Accuracy of prediction methods for rain noise levels

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ABSTRACT

Determining levels of rain noise can be an important design aspect for various types of buildings, particularly education facilities. Measurements of rain noise levels can be carried out using relevant ISO standards (ISO 140-18:2006, ISO 10140-1:2010/Amd 2:2014, ISO 10140-5:2010 Amd 1:2014) which specify artificial rain types with, for example, constant drop size. While this can provide an indication of the levels of rain noise that might occur in practice, it is not necessarily trivial to estimate real or natural levels of rain noise from the artificial rain noise measurements. The relationship between natural and artificial rain noise levels can be better understood using prediction models. Predicting rain noise levels can also prove helpful in evaluating a range of alternative roof construction types, as rain noise measurement data is often only available for a limited number of construction types. This paper provides a brief overview of a prediction method for rain noise. Emphasis is given to relevant tolerances on prediction accuracy, with reference made to variation in laboratory rain noise level measurements (that is, measurement reproducibility). Prediction results are presented for a number of different constructions to demonstrate the extent of agreement between the prediction method and laboratory results.

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1. INTRODUCTION

Predicting rain noise levels can prove to be very helpful when evaluating a range of alternative roof construction types, as rain noise measurement data is often unavailable or else only available for a limited number of construction types. However the usefulness of prediction methods will depend on their accuracy and whether or not the results can be trusted as the basis for a particular acoustic design. This then raises the question of how to evaluate the accuracy of rain noise predictions.

This paper provides a brief overview of a prediction method for rain noise before considering the tolerances on prediction accuracy, with reference made to guidance in relevant standards along with review of a published case study of laboratory rain noise level measurements. Prediction results are then presented for several constructions to directly demonstrate the extent of agreement between the prediction method and laboratory results.

2. PREDICTION MODEL

2.1 Point force excitation

The basis for rain noise prediction models is point force excitation of bending waves in a thin plate. Where forces on a roof are generated by falling rain, it suffices to initially consider the impact of one rain drop and to correct the resulting model for the number of drops per unit time based on the type of rain that is incident on the roof.

2.2 Sound radiation from a vibrating plate

Once a plate is excited by an impacting force, the level of radiated sound can be derived from the vibration velocity across the plate (1, 2). The plate's vibration velocity is often taken as the average velocity of the resonant vibration field, without consideration of near field vibration. In this case, the vibration velocity can be described (3) as:

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$$\langle v^2 \rangle = \langle F^2 Y \rangle \big/ \omega\eta\rho_s S \tag{1}$$

Where Y is the driving point admittance of the plate (the reciprocal of the driving point impedance) η is the loss factor, ρ_s (kg/m^2) is the surface density and S (m^2) is the surface area of the plate. Once the vibration velocity is determined, the radiated sound level can be calculated by accounting for panel area and radiation efficiency:

$$\text{Radiated sound power } =< \text{v}^2 > \rho_0 c_0 S\sigma \tag{2}$$

Where ρ_0 is the density of air, c_0 is the speed of sound in air and σ is the radiation efficiency.

2.3 Ceilings

Work by Sharp (4) may be used to describe the effects of a ceiling beneath a vibrating (roof) plate. The airborne and structure borne paths through the ceiling can be considered separately.

For the airborne path, Sharp's transmission loss equations can be rearranged to isolate the effect of the air cavity and ceiling panel. These effects can then be used to calculate the reduction in sound radiated from the roof due to a ceiling without structural connections:

Radiated sound power (Airborne)	= Radiation sound power (roof) - ΔTL_M	$f < f_0$	(3)
	= Radiation sound power (roof) – ΔTL_{m2} – 20log(fd) + 29	$f_0 < f < f_1$	
	= Radiation sound power (roof) – ΔTL_{m2} - 6	$f > f_1$	

It is assumed that the ceiling cavity includes some sound absorptive material, to dampen any cavity standing waves. TL_{m1} and TL_{m2} are the mass law transmission losses of the roof and ceiling respectively, M = m1 + m2 and d (m) is the separation between the two panels. f_1 is equal to 55/d and f_0 is the mass-air-mass resonance of the panel-cavity-panel system and is given by $113/(m_e d)^{1/2}$ where m_e (4) is as follows:

$$m_e = 2m_1 m_2 \big/ (m_1 + m_2) \tag{4}$$

At low frequencies the ceiling system is assumed to behave as a lumped mass. Accordingly, ΔTL_M is the difference between the mass law transmission loss of the roof only, TL_{m1}, and the combined mass law transmission loss TL_M of the roof and the ceiling when treated as an equivalent single plate.

Where there are structural connections to the ceiling these will reduce the improvements in sound reduction from the airborne path. Assuming that the ceiling lining is sufficiently damped for the effect of the structural connection to be controlled by non-resonant radiation, an expression for the radiated sound power due to line connections (3) is:

$$W_{Ceilingtsnucture} = 2\rho_0 c_0 n l \lambda \langle v_{connection}{}^2 \rangle \big/ \pi \tag{5}$$

Where n is the number of line connections, of length l (m) and $\lambda_c = c_0/f_c$ is the wavelength at the critical frequency of the ceiling lining. $\langle v_{connection}{}^2 \rangle$ is the non-resonant vibration velocity of the ceiling panel at the line connection. Sharp (4) provides an expression for this vibration velocity as a function of the vibration velocity of the roof (at the line connection) and the relative impedance of the purlins as seen by the roof and ceiling:

$$v_{connection} = Z_1 + Z_2 \big/ Z_1 \tag{6}$$

2.4 Additional considerations

A number of adjustments can be made to the prediction model to account for specific aspects of particular constructions. These include:

- Adjustment of the driving point impedance of light weight roofs in the low frequency region to account for the impedance of the purlins (5)
- Adjustment of the driving point impedance of light weight roofs to account for potentially significant modal response of a roof corresponding to the first few fundamental modes of the roof plate, including the section of the roof between purlins

3. RAIN TYPES

With a model established for predicting noise from a single point force (or drop of rain), attention can be given to the types of rain drops and, thereafter, rainfall that may occur. In particular, two types of rainfall are likely to be of interest in acoustic prediction models: natural and artificial.

3.1 Rain drops

The force of a rain drop on a plate can be found from the rate of change of momentum of the drop as it is decelerated during impact and as its downward velocity is directed radially outwards. The rate of change of momentum will depend on the shape of the drop at impact (6).

While a drop can be assumed spherical in shape at the start of its descent it could be expected that the shape distorts as the drop falls, with the base of the drop becoming flatter. For calculation purposes, idealized drop shapes can be assumed. Different shapes, such as cylindrical, cylindrical-hemispherical and parabaloidal can be considered. (6, 7). For the predictions presented later in this paper, parabaloidal drop shapes are assumed.

3.2 Natural rainfall

Natural rainfall comprises a range of different drop sizes. Each drop will have a particular mass and an associated impact velocity, which can be taken as the drop's terminal velocity. The distribution of drop sizes in natural rain can be estimated by an idealized exponential distribution, such as the Marshall-Palmer distribution, which assumes a degree of temporal and spatial averaging of the natural rainfall (8).

$$N_D = N_0 e^{-\Lambda D} \tag{7}$$

where D is the drop diameter, $N_D \delta D$ is the number of drops in unit volume of space with a drop size in the range D to (D+ δD) and N_0 is the value of N_D for D = 0 (9). Marshall and Palmer (8) give the values of parameters as $N_0 = 8000\ m^3mm^{-1}$ and $\Lambda = 4.1R^{(-0.21)}\ mm^{-1}$, where R is the rainfall in mm/hr.

3.3 Artificial rainfall

Laboratory measurements of rain noise, when carried out according to the following documents, require the use of artificial rain.

Table 1: Standards with advice about laboratory rain noise measurements

Document	Status	Reference
ISO 140-18:2006	Withdrawn	(10)
ISO 10140-1:2010/Am2:2014	Current	(11)
ISO 10140-5:2010/Am1:2014	Current	(12)

Section 1 *Scope* of ISO 140-18:2006 offers the following justification for the use of artificial rain:

> *This part of ISO 140 is based on measurements with artificial raindrops under controlled conditions using a water tank in a laboratory test facility in which flanking sound transmission is suppressed. Measurements using real rain, although a useful means for validation purposes, are not included because of the variable, unpredictable and intermittent nature of real rain.*

The features of artificial rain are a known rainfall rate, with drops which are approximately constant in size and which fall from a known height above a test plate. ISO 10140-5:2010/Am1:2014 requires that measurements be carried out using rain classified as Heavy and, optionally, Intense. Properties of these rainfall types are detailed in Table 2.

Table 2: ISO 10140-5:2010/Am1:2014 rainfall specifications

Type	Rainfall rate (mm/hr)	Typical drop diameter (mm)	Fall velocity (m/s)
Heavy	40	5	7
Intense	15	2	4

Artificial rain is typically generated from a header tank positioned above a test plate, whose base has been perforated with holes sufficient to produce drops of the required size. Discussions for the remainder of the paper will be focused on artificial rain.

4. PREDICTION TOLERANCES

A reasonable objective for a rain noise prediction method is to replicate laboratory rain noise measurements of roof systems. This provides a bound on prediction accuracy, in the best case, of being equivalent to the accuracy of laboratory measurements. In this sense, indicators of laboratory measurement accuracy such as reproducibility become targets for the accuracy of a prediction method. Guidance on laboratory measurements of rain noise can be found in the documents detailed in Table 1 above.

4.1 Laboratory rain noise measurement tolerances

Perhaps unsurprisingly, given the comparatively young age of the standards, advice about measurement uncertainty offered by the documents in Table 1 is concise. ISO 140-18:2006 dedicates a section to the topic of uncertainty and notes[2]:

> *…at the time when this part of ISO 140 was being prepared, insufficient information was available on how to draw up a statement in accordance with the GUM.*
> […]
> *Interlaboratory testing should be performed as soon as possible to determine interlaboratory reproducibility, especially for reporting the result of rainfall noise generation from a normalized specimen.*

ISO 140-18:2006 was withdrawn in 2014 with the publication of amendments to the ISO 10140 suite of acoustic standards which address rain noise. Of these amendments, ISO 10140-1:2010/Am2:2014 does not offer any direct discussions of uncertainty of rain noise measurements. ISO 10140-5:2010/Am1:2014 does include some consideration of such tolerances, with Annex I.1 stating the following:

> *Standard reference test specimens are described in this annex for quality control and to check the reproducibility of laboratory rain sound measurements in different laboratories.*

Annex I.2 then details a *small test specimen* comprising 6 mm thick single pain glass. Annex I.3 is intended for a *large text specimen* but simply notes that:

> *No reference test specimen is defined.*

On the basis of the comments about rain noise measurement uncertainty included in the above documents, particularly those released recently in 2014, it would seem that there is little in the way of interlaboratory test data available at present. In turn, guidance on suitable levels of laboratory test repeatability and reproducibility is very limited.

[2] GUM in the quoted text refers to the ISO Guide to the Expression of Uncertainties in Measurement

4.2 Proxies for laboratory rain noise measurement tolerance

Until such time as there is a robust set of interlaboratory rain noise measurement test data available, indicators of measurement accuracy will need to be estimated in other ways. For example, guidance about the uncertainty of laboratory airborne and impact sound insulation measurements could be used to help inform the accuracy for rain noise measurements. Impact sound insulation measurements could be particularly relevant in this context given that both tapping hammer and rain noise tests involve exciting a test sample with a series of point forces.

Table A.2 of ISO 140-2:1991 (13) provides a set of frequency dependent reproducibility values for impact sound insulation measurements using a standardized tapping machine. The values range from 2.5 dB at frequencies between 500 Hz to 3150 Hz up to 5 dB at 100 Hz. This could suggest that rain noise measurements may also have a reproducibility value in the order of 2.5 dB to 5 dB.

It should be noted however that the values quoted in Table A.2 of ISO 140-2:1991may not be valid tolerances for reproducibility in the strict sense, as Warnock and Birta (14) note:

> *…the reproducibility values are based on tests made by different measurement teams on the same 140 mm slab in a single laboratory. While this may be the best information available, it is not a valid measure of reproducibility.*

On this basis, valid impact sound insulation reproducibility values may be larger than those listed in the standard and it could follow that rain noise measurement reproducibility is also larger. Moreover, it could be argued that while tapping machines and rain fall both lead to point force excitation, the generation of a point force with a tapping machine, and 0.5 kg tapping hammers, has a fundamentally different nature to that of rain fall. In turn it could be reasoned that there is in fact a limited amount to infer about the accuracy of rain noise measurements from a tapping machine test.

Anecdotally, work by Chéné, Guigou-Carter & Larsen (15) suggests that reproducibility tolerances for rain noise measurements may indeed be different to, and arguably larger than, those for impact sound insulation. Their study includes comparison of round robin rain noise measurements carried out across two acoustic laboratories. Both labs reportedly contributed to the working group which developed ISO 140-18:2006 and the reported measurements at each lab were carried out in accordance with that standard (which was the current at the time of the study).

From the initial measurements in 2006, the test arrangement which resulted in the largest measured difference in A-weighted rain noise levels was reported and its associated level difference spectrum is shown in Figure 1 as Result A. Similarly Result B in Figure 1 shows the results from the test arrangement for the smallest measured difference in noise levels. For reference, Figure 1 also includes the reproducibility values for impact sound insulation from Table A.2 of ISO 140-2:1991. The ISO 140-2:1991 values represent a statistical confidence interval for interlaboratory variability rather than a strict threshold of acceptability and, as noted above, their validity is unclear. Nonetheless, they are included in the figure to contextualize the round robin sound level differences.

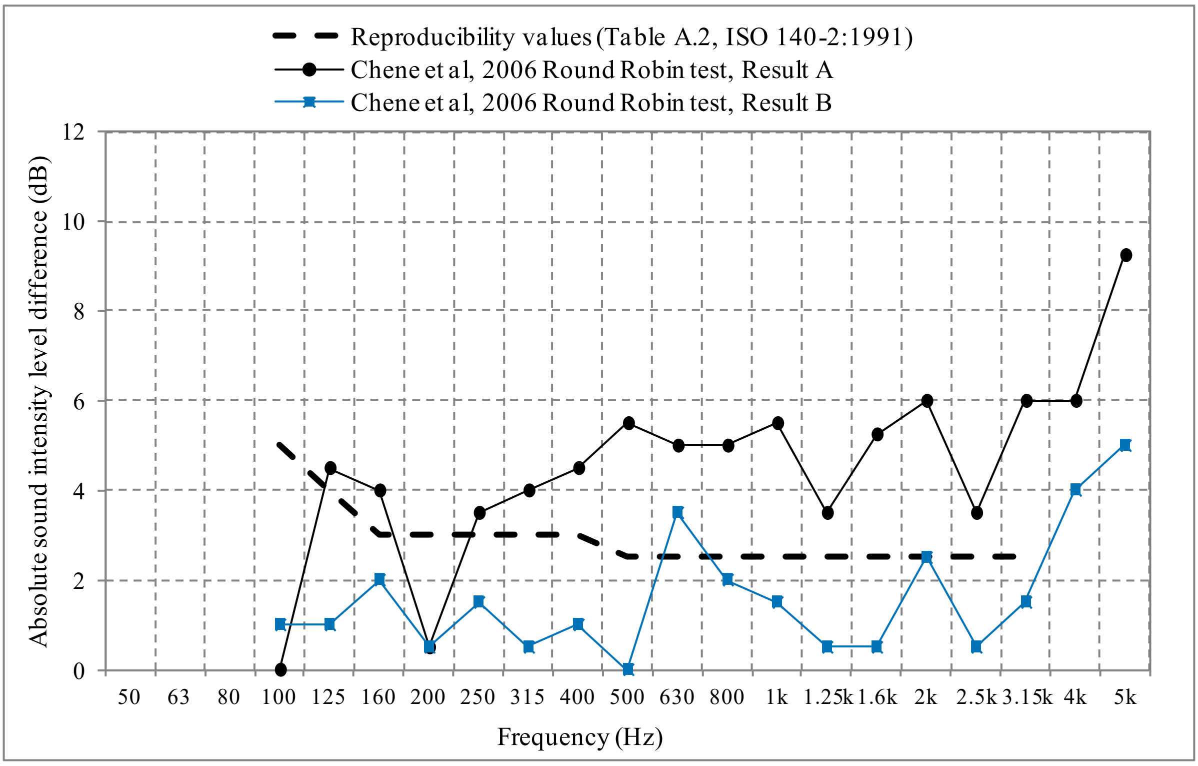

Figure 1 – Interlaboratory variation in measured rain noise levels (Initial)

Figure 2, below, shows a similar set of data relating to a follow up set of round robin measurements in 2007 after the labs had collaborated and adjusted particular aspects of the measurement system, in particular the method of generating artificial rain fall.

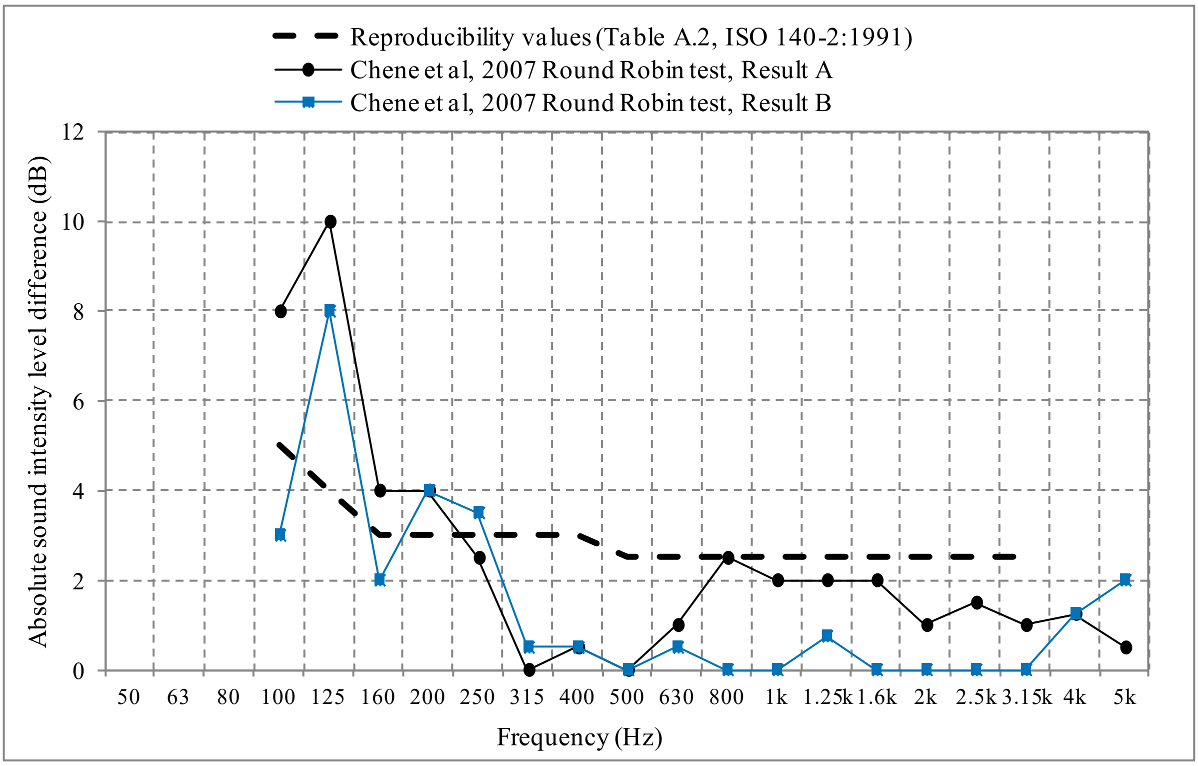

Figure 2 – Interlaboratory variation in measured rain noise levels (Follow up)

The sound level differences in the follow up measurements are generally less than those of the initial measurement set. However, given that both sets of measurements were reportedly carried out in accordance with the standard that was relevant at the time, the case study suggests that measurement tolerances for rain noise may be significantly larger than those that may apply to impact sound insulation measurements.

4.3 Discussion

It is apparent that there is a shortfall of interlaboratory rain noise measurement data available which prevents a reliable quantification of repeatability and reproducibility tolerances for rain noise measurements. Anecdotally, work by Chéné, Guigou-Carter & Larsen indicates the potential for such tolerances to be larger than those of other types of building acoustics measurements, particularly impact sound insulation measurements. In light of these observations it is difficult to establish a target for prediction accuracy based on laboratory performance tolerances.

5. COMPARISON OF PREDICTIONS AND MEASUREMENTS

Comparisons are provided between laboratory rain noise measurements and predictions based broadly on the model outlined above. Data relates to Heavy artificial rainfall.

5.1 6mm glazing

Figure 3 presents three sets of rain noise data for 6 mm glass (2, 10, 15), including reference sound intensity levels for a small test sample according to ISO 140-18:2006 (the values are also presented in ISO 10140-5:2010/Am1:2014). The figure also shows the predicted level of rain noise for a pane of 6 mm glass characterized with a density of 2430 kg/m^3, a Youngs Modulus of 52.2 GPa and a damping coefficient of 0.02. The glass pane size is modeled as 1.5 m x 1.25 m.

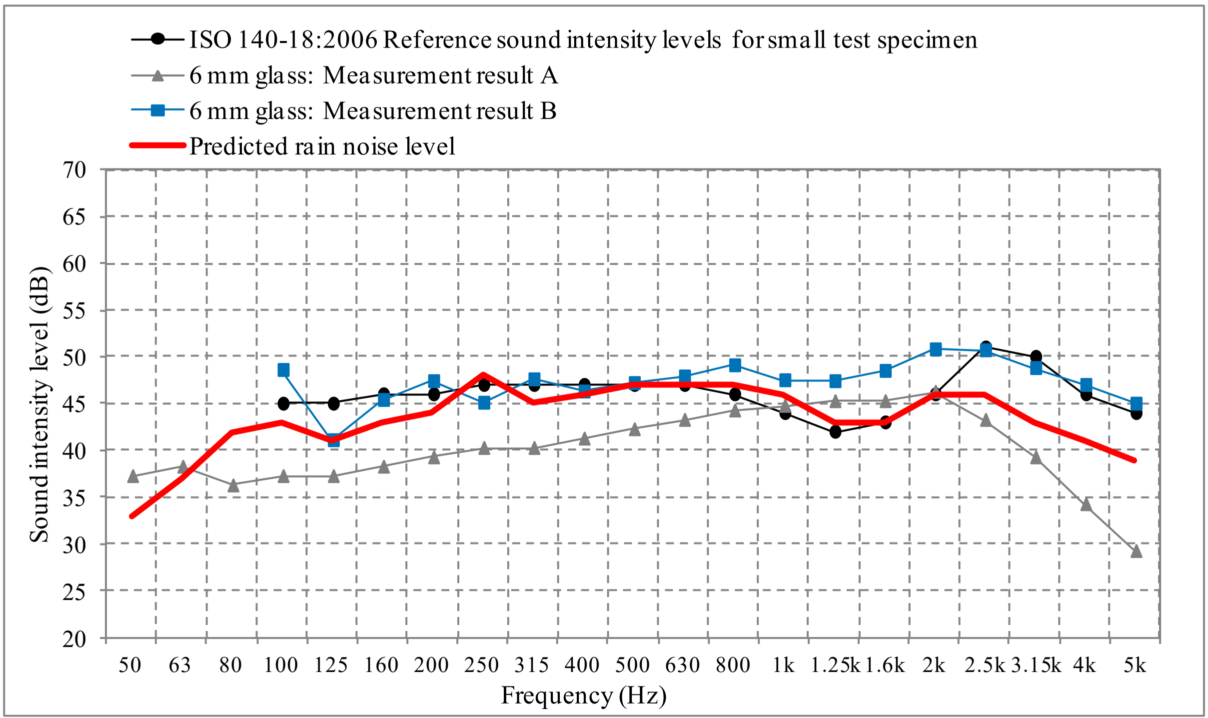

Figure 3 – Comparison of predictions with published rain noise performance data (6 mm glazing)

Figure 4 re-presents this data as differences in sound intensity level relative to the prediction. As a point of context, the reproducibility data from Table A.2 of ISO 140-2:1991 is also shown.

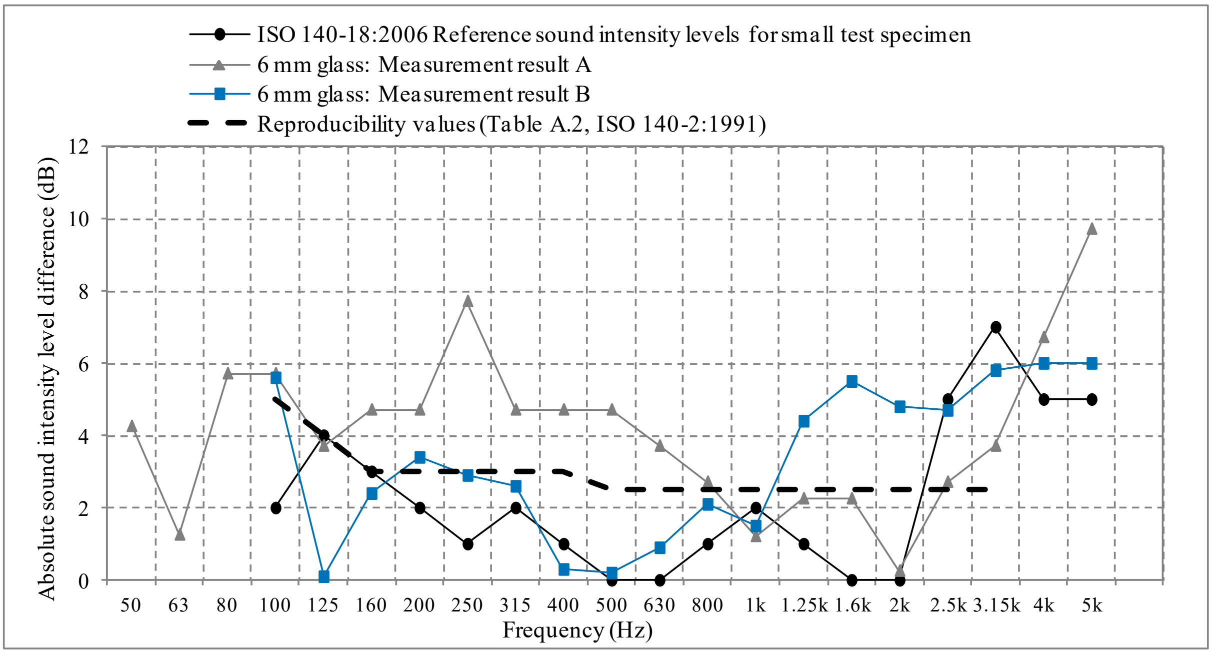

Figure 4 – Variability between predictions and published rain noise performance data (6 mm glazing)

It can be seen from these figures that the variation between each available set of rain noise data and the predicted levels is not insignificant. The variations are, however, of the same order of magnitude as the round robin sound level differences presented in Figure 1 and Figure 2 above.

5.2 Double glazing

Figure 5 presents a comparison of predictions with laboratory rain noise measurements for a double glazing system comprising 6 mm glazing, a 12 mm air gap and a second pane of 6 mm glazing (16). The predicted level of rain noise is also presented, based on glass with the same characterization as in Section 4.1 above, and a test sample size of approximately 1.5 m x 1.25 m. Prediction accuracy is reasonable in this example.

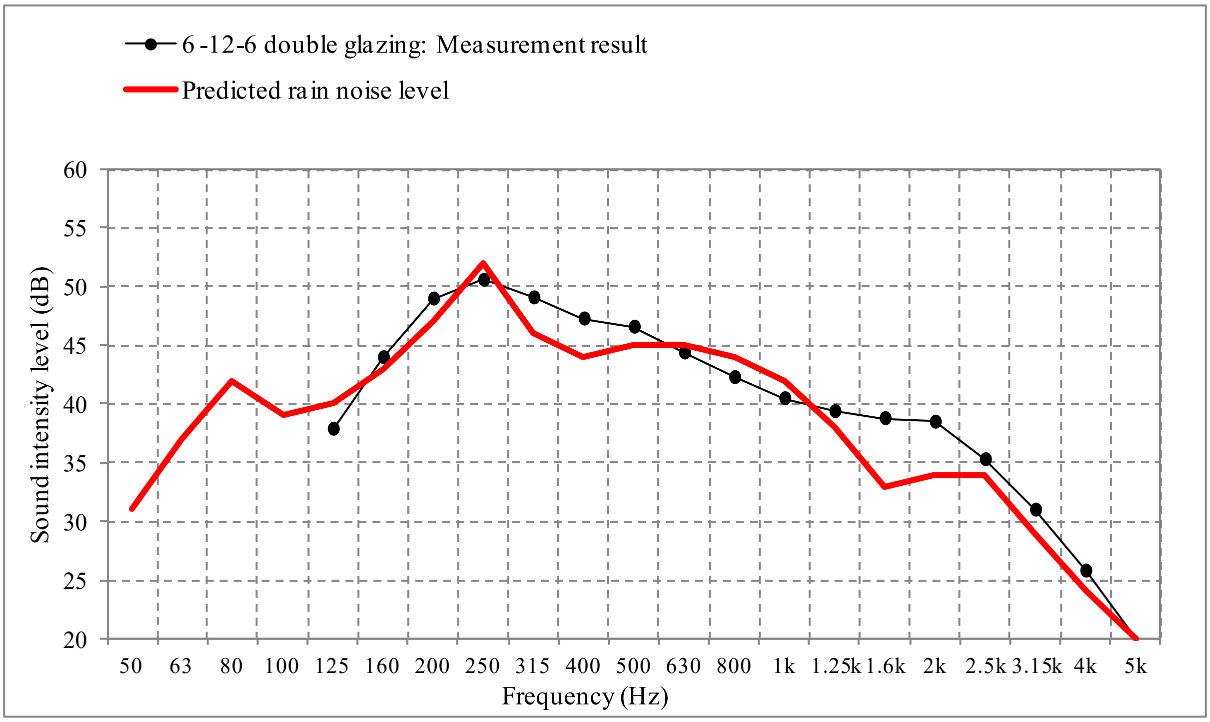

Figure 5 - Comparison of predicted and measured rain noise data (6-12-6 double glazing)

5.3 Profiled aluminum

Figure 6 presents a comparison of predictions with a laboratory rain noise measurement for trough-style 0.9mm thick profiled aluminum roof sheeting (17). The predicted level of rain noise is based on 0.9 mm aluminum characterized with a density of 2900 kg/m^3, a Youngs Modulus of 85.2 GPa and a damping coefficient of 0.001. The panel size is modeled as 2.4 m x 4 m.

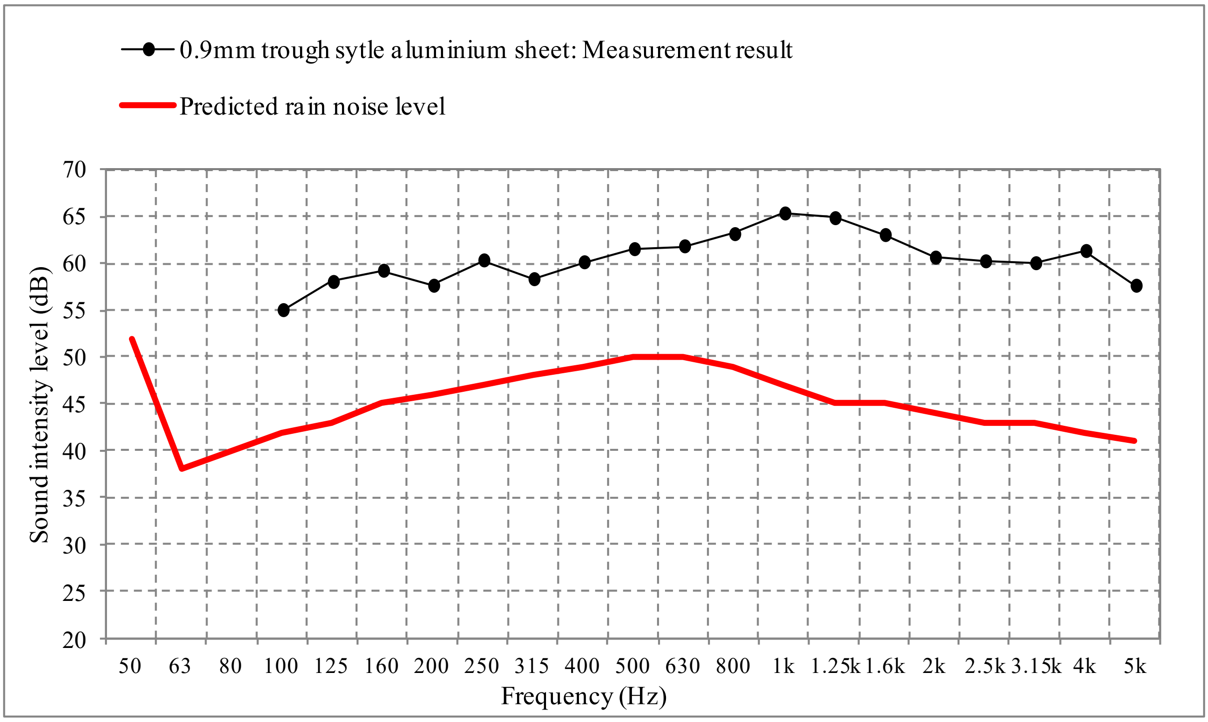

Figure 6 - Comparison of predicted and measured rain noise data (Trough style profile aluminum sheet)

Agreement between measured and predicted results is noticeably less in this example. It should be noted that a full test report for the measured data was not available and some of the observed difference may be due to invalid assumptions about the measurement set up and expression of results.

6. SUMMARY

There is an apparent lack of interlaboratory rain noise measurement data available. This lack of data hinders an evaluation of laboratory repeatability and reproducibility tolerances for rain noise. In turn, it is difficult to relate the accuracy of rain noise predictions to any expected levels of laboratory accuracy. In this context, the ability to evaluate the accuracy of rain noise predictions is currently limited as are the benefits of such prediction methods for evaluating a wide variety of construction types. In simple terms, it is difficult to know how accurate the results are. A handful of direct comparisons between predictions and available, published measured results in this paper indicate the potential for accurate predictions and, concurrently, for poor agreement depending on the construction being modeled.

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