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Improvement on Nighttime Sound Insulation of Windows by External Shutters – Part 2: Calculation of Weighted Sound Reduction Index

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Abstract

The current version of the German standard for sound insulation in buildings, DIN 4109, explicitly takes into account the external noise level at night. If the external noise level at night is no more than 10 dB lower than during the day, the required sound reduction is based on the relevant external noise level at night. In this case, a surcharge in sound reduction of up to 10 dB must be considered in bedrooms due to the increased disturbance at night. For such external noise situations, temporary sound reduction in form of an external enclosure can be an economical solution if the existing roller shutters provide an improvement instead of expensive soundproof windows. As part of a research project conducted jointly with Rosenheim University of Applied Sciences (TH Rosenheim) and the Rosenheim Institute for Window and Façade Technology, (ift Rosenheim) the sound reduction of various combinations of glazing and shutters was determined in the laboratory of ift Rosenheim. Several parameters e.g. the distance between the glazing and the shutter, the surface-related mass of the shutter, the type and the sound reduction of the glazing and the airtightness of the shutter were identified as most important for the airborne sound improvement. To implement the experimental findings in the German standard DIN 4109 a simple calculation procedure with single number quantities (SNQ) has to be developed.

Keywords: *Sound reduction; windows; external shutters; night time noise level*

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1. Introduction

Protection against external noise in living and sleeping areas is one of the fundamental requirements for building construction. DIN 4109-1 [1] determines the required resulting sound reduction index (SRI) of the external building element based on the relevant external noise level and the type of room use. For rooms used predominantly for sleeping, DIN 4109-2 [2] provides for a separate provision: where the difference in assessment levels between the daytime and night-time periods is less than 10 dB(A), a 10 dB(A) allowance has been applied since 2016 to protect night-time sleep.

This regulation frequently applies to roads with night-time delivery traffic or along railway lines with a high proportion of freight traffic. For bedrooms, the requirements then exceed the values applicable during the day, meaning that correspondingly higher sound insulation values for the external building elements are required. As windows are generally the weakest external building elements, appropriate improvements – and the associated higher costs – would need to be provided for here.

If the additional sound reduction required during the night can be achieved by temporarily using an existing component (roller shutters), there is no need for the acoustically enhanced (and expensive) windows. The majority of buildings are constructed with external roller shutters, which are usually closed at night. Together with the glazing, these form a double-shell system whose acoustic potential has not yet been taken into account in the standards.

To this end, a research project (TempSchall) was launched, with the aim, on the one hand, of identifying potential areas for improvement and, on the other, of generating calculation values for the design of night-time noise protection using roller shutters. The research project is being carried out at three locations: the ift Rosenheim is conducting sound measurements, Rosenheim University of Applied Sciences is performing simulation calculations, and at Stuttgart University of Applied Sciences, a simplified calculation method is to be developed to determine the improvement achieved by roller shutters. This calculation method is then to be incorporated into the standardisation process. Selected results from the measurements carried out on the sound reduction of roller shutters and on the improvement in window sound reduction achieved by roller shutters are presented below. Furthermore, simplified calculation formulas derived from these results for the sound reduction of windows fitted with roller shutters are shown.

2. Measurement Results

All the measurements were carried out in the window test stand of ift Rosenheim. To install the roller shutters in different distances to the glazing the niche of the window test stand was widened. Therefor probably the niche effect (decreasing SRI when the test element is placed in the middle of the niche) becomes more dominant. The installation of the windows and roller shutters the measurement procedure and the various sealing conditions are described in detail in [3].

2.1 Sound reduction of roller shutters

In Fig. 1 the measured SRI of 8 different roller shutters is shown. The range of surface mass of the shutters vary from 3 kg/m² to 12 kg/m². The sound reduction for a very light and a heavy plate expected according to Eq. (1) are also shown in the figure.

$$R = 20\log(fm') - 47.6\,dB \qquad (1)$$

The shutters follow the mass law in a wide frequency range. At high frequencies the increase in sound reduction is reduced probably due to leakage between the roller shutter and the guide rail. It seems that no coincidence dip occurs because the roller shutters have a reduced stiffness (at least in one direction). The increase in sound insulation at very low frequencies (50 – 63 Hz) is due to the test opening for windows.

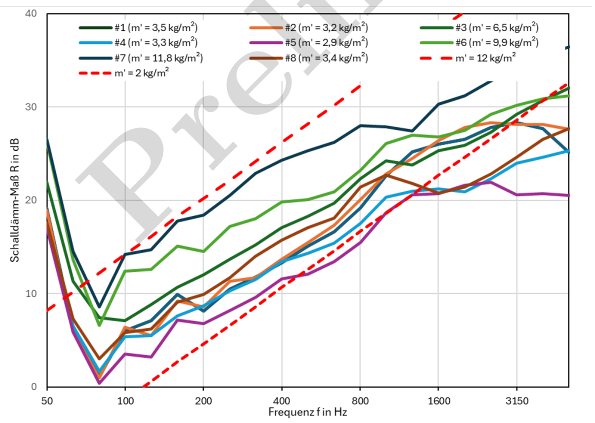

Figure 1. SRI R for different roller shutters compared to the mass law according to Eq. (1)

2.2 Sound reduction of windows

Three different triple-glazed windows were used for the tests. A standard window with no specific sound reduction requirements (A: 4/12/4/12/4), a window with improved sound reduction (B: 8LSG/12/4/12/6) and a window with high-quality sound reduction (C: 12LSG/12/4/12/8LSG). Figure 2 below shows the SRI of the three windows as a function of frequency.

The SRI of the windows under investigation increases with frequency; however, due to the triple glazing, low sound reduction ($R < 20$ dB) is observed at low frequencies. As the glass thickness (and thus the mass per unit area) of the outer panels increases, the SRI begins to rise at even lower frequencies, in line with the associated lower resonance frequency. In the high-frequency range, the drop in the SRI at the coincidence frequency is clearly visible for Window A at 3150 Hz. This is due to the three panels installed in this glazing, each with a thickness of $d = 4$ mm. For the other two windows – Window B: 8 mm laminated safety glass and 6 mm float glass, and Window C: 12 mm laminated safety glass and 8 mm laminated safety glass – the greater glass thickness results in an earlier inflection point in the sound reduction curve. Due to the different glass thicknesses and the use of laminated safety glass (further dampened by a film), the drop in performance is significantly less pronounced.

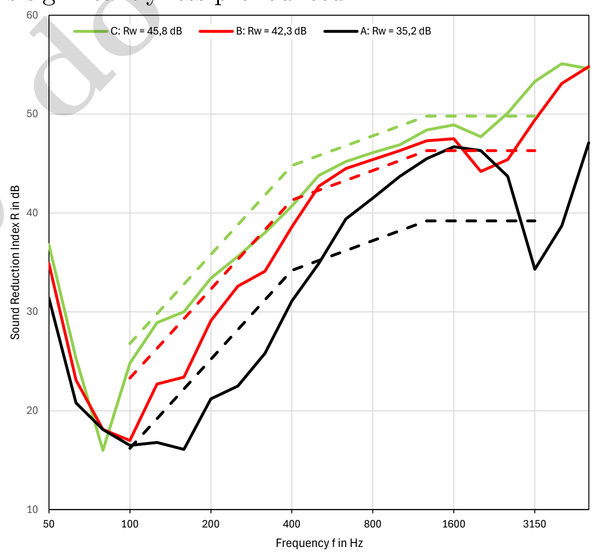

Figure 2. SRI R for 3 different windows with their reference curve. A: R_w = 35.2dB, B: R_w = 42.3 dB, C: R_w = 45.8 dB

The frequency range in which the measurement curve falls below the shifted reference curves is between 100 Hz and 500 Hz for windows A and B, and for window C it covers almost the entire frequency range relevant to the rating. Whilst the low frequencies are the most important for improving sound reduction in windows A and B, the entire frequency range should be improved for window C.

2.3 Sound reduction of windows with closed shutters

The three windows were tested with 10 different roller shutters, whilst the distance between the roller shutter and the glazing was also varied. Given the large number of results, the key physical principles and phenomena are explained here on the basis of a few selected measurements. Figure 3 shows the SRI for window A (R_w = 35 dB) with shutter 1 (m' = 3.5 kg/m²) for different distances (93 mm – 343 mm) between the glazing and the roller shutter.

Starting at low frequencies, the following acoustic phenomena can be observed: The two panels – the glazing and the roller shutter – are coupled via the air layer in between and form a mass–spring–mass system whose resonance frequency f_r can essentially be determined by the smaller mass m'_A (roller shutter 3.5 kg/m² << glazing 30 kg/m²) and the distance between the panels d in metres, using the following equation:

$$f_r = 160 \sqrt{\frac{0.14}{d m'_A}} \; in \; Hz \qquad (2)$$

As the distance between the glazing and the roller shutter decreases, the resonance frequency increases. Compared with measurements taken on the window without a roller shutter, sound reduction deteriorates at frequencies below 80 Hz for distances of up to approximately 200 mm.

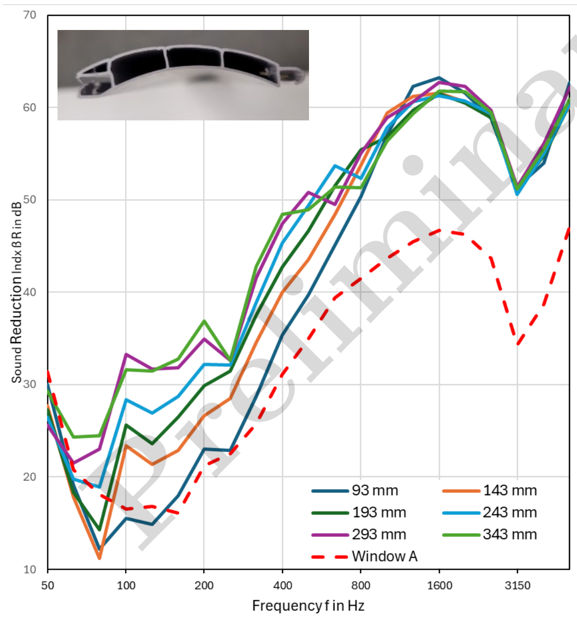

Figure 3. SRI R for roller shutter 1 combined with window A compared to SRI of Window without shutter for 6 spacings. A picture of a single piece of the roller shutter 1 is also shown.

At 125 Hz, a first dip in the SRI can be observed in all measurements, followed by a second dip at 250 Hz. These two dips are caused by standing waves in the undamped cavity measuring 1.50 m × 1.25 m. At 125 Hz, exactly half a wavelength fits into the cavity, and at 250 Hz, one full wavelength. The dips are significantly more pronounced at greater distances, as the sound waves can propagate more freely within the cavity.

Furthermore, smaller dips can be seen from 500 Hz onwards. These dips are standing waves in the cavity between roller shutter and glazing and a dependence on the distance between the glazing and the roller shutter is evident. As the distance decreases, the frequency of the dip increases in inverse proportion. Here, exactly half a wavelength fits into the cavity for every distance. At 3150 Hz, the dip due to the the coincidence frequency of the 4 mm glazing can be observed.

The difference between the SRI of the window with and without roller shutters is shows in Figure 4. Here, too, the reduced sound reduction at low frequencies can be seen in the resonance frequency range. Following a very steep rise in the improvement achieved by the 'add-on structure' immediately after the resonance frequency, small dips can also be seen here in all data series at 125 Hz and 250 Hz. In contrast, the dips in the 400–800 Hz frequency range occur in stages due to the varying distances, which are proportional to half the wavelength.

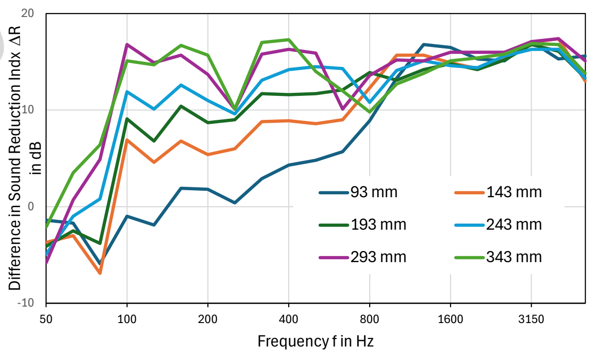

Figure 4. Difference in SRI R for roller shutter 1 combined with window A and SRI of Window A without shutter for 6 spacings.

2.4 Measurement of Reverberation Time in the Airgap between Windows and closed Shutter

If the cavities between the two shells become large relative to the airborne sound wavelength (for f ≥ c / (2d)), a diffuse sound field may develop there. The sound-transmitting double-shell system consequently changes from a system coupled by the stiffness of the air spring to two independent systems. For this "three room system", the sound reduction between the source room and receiver room via an intermediate space – the 'cavity' – is calculated, in simplified terms, by adding together the sound reduction indices of the two shells.

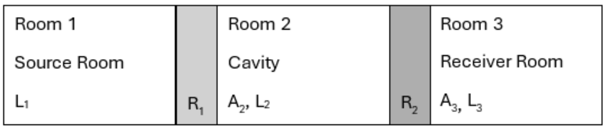

Figure 5. Sketch of the sound transmission when the spacing between the two shells becomes large in respect to the wavelength.

The overall SRI of the three-room-system marked R_{1-3} system shown in Fig. 5 is then composed of the sound reduction indices R_1 and R_2 of the two individual shells, as follows:

$$R_{1-3} = L_1 - L_3 + 10\lg\frac{S}{A_3} \qquad (3)$$

$$R_1 = L_1 - L_2 + 10\lg\frac{S}{A_2} \qquad (3a)$$

$$R_2 = L_2 - L_3 + 10\lg\frac{S}{A_3} \qquad (3b)$$

If Eq. (3a) is solved for L_1 and Eq. (3b) is solved for L_3 and both are substituted into Eq. (3), the following Eq. (4) is obtained.

$$R_{1-3} = R_1 + R_2 - 10\lg\frac{S}{A_2} \qquad (4)$$

Brekke [4] also reaches this conclusion. He states that above the cut off frequency, where half the wavelength matches the depth of the cavity then Eq. 4 can be applied. To calculate the total sound reduction R_{1-3}, the sound reduction indices of the individual shells and the equivalent sound absorption area in the cavity A_2 are required. As part of the research project, the reverberation time in the cavity was therefore determined. A photograph of the test setup is shown in Fig. 6.

Figure 6. Small dodecahedron in the airgap between roller shutter and window to measure the reverberation time.

Due to its dimensions, a homemade dodecahedron with a diameter of approximately 0.2 m was used as the sound source. The measured reverberation time T for the cavity in the range 500 Hz – 5 kHz is shown in Fig. 7. The average value for the frequency range 1 kHz – 5 kHz is T = 0.31 s.

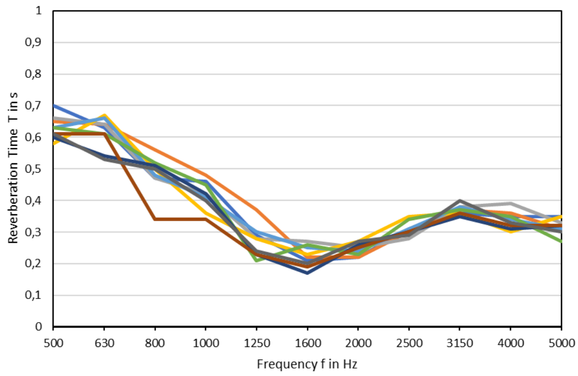

Figure 7. measured reverberation times in the air gap between window and shutter.

Using this reverberation time, the Schroeder frequency for the cavity with a volume of V = 0.55 m³ is $f_S = 2000 \times \sqrt{(0.31/0.55)} \approx 1500$ Hz. Due to the geometry of the cavity (a flat space), an ideal diffuse sound field is not to be expected. Nevertheless, the Schroeder frequency indicates that the sound reduction behaves in accordance with the conditions mentioned above, and that a three-room system can be assumed in this frequency range, allowing the SRI of the overall structure to be estimated using Eq. (4). Fig. 8 compares the measured SRI of the overall structure according to Eq. (3) with the calculated sound reduction derived from Eq. (4), as well as with a simple sum of the sound reduction indices of the window R_1 and roller shutter R_2. Whilst the simple sum of the sound reduction indices of the window and roller shutter clearly overestimates the expected overall sound reduction, the calculation according to Eq. (4) – taking into account the reverberation time measured in the cavity – falls within the range of the measured SRI.

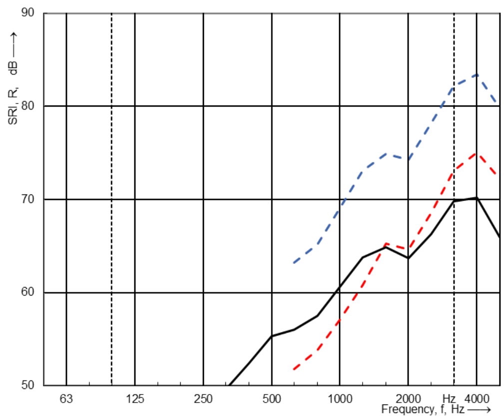

Figure 8. Comparison of the measured SRI for the window C with shutter 1 (black) with the calculated SRI (dotted lines) according to Eq. (4) (red) and by adding the SRI of the window R_1 and the SRI of the shutter R_1 (blue).

It is clear that, due to the geometry of the cavity (a flat space), an ideal diffuse sound field with uniformly distributed absorption does not exists in the cavity, meaning that greater deviations are to be expected here. Nevertheless, the results show a clear trend and explain the deviation – a slight improvement in the attachment structure at higher frequencies – compared with the theory of improvement achieved through the attached roller shutter.

3. Single Number values of Sound reduction improvement

In Germany, the requirements for external building components have so far been formulated using the parameter weighted apparent SRI R`$_w$. With the planned revision of DIN 4109, the spectrum adaptation term C and C_{tr} will be taken into account, depending on the actual external traffic noise spectrum. The adjustment value C will then be used for rail traffic at medium and high speeds, whilst the value C_{tr} will be used for low-frequency-dominated spectra, e.g. from urban road traffic and low-speed rail traffic. The improvement provided by a closed roller shutter should be easy to apply when verifying night-time noise protection. To this end, the improvement must be consistently quantified using the SNQ ΔR_w, $\Delta(R_w + C)$ and $\Delta(R_w + C_{tr})$.

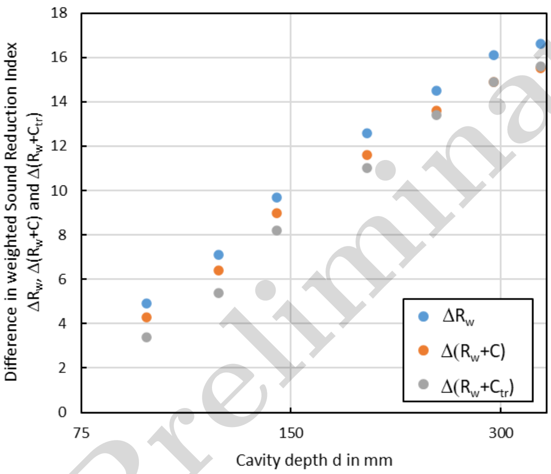

Figure 9. Difference in weighted SRI ΔR_w, ΔR_w+C , ΔR_w+C_{tr} for roller shutter 1 combined with window A and SRI of Window A without shutter for 6 spacings.

Figure 9 shows the SNQ of the difference within the three single-number values ΔR_w, $\Delta(R_w+C)$ and $\Delta(R_w+C_{tr})$ for Window A with and without roller shutter 1, as a function of the distance between the glazing and the roller shutter. Over a wide range, a linear improvement (due to the logarithmic scale) with distance can be observed.

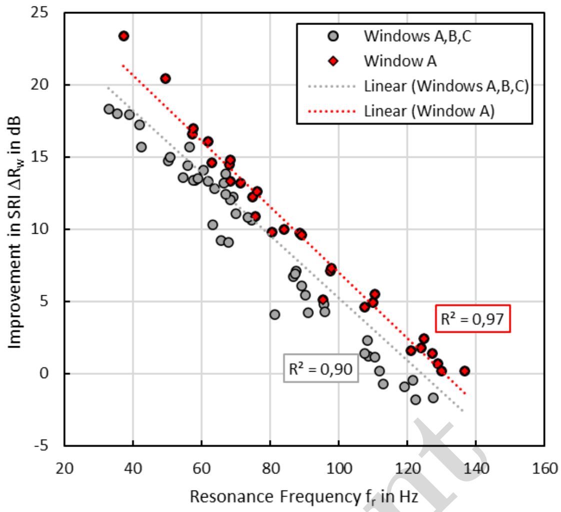

Figure 10. Improvement in weighted SRI ΔR_w for 8 different roller shutters combined with window A (red) and with Windows A, B, C (grey) for different spacings depending on the resonance frequency calculated from spacing d and surface mass m'$_A$ of the roller shutter.

In the course of the investigations, it was demonstrated that, in addition to the distance d, the mass per unit area of the roller shutter and thus the resonance frequency f_r of the mass-spring system, calculated according to Eq. (2), significantly determine the improvement in the figure values. Figure 10 illustrates that the weighted SRI of the window also influences the airborne sound improvement.The coefficient of determination for the calculation of all windows is significantly lower than that for window A. This demonstrates that the improvement in weighted SRI ΔR_w depends not only on the resonance frequency f_r, but also on the weighted SRI of the window R_w.
Since the resonance frequency of the glazing–air gap–roller shutter system is, in turn, essentially determined by the distance d between the glazing and the roller shutter, as well as by the mass per unit area m'$_A$ of the closure (roller shutter), the regression can be carried out using these input parameters. Using multivariate regression, the coefficients for the parameters distance d, mass per unit area m'$_A$ and the weighted SRI R_w of the window can be determined for the following approach.

$$\Delta R_w = \alpha \log\left(\frac{d}{1\,\text{m}}\right) + \beta \log\left(\frac{m'_A}{\text{kg/m}^2}\right) + \kappa (R_w)_F + \gamma \quad \text{in dB} \qquad (5)$$

Eq. (5) can be written in a more general form, as shown in Eq. (6), taking into account the spectrum adjustment values that are expected to be required in DIN 4109 in future.

$$\Delta(R_w + C_x) = \alpha \log\left(\frac{d}{1\,\text{m}}\right) + \beta \log\left(\frac{m'_A}{\text{kg/m}^2}\right) + \kappa (R_w + C_x)_F + \gamma \text{ in dB} \quad (6)$$

Here, C_x represents both the spectrum-adaptation terms C, C_{tr} and extended with $C_{tr,50\text{-}3150}$. The coefficients used to calculate ΔR_w, ΔR_w + C, $\Delta(R_w$ +

C_{tr}) and $\Delta(R_w + C_{tr,50-3150})$, which were determined on the basis of a **preliminary dataset** of n = 76 measured values, are shown in Table 1. The influence of the different design of the guide rails (brush seals or "Keder"-gasket) will be treated later.

Table 1. Coefficients for calculating the airborne sound reduction improvement according to Eq. (5) and Eq. (6) achieved by roller shutters, as a function of the mass per unit area m'_A, the distance d and the weighted SRI R_w, as well as the calculated coefficient of determination.

SNQ	α	β	κ	γ	R^2
ΔR_w	+22,52	+14,73	−0,27	+29,36	0,96
$\Delta(R_w + C)$	+22,53	+15,05	−0,23	+26,38	0,96
$\Delta(R_w + C_{tr})$	+25,20	+16,11	−0,25	+27,03	0,97
$\Delta(R_w + C_{tr,50-3150})$	+20,74	+15,37	−0,56	+28,56	0,93

Table 1 shows that the coefficients α, β and κ are very similar for the different SNQ. In order to establish the simplest possible calculation for standardisation, an average value was calculated for the coefficients α, β and κ, This value was rounded to two significant digits. The calculation of the airborne sound improvement using these simplified coefficients showed an almost equivalent degree of agreement.

Table 2. Simplified coefficients for calculating weighted airborne sound reduction improvement in accordance with Eq. (5) and Eq. (6).

SNQ	α	β	κ	γ	R^2
ΔR_w	+23	+15	−0,25	+28,6	0,96
$\Delta(R_w + C)$	+23	+15	−0,25	+27,8	0,96
$\Delta(R_w + C_{tr})$	+23	+15	−0,25	+26,1	0,96
$\Delta(R_w + C_{tr,50-3150})$	+21	+15	−0,55	+28,5	0,93

The improvement in airborne sound reduction provided by roller shutters on windows can therefore be estimated from the preliminary data set as follows:

$$\Delta R_w = 23\log\left(\frac{d}{1\,m}\right) + 15\log\left(\frac{m'_A}{kg/m^2}\right) - 0{,}25(R_w)_F + 28{,}6\ dB \qquad (7)$$

$$\Delta(R_w + C) = \Delta R_w - 0{,}8\ dB \qquad (8)$$

$$\Delta(R_w + C_{tr}) = \Delta R_w - 2{,}5\ dB \qquad (9)$$

These results have to be corrected by adding a correction value due to the sound transmission of the different design of the guide rails.

4. Conclusions

Tests were carried out using various roller shutters fitted at different distances in front of three different windows. The roller shutters can improve night-time sound reduction. The improvement depends mainly on the mass per unit area of the roller shutter and the distance between the glazing and the roller shutter. With standard roller shutters, significant improvements can be achieved even at distances of d ≥ 100 mm. Heavy roller shutters (m' = 10 kg/m²) achieve improvements even at distances of d ≥ 50 mm. Using the parameters distance, mass per unit area of the roller shutter and the weighted SRI of the window (including the spectrum adaptation terms), the improvement in overall sound reduction (again taking the spectrum adaptation terms into account) achieved by the roller shutter can be determined with a high degree of accuracy.

5. Outlook

Further investigations are required to clarify how the influence of different guide rail designs ("Keder"-gasket or brush seals) and any leaks should be recorded and taken into account in accordance with standards.
Furthermore, the investigations will also measure the improvement in airborne sound reduction achieved by sliding or folding shutters. There are also plans to compare further data – which has not yet been included in the analysis – with the calculation model in order to obtain an independent assessment of the accuracy of the predictions.

6. Acknowledgments

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