2 in Table1 (which is very close in terms of the excitation power spectrum to the natural rainfall with a 40 mm/h rate as seen in the previous section).

Table 2 : Structural characteristics of the glass component.

	Density (kg/m^3)	Young Modulus (GPa)	Poisson Coefficient	Loss Factor (%)
Glass	2500	62	0.22	5

Single Glazing

The radiated power for the single glazing system is presented in Figure 3 for the different models considered. First it should be noticed that for this system and for the rainfall excitation considered, the maximum acoustic radiation occurs close to the critical frequency of the panel (1250 Hz) since, in that frequency range, its radiation efficiency is important and the excitation spectrum close to its maximum. As expected, above the critical frequency of the system the different models agree very well since the radiation efficiency is close to 1. Below the critical frequency, the infinite size CASC results show low radiated power levels as the radiation efficiency for infinite structure is quite low but not null since supersonic waves exist in the structure due to the damping in the structure (see [6]). The results from the SEA and modal approaches agree fairly well. Note that the high level of radiated power at the critical frequency for the SEA modal comes from the evaluation of the radiation efficiency with Leppington formula (this formula does not take into account the loss factor in the structure). Finally, the radiated power obtained with a spatial filtering technique to take into account the finite size of the structure (noted CASC – Finite Size in Figure 3) is over-evaluated below the critical frequency compared to that obtained with modal and SEA models. The difference is about 3 dB around 100 Hz.

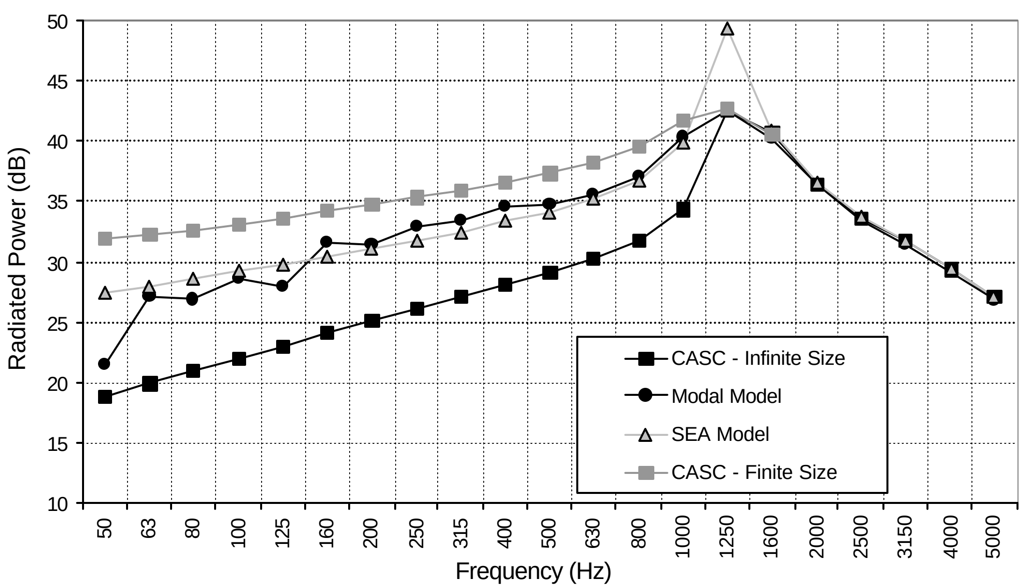

Figure 3: Sound radiated power for the single glazing.

Double Glazing

The radiated power for the double glazing system is presented in Figure 4. As expected, above the critical frequency of the panels constituting the double glazing (1250 Hz) the different models presented agree very well. In this case, the maximum sound radiation occurs in the frequency range from the system resonance frequency (associated with the air cavity around 315 Hz) to the first panel critical frequency. The spatial filtering technique applied to the infinite multi-layered structure model to take into account the finite size of the structure is associated to an increase of radiated power compared to the infinite structure case only below the cavity resonance frequency. However, the predicted radiated power between the resonance frequency and the critical frequency is unchanged by the use of this technique. Therefore, it is under-evaluated compared to the results obtained with the modal model in that frequency range. More work is needed regarding the spatial filtering technique in the case of structural excitation with the presence of a cavity coupling structural elements.

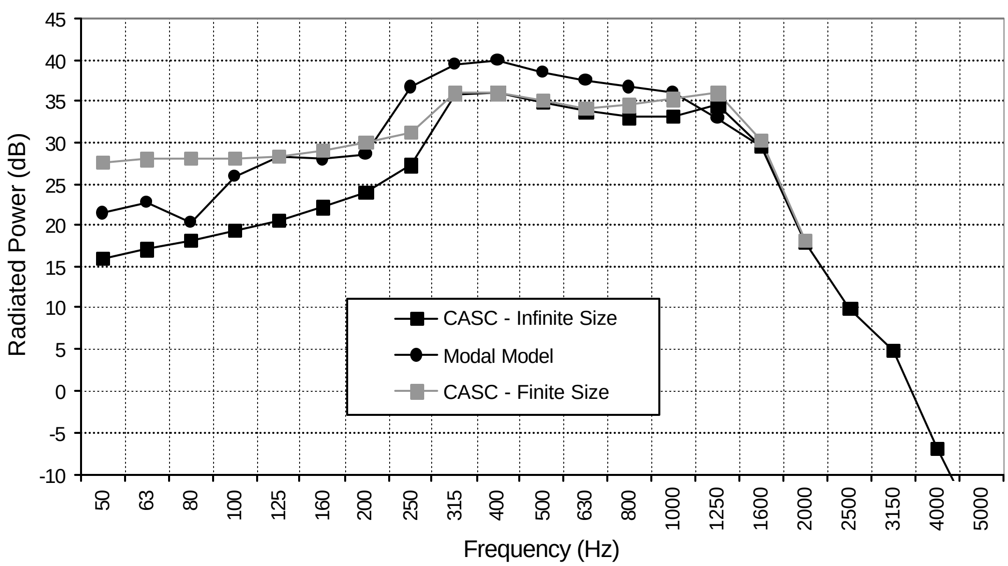

Figure 4: Sound radiated power for the double glazing.

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