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PREDICTION OF RAINFALL NOISE ON SINGLE AND DOUBLE GLAZING

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1. INTRODUCTION

In modern buildings, extensive use is made of spaces covered by large glazed surfaces. These architectural elements constitute difficulties with regard the to interior acoustical climate and the noise shielding from the environment. One particular problem is the sound insulation of rainfall noise on the glazing: excessive rainfall noise increases interior background levels and compromises the speech intelligibility.

This paper reports on experiments and numerical simulations of the problem. In a laboratory set-up, the sound power radiated by different types of single and double glazing subjected to artificial rainfall has been measured. A numerical model was used to predict the sound radiation of single and double glazing subjected to a random point force excitation.

2. EXPERIMENTAL SET-UP

Figure 1 shows a part of the experimental set-up. The glazing is mounted on top of a horizontal measurement opening located between two transmission rooms. A double wall construction with high sound insulation gives the necessary support and inclination for the test specimen. For each test, two glass panes are used, simply supported on top of the double wall, with all joints properly sealed against air and water leaks.

Rainfall is simulated by four water jets suspended at the ceiling of the upper room. Water is ejected upwards, causing raindrops to fall freely from a height of 3 m on the glass surface. Water collection, pump and ejectors are built as a closed circuit to allow continuous operation of the set-up over a long measurement period. Care was taken to maintain a constant rainfall rate of 50 $l/(m^2h)$, evenly distributed over the glazing, for all tests in the measurement program.

During a test, the average sound pressure level in the receiving room was monitored for a period of 30 minutes. This quantity was normalised with respect to the surface of the glazing and the sound absorption in the receiving room as follows:

$$L_{pn} = L_{pr} - 10\log(S / A)$$

where:
L_{pr}: the sound pressure level measured in the receiving room (dB);
S: the surface of the glazing (4.45 m^2);
A: the sound absorption measured in the receiving room (m^2).

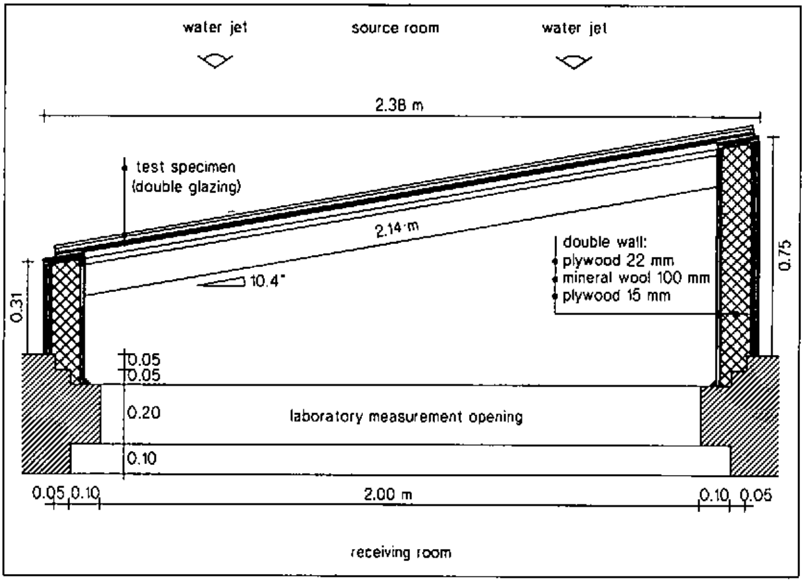

Fig.1. Measurement set-up

3. CALCULATION MODEL

Basic Equations

In this paper, the problem of predicting rainfall noise on glazing is reduced to calculating the sound radiation of a single or double wall under random point force excitation. It is assumed that the force spectrum of the rain impact is known and that the dynamics of the wall are not significantly changed by the thin water layer on top of the plate facing the source room. The test panel is mounted in an infinitely extended rigid baffle separating two semi-infinite fluid regions which represent the source and the receiving room. A single glazing is modelled as a thin, homogeneous plate with isotropic material characteristics. A double glazing is modelled as two parallel plates separated by a fluid layer. Mechanical connections between both plates are not taken into account. The basic equations of motion for the problem involving the double glazing are as follows:

- the sound field in the three fluid regions is governed by the Helmholtz equation. Different characteristic wavenumbers are introduced to account for different wavespeeds in the fluids, as would be the case for a heavy gas in the cavity of a double glazing;
- The displacement of both plates is governed by the thin-plate bending wave equation. Harmonic point force excitation is assumed for plate 1, and both plates are submitted to a sound pressure difference from the respective fluid regions at both sides;

These equations are complemented by the following boundary conditions:

- the Sommerfeld radiation condition is imposed for the sound pressure radiated towards the semi-infinite fluid regions 1 and 3;
- rigid wall boundary conditions are imposed at the four edge surfaces of the cavity;
- mechanical boundary conditions are imposed on the edges of both glass plates of the double glazing.

Finally, the coupling between the displacements of the plates and the sound pressures in the fluid regions is implemented in continuity conditions for the displacements at the plate-fluid interfaces.

Numerical Solution

The governing equations are solved using a modal summation approach [1]. The displacements of the plates are expressed as modal summations over the eigenmodes of the plates in vacuum. The corresponding modal amplitudes constitute the principal unknowns of the problem.

The sound radiation of the individual modes is characterised by a radiation impedance matrix: its diagonal elements represent the interaction of a single plate mode with the surrounding fluid; its off-diagonal terms represent the interaction of different plate modes ($kl \neq mn$) through the surrounding fluid [2].

The sound field in the cavity is expressed as a series expansion in the co-ordinates parallel to the surface of the panel, whereas the pressure variations perpendicular to the plate surface are expressed by pairs of travelling waves.

The final solution is obtained by eliminating the modal amplitudes of the sound pressure in the cavity through the continuity conditions and by introducing the resulting expressions in the equations of motion of the plates. In this way, a system of linear equations in the plate amplitudes is obtained. From its solution, the different dynamic quantities of the problem can be calculated. The sound intensity radiated by the panel is obtained as the product of plate velocity and sound pressure on the plate surface. The sound radiation due to rainfall is obtained by randomly varying the positions of the point force and averaging the radiated intensity.

Theoretically, the numerical solution requires the evaluation of infinite summations and matrices of infinite dimensions. To allow for practical calculations, the dimensions have to be restricted and the summations truncated to a finite number of terms. By means of a two-dimensional (beam) model of the double glazing, it has been verified that the off-diagonal terms of the radiation impedance matrix can be neglected without seriously compromising the accuracy. Plate modes are selected or omitted depending on their estimated mechanical response and their coupling to the surrounding fluid. Cavity modes are selected up to the cut-off frequency of the cavity, characterised by an imaginary trace wavenumber in the modal expansion of the sound pressure.

4. EXPERIMENTAL AND NUMERICAL RESULTS

Experimental Results

Table 1 lists a selection of the glazing tested and the normalised A-weighted sound pressure level measured with a rainfall rate of 50 l/(m²h).

	types of glazing tested	Lpn(A)
1	12 mm: single	60.9
2	6+1+6 mm: single layered, pvb foil as damping layer	55.1
3	6+1+6 mm: single layered, resin as damping layer	50.9
4	4+1+4/12/6+1+6: double layered, pvb foil as damping layer	51.4
5	4+1+4/12/6+1+6: double layered, resin as damping layer	45.0

Table 1. Overview of glazing tested and global A-weighted SPL radiated.

Figure 2 shows the results in one-third octave bands. The large influence of the presence of a damping layer on the mechanical response and sound radiation is readily observed. For the single glazing, the sound radiation is reduced with 5 and 10 dB(A) by applying a pvb or resin damping layer, respectively. For the double glazing, the resin damping layer is up to 6 dB(A) more efficient as compared to the pvb layer.

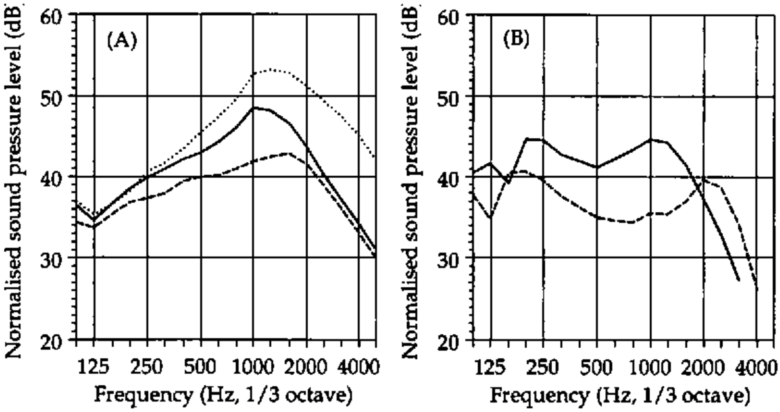

Fig.2. Sound radiation under rainfall excitation.

(A) 12 mm single glazing:
(------), massive
(——), pvb-layered
(— — —), resin-layered

(B) 4.1.4/12/6.1.6 mm double glazing:
(——), pvb-layered
(— — —), resin-layered

These results are explained by the lower bending stiffness and increased internal damping of the layered panels, as compared to a massive plate. In this respect, the resin layer performs better than the pvb layer. The resin layer is relatively soft and is subject to larger deformations when it is applied between two plates loaded in bending. This results in a lower overall bending stiffness and a higher damping compared to the plates bonded by a pvb layer.

To verify the results of the rainfall experiments and to obtain input data for the simulations, the modulus of elasticity and the internal loss factor of massive and layered glass samples was measured. These parameters are calculated from point impedance measurements on small, freely suspended beam samples. Figure 3 shows the results obtained at different resonance frequencies. The lower stiffness and higher loss factor of the resin-layered glass are in line with the measurement results of the rainfall noise.

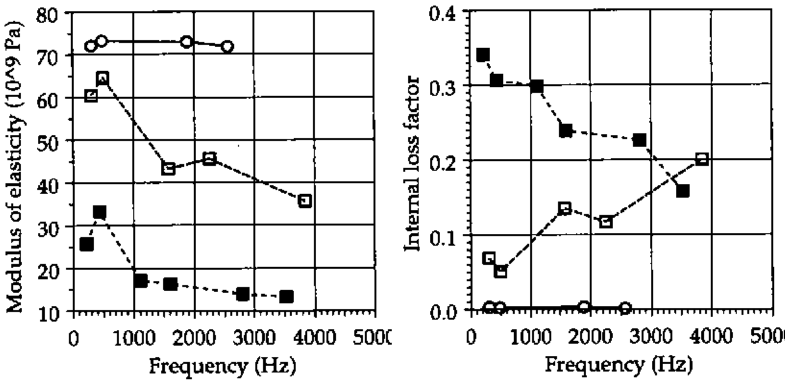

Fig. 3: Modulus of elasticity and internal loss factor measured on small beam samples:(——) 8 mm massive glazing; (– – –) 4+0.45+4 mm pvb-layered glazing; (- - - -) 4+1.50+4 mm resin-layered glazing

Numerical results

Using the model presented in the previous section and the measured material data, the sound radiation of the different panels was calculated. As no exact force spectrum is available, the results are presented as a reduction in radiated sound power level with regard to a reference situation.

Figure 4a shows the results for the single glazing. The improvements by applying a damping layer are correctly predicted, although at higher frequencies a considerable deviation is observed. Figure 4b shows the result for the double glazing. In the low- to mid-frequency range the resin-layered glass performs better than the pvb-layered glass, due to its higher critical frequency and higher internal damping. At high frequencies, however, this effect becomes negative due to the strong sound radiation at the critical frequency.

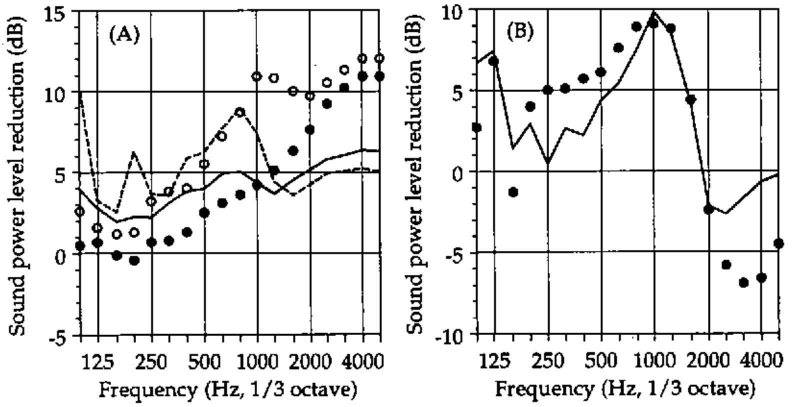

Fig. 4: Reduction of the sound power level radiated under rainfall excitation:

(A) Improvement of a layered glazing over a massive glazing:
(•), pvb layer, measurement
(——), pvb layer, calculation
(o), resin layer, measurement
(- - - -), resin layer, calculation

(B) Improvement of a resin layer over a pvb layer
(•) measurement
(——) calculation

CONCLUSIONS

In this paper, experimental and numerical results for the sound radiation of glazing subjected to rainfall excitation have been presented. The results show how the sound radiation can be reduced by means of layered glass panes or by using double, layered glazing. The accuracy of the calculations is sufficient to compare different compositions of the single and double glazing. However, it should be emphasised that the complexity of the boundary conditions can compromise the accuracy of the results in some cases.

References

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