inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Accuracy of prediction methods for impact sound pressure levels

Daniel GRIFFIN[1]

[1] Marshall Day Acoustics Pty Ltd, Australia

ABSTRACT

There are various methods available for predicting impact sound pressure levels of floors. Understanding the accuracy of these prediction methods can be an important aspect of designing or refining a proposed flooring system. This paper provides a brief outline of some available prediction methods for massive (typically concrete) floors and light weight floor constructions. Consideration is given to what tolerances are suitable for evaluating prediction accuracy, with reference made to variation in laboratory measurements of impact sound pressure level (measurement reproducibility). Prediction results are presented for a number of different constructions to demonstrate the extent of agreement between prediction methods and laboratory results. Both massive and light weight flooring systems are considered, with various arrangements of floor covers and ceilings.

Keywords: Impact, Repeatability, 51.5

1. INTRODUCTION

Predicting the sound reduction of a floor/ceiling involves evaluating a difference in sound pressure levels between the source and receiver room. Any uncertainty in the source characteristics will be cancelled out by taking the difference. In contrast, predicting impact sound pressure levels (ISPLs) involves evaluating absolute sound pressure levels. Therefore any variation in the characteristics of the source, which is typically a point force from a standardised tapping machine, may cause additional variation between predicted and measured levels. A handful of well established methods for predicting ISPLs to engineering accuracy are briefly outlined here. To gauge the reliability of these methods, comparisons are made between predictions and laboratory measurements of ISPL. To provide context to these comparisons, consideration is given to indicative uncertainty tolerances for laboratory ISPL measurements.

2. Prediction models

2.1 Force functions

The basis for prediction models for ISPLs is point force excitation of bending waves in a thin plate. Where forces on a floor are provided by a tapping machine, it suffices to consider the impact of one of the five hammers initially and to correct the resulting model for the number of hammers.

2.1.1 Massive floors

For massive floors such as concrete, which have considerable driving point vibration impedance, the impact from a tapping machine hammer can be considered purely elastic (1). The velocity of the hammer onto the plate at impact equals the velocity of the hammer off the plate after impact. The periodic impact force of the hammer can be described by a Fourier Series (2). The frequency components of the series can be described as in Equation 1 (2):

$$F_n = \frac{2}{T}\int_0^T f(t)\cos(2\pi nt/T)dt \approx \frac{2}{T}\int_0^T f(t)dt = \frac{2}{T}\int_0^T m.(dv/dt)dt = \frac{2m}{T}\sqrt{2gh} \qquad (1)$$

[1] dgriffin@marshallday.com.au

Here T (s) is the time between impacts, m (kg) is the mass of the hammer, v (m/s) is the hammer velocity, h (m) is the fall height and g (m/s^2) is acceleration due to gravity.

2.1.2 Lightweight floors

For lightweight floors such as plywood, orientated strand board or chipboard membranes on floor joists the impact from a tapping machine hammer is typically not purely elastic. The character of the surface of the plate local to the point of impact (contact stiffness) (3) as well as the plate's driving point vibration impedance can influence the magnitude of the force applied by the tapping hammer. Brunskog & Hammer (4) provide an expression for a force function which includes resistance and damping components to account for the contact stiffness and driving point impedance of the plate. The frequency components of the force function[2] are detailed in Equation 2:

$$F_n = \frac{vKm\left(1+e^{-t_{cut}(i\omega+k/2R)}\right)}{k-\omega m+i\omega Km/R} \quad (2)$$

This equation relates to a rebounding hammer (rather than a hammer that sticks to the floor), where K is the contact stiffness, R is the plate impedance, ω is the angular frequency and t_{cut} is proportional to K/m.

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, 3). 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 (5) as:

$$\langle v^2 \rangle = \left. \langle F^2 Y \rangle \middle/ \omega\eta\rho_s S \right. \quad (3)$$

Where Y is the driving point admittance of the floor (the reciprocal of the driving point impedance) η is the loss factor, ρ_s (kg/m^2) is the surface density of the plate 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:

$$\text{Radiated sound power } = < \mathrm{v}^2 > \rho_0 c_0 S\sigma \quad (4)$$

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 Floor covers

The reduction of ISPLs through the use of floor covers such as carpet, vinyl, tiles and underlay or floating floors can be modelled as an adjustment of the force function. The floor covers are generally considered as a mass-spring system acting between the tapping hammer and floor plate, with the properties of the spring and the mass determined from the cover's thickness, density, stiffness (Youngs Modulus) and damping. Ver (2) details several models for the effect of floor covers which, theoretically, result in reducing ISPLs by between 30-40dB per decade above the natural or resonant frequency of the cover. Alternatively, the reduction of ISPLs can be quantified directly from appropriate laboratory measurements, such as according to AS ISO 140-6:2006 (6). Most often, these measurements relate to massive floors only.

2.4 Ceilings

Work by Sharp (7) may be used to describe the effects of a ceiling beneath a vibrating (floor) 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 floor plate due to a ceiling without structural connections:

[2] For the case of 'Under Critical' oscillation, where the hammer rebounds off the plate after impact

$$\text{Radiated sound power (Airborne)} = \begin{cases} \text{Radiation sound power (floor)} - \Delta TL_M & f < f_0 \\ \text{Radiation sound power (floor)} - \Delta TL_{m2} - 20\log(fd) + 29 & f_0 < f < f_1 \\ \text{Radiation sound power (floor)} - \Delta TL_{m2} - 6 & f > f_1 \end{cases} \quad (4)$$

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 floor plate 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 (7) is as follows:

$$m = {2m_1 m_2}\big/{(m_1 + m_2)} \quad (5)$$

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 floor plate only, TL_{m1} and the combined mass law transmission loss TL_M of the floor plate 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 (5) is:

$$W_{Ceilingtsructure} = {2\rho_0 c_0 n l \lambda \left\langle v_{connection}{}^2 \right\rangle}\big/{\pi} \quad (6)$$

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 (7) provides an expression for this vibration velocity as a function of the vibration velocity of the floor plate (at the line connection) and the relative impedance of the floor joists as seen by the floor plate and ceiling:

$$v_{connection} = {Z_1 + Z_2}\big/{Z_1} \quad (7)$$

2.5 Additional considerations

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

- Empirical adjustment of the force function for light weight floors at high frequencies. Though limited in application, adjustments can correct for observed differences between measurements and available prediction models, which can regularly over-estimate measurements results.(8)
- Adjustment of the driving point impedance of light weight floors in the low frequency region to account for the impedance of the floor joists (9)
- Adjustment of the driving point impedance of light weight floors to account for potentially significant modal response of floor plates corresponding to the first few fundamental modes of the floor plate, including the section of the plate between floor joists

3. Prediction tolerances

A reasonable objective for ISPL prediction methods is to replicate laboratory ISPL measurements of floor ceiling systems, for example, according to AS ISO 140-6:2006. 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 predictions.

Guidance on determining the uncertainty of laboratory measurements is provided in ISO 140-2:1991 (10) and, more recently, ISO 12999:2014 (11). Both documents provide indicative one-third octave band uncertainty data for ISPL measurements as either: reproducibility; in-situ deviation, or; repeatability. These different conditions are described in Table 1.

Table 1 – Uncertainty conditions

Condition	ISO 12999-1:2014 definition
Repeatability	Condition of measurement that includes the same measurement procedure, same operators, same measuring system, same location…
In-situ	Condition of measurement that includes the same location and replicate measurements on the same object by different operators using different measuring systems
Reproducibility	Condition of measurement that includes different locations, operators, measuring systems…

Both standards (10, 11) acknowledge that the availability of data for quantifying typical levels of reproducibility for ISPL measurements is limited. Warnock & Birta (12) compare the ‘tentative’ reproducibility values in Table A.2 of ISO 140-2:1991 with their rebuild repeatability values where “*the same floor was constructed and tested eight times in the laboratory over a period of about 1 year using new materials each time*.” The Warnock & Birta study notes:

> *As expected, the rebuild repeatability is greater than the re-test repeatability. It is surprising, however, to note that the reproducibility given for the ISO tapping machine test in ISO140-2 is smaller at some frequencies than the rebuild r. The reason for this becomes clear on reading the footnote in ISO 140-2 that says 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.*

ISO 12999-1:2014 does not provide any typical reproducibility uncertainty values[3].

Figure 1 shows the range of uncertainty values provided by the two standards along with retest and rebuild repeatabilities from Warnock & Brita. The figure also presents a re-install repeatability from Warnock & Brita, determined using a 150 mm thick concrete slab which was re-installed to the same test chamber six times and re-measured. Warnock & Brita’s results suggest that the data provided in the standards is perhaps an optimistic account of the measurement uncertainty that may occur in practice.

[3] Referred to in that standard as ‘Situation A’.

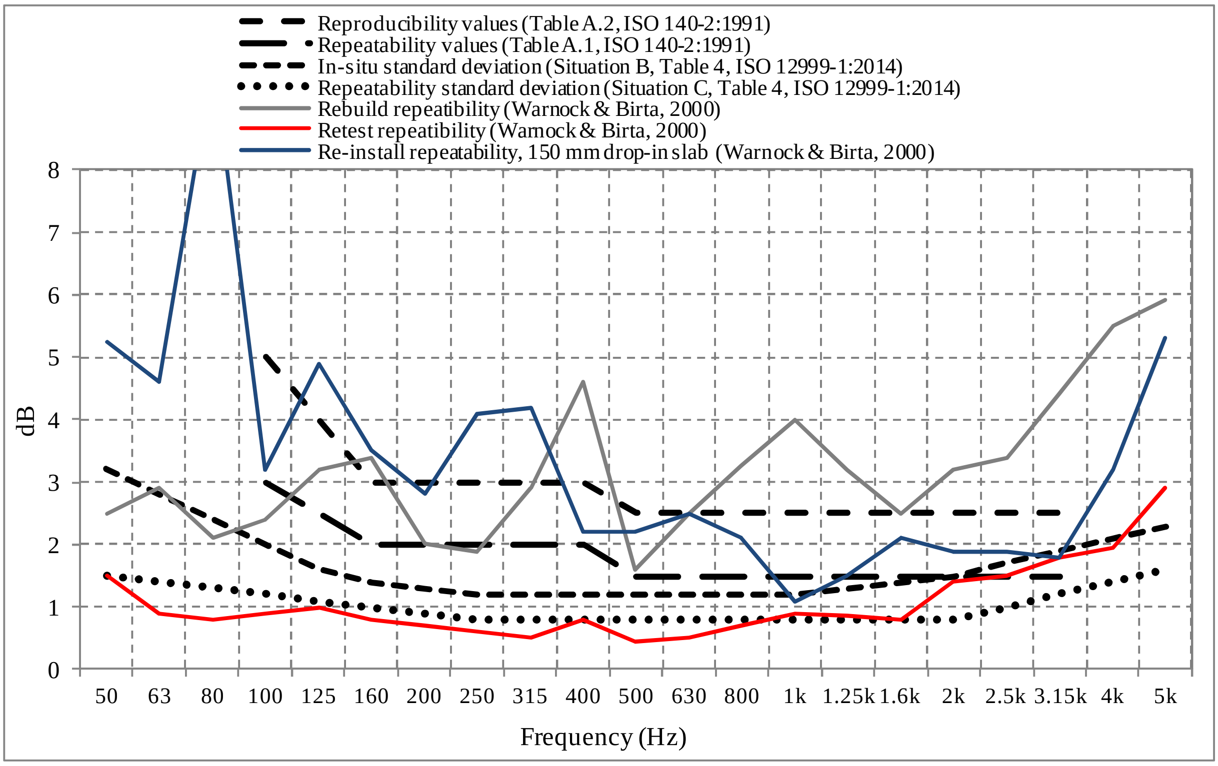

Figure 1 – Examples of uncertainty for impact insulation measurements

4. Comparison of predictions and measurements

Comparisons are provided between laboratory ISPL measurements and predictions based broadly on the models outlines above. Unless otherwise noted, measured data has been drawn from National Research Council Canada (NRC) test reports (12, 13).

4.1 Floors

Measured ISPL data for a nominally 150mm thick concrete floor slab across 10 different laboratories is presented in Figure 1 along with the predicted levels. The spread in laboratory data, as shown by the thin solid and dashed lines on the figure, is considerable. Given this spread, the predicted ISPLs are fairly robust.

Figure 2 below compares measured and predicted levels for a light weight floor on joists.

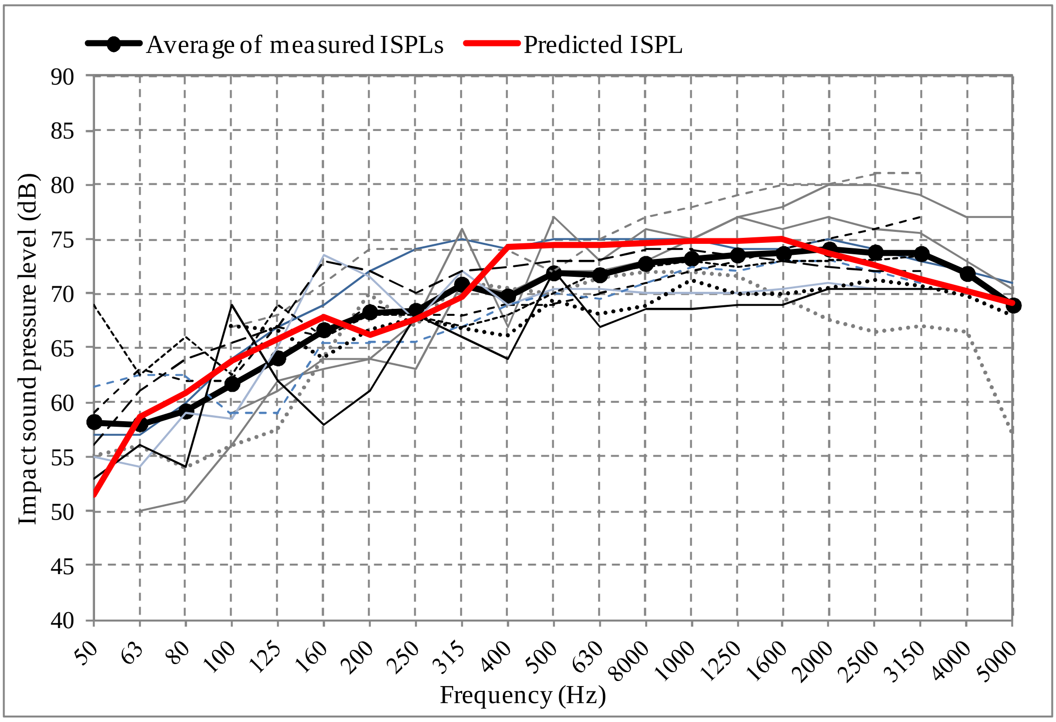

Figure 1 – Comparison of predicted ISPL for a 150 mm concrete floor with measurements from a variety of laboratories.

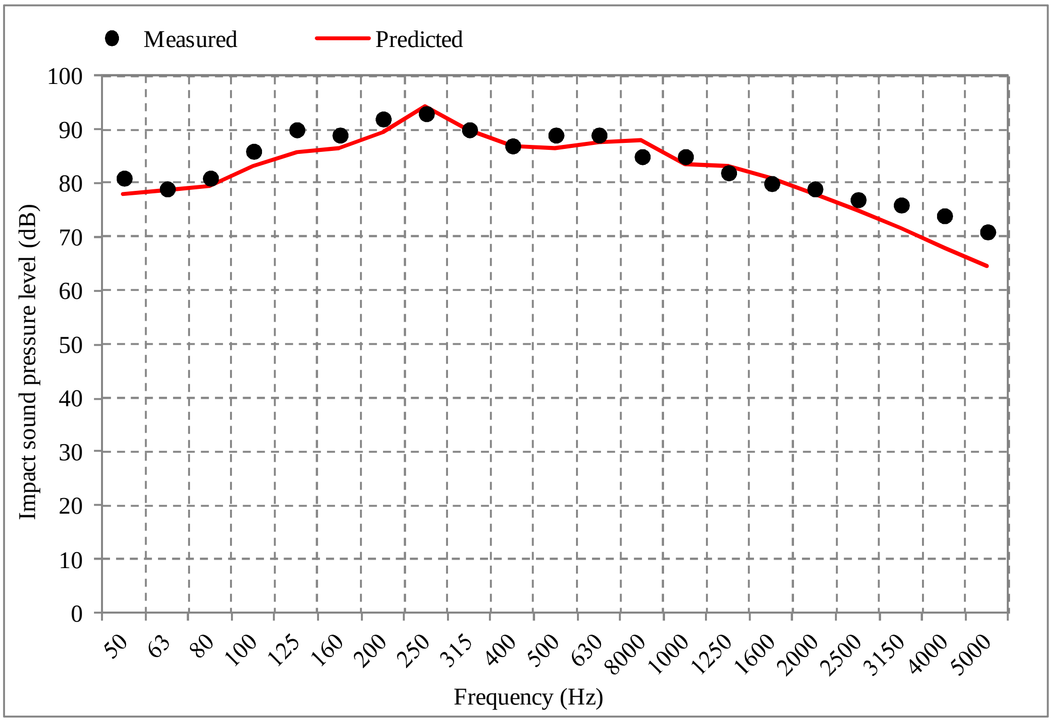

Figure 2 – Comparison of predicted and measured ISPLs for a light weight floor system comprising 2 layers of 13mm Plywood (NRC test ref IIF-96-066)

4.2 Floors with ceilings and covers

Figure 3 shows an example of a lightweight floor with a ceiling mounted on resilient channels and a cavity without any sound absorptive infill. Figure 4 shows an example of a lightweight floor with a ceiling mounted on resilient channels including some sound absorptive infill in the cavity. The two scenarios presented in Figure 4 are with and without a carpet floor cover. The predicted ISPL for the system with a floor cover accounts for the effect of the carpet from measured reductions in ISPL.

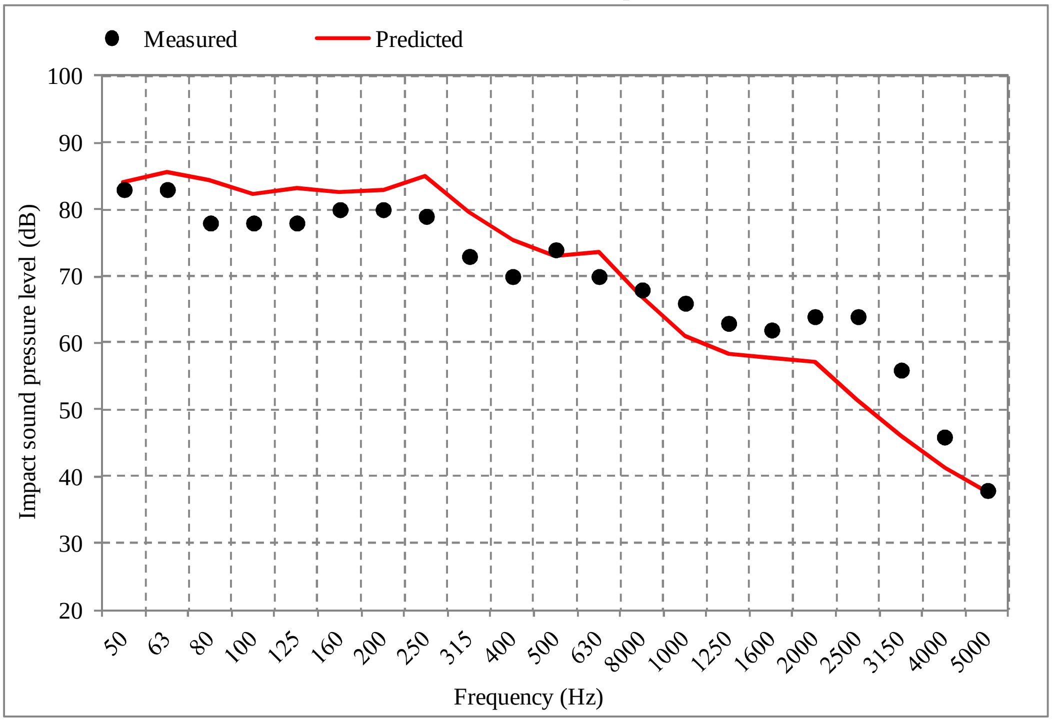

Figure 3 – Comparison of predicted and measured ISPLs for a light weight floor system with a ceiling (NRC test ref IIF-96-019)

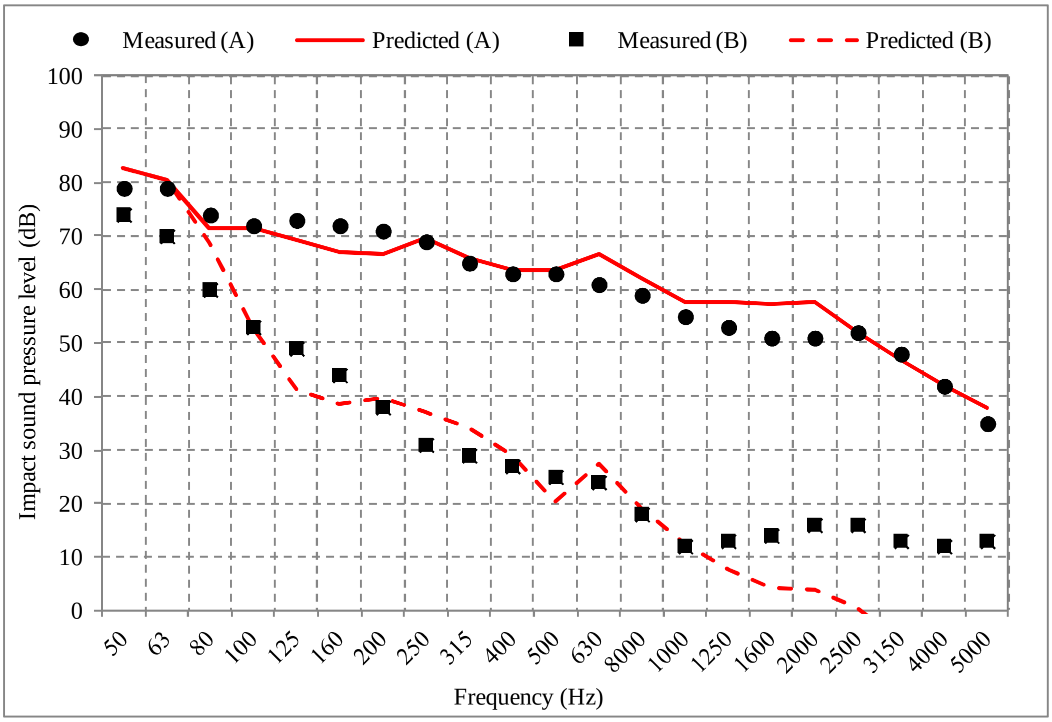

Figure 4 – Comparison of predicted and measured ISPLs for a light weight floor system with a ceiling and with/without a carpet floor cover (NRC test ref (A) 'Mean ref' test (B) IIF-96-016)

Figure 5 shows predicted ISPLs for a thicker lightweight floor with a ceiling. The floor plate comprises 35 mm concrete + 15 mm orientated strand board. ISPL predictions for thick light weight panels tend to be less reliable than for thinner lightweight panels. Significant discrepancies between measured and predicted data can occur, particularly at higher frequencies.

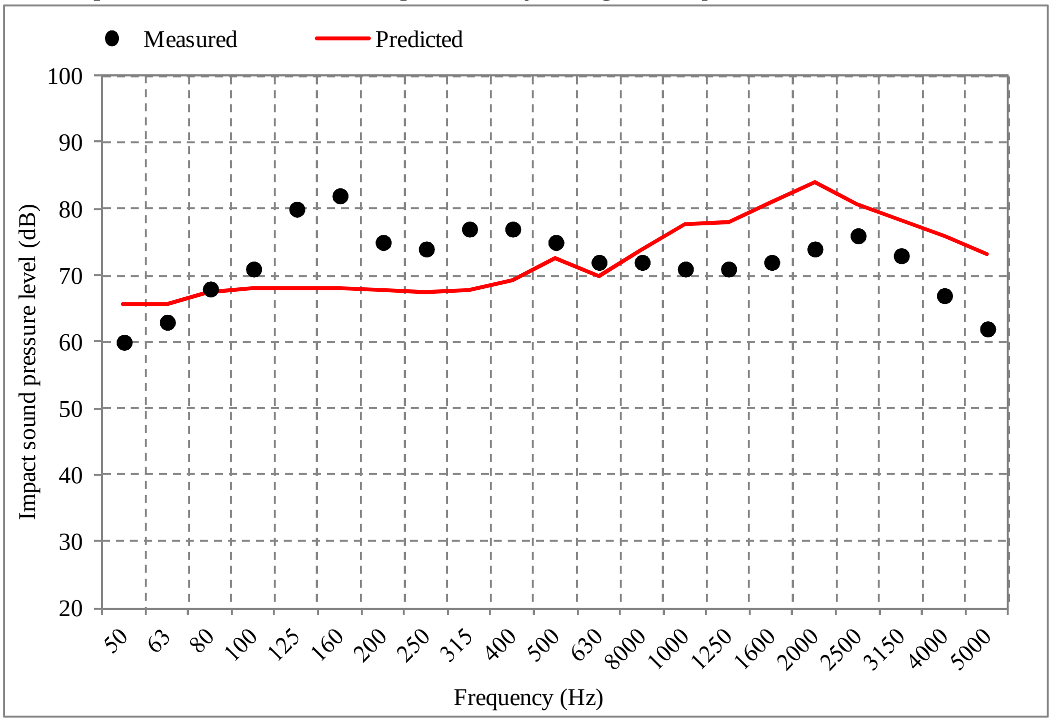

Figure 5 – Comparison of predicted and measured ISPLs for a comparatively thick light weight floor system with a ceiling (NRC test ref IIF-96-056)

4.3 Overall accuracy

The agreement shown in the figures above is generally good. However, such a limited set of comparisons does not provide a robust overview of general accuracy.

To quantify the accuracy over a wide range of constructions a large number of comparisons have been made between theory and measurements. Over 200 different floor constructions have been modelled spanning a range of different floor plates and ceiling configurations. The majority of measured data has been obtained from National Research Council (NRC) documents (12, 13). Predictions were made for each construction using published construction descriptions and material properties.

Figure 6 presents a summary of comparisons for constructions without ceilings (floor plates only). The figure shows the average difference between predicted and measured ISPLs both for 1/3 octave band centre frequencies and also the overall IIC/$L_{n,w}$ values. The error bars shown for the average differences represent one standard deviation.

The ISO 140-2:1991 tentative reproducibility values are also shown on the figure. It is important to recognise that these values, which effectively represent a 95% confidence interval, are not strictly comparable with the error bars of the average differences (which show one standard deviation). However, the significant variation between the ISO documented indicators of uncertainty and the results from Warnock & Brita, as shown in Figure 1 above, suggest that the ISO values are onerous as a 95% confidence interval. In the absence of any apparent alternative, the ISO values have been included in Figure 6 as a 'rule of thumb' reference only, to provide context to the range of average differences between predictions and measurements. In these figures, any consideration of the ISO values as confidence intervals should be avoided.

Figure 7 presents a similar summary of comparisons for the entire set of relevant floor constructions reviewed, including those with ceilings of various configurations.

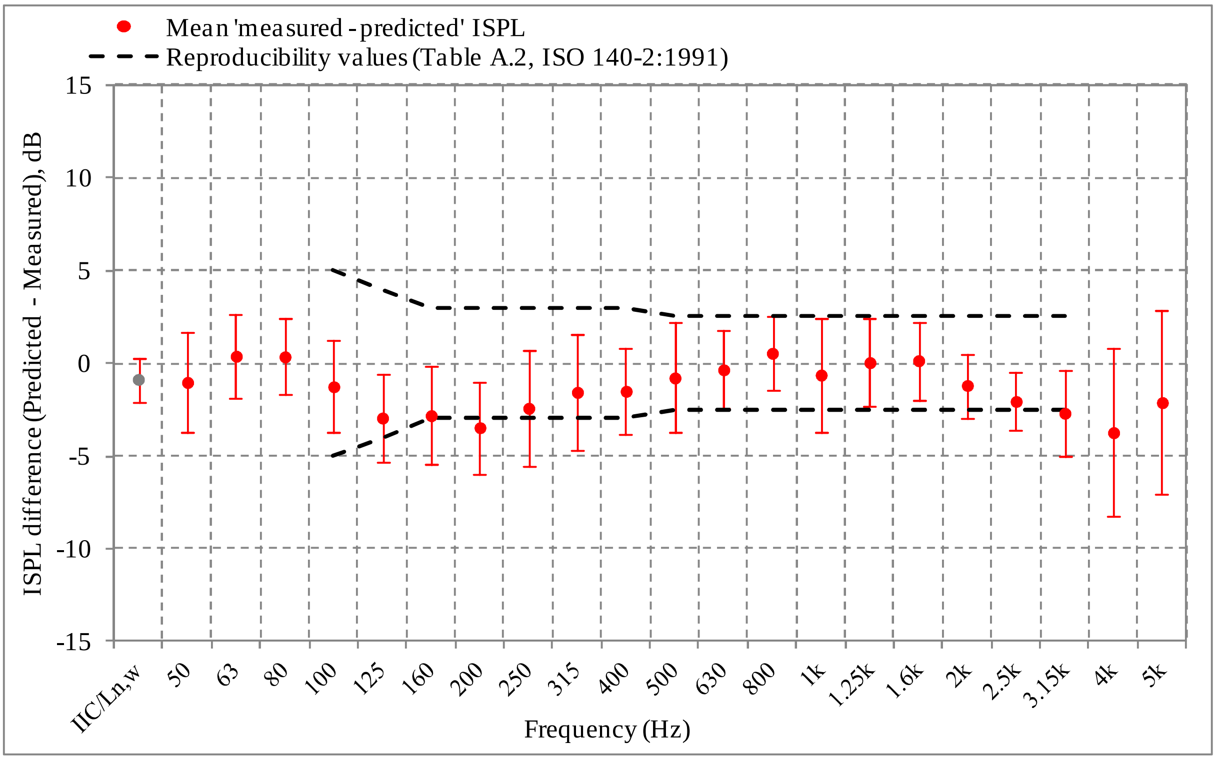

Figure 6 – Mean 'measured – predicted' ISPL for 16 floor plates from (12, 13) ± one standard deviation

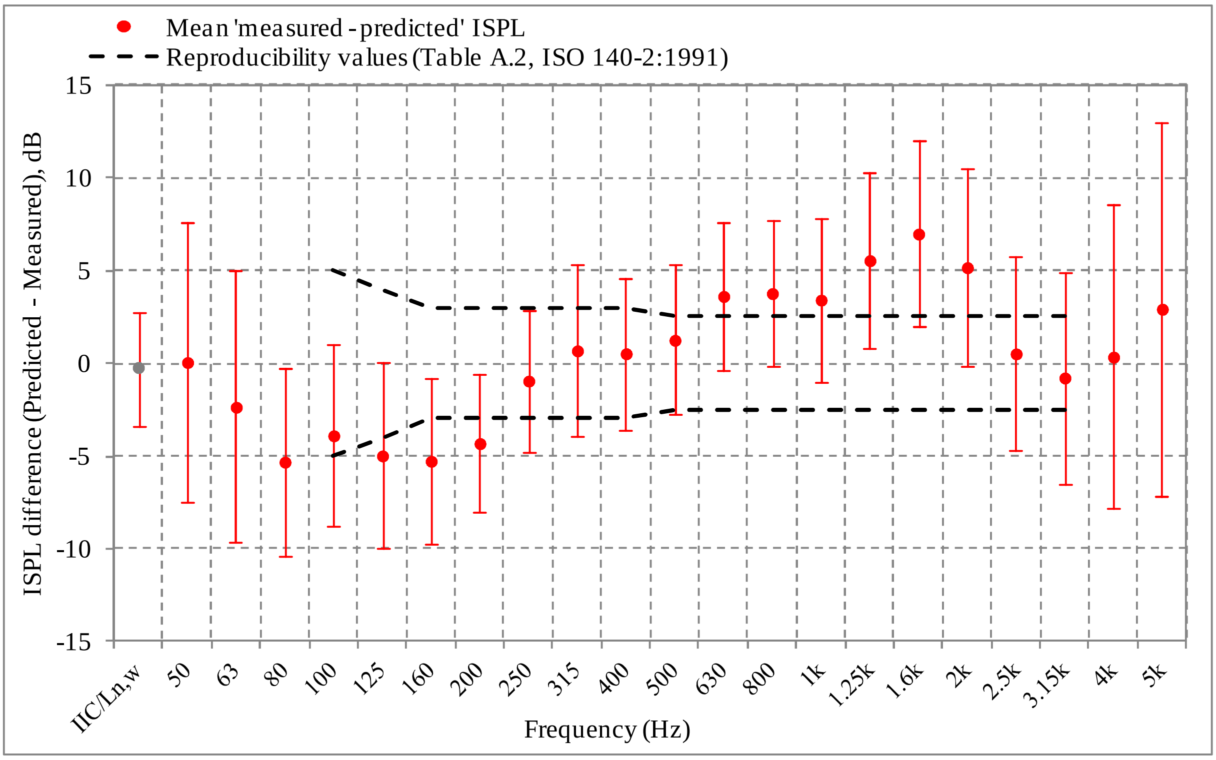

Figure 7 – Mean 'measured – predicted' ISPL for 164 floor constructions from (12, 13) ± one standard deviation

The mean difference in IIC/L_{nw} between measurement and theory is less than 0.5 dB with 80% of results found to lie within ± 4 dB. In this sense, the agreement is reasonable and is of a similar order of magnitude to the rates of variability of measured results documented by Warnock & Brita. However, the results for a specific set of measurement data can occasionally vary significantly form predicted levels, particularly for thick, light weight floor plates. Additionally, the variation in individual 1/3 octave bands is much more significant that the overall, weighted index. On average, the 1/3 octave band predicted ISPLs are lower than measured values at low frequencies and higher than measured ISPLs at high frequencies. It can also be observed that the deviations (shown by the error bars) from mean 1/3 octave band values are comparatively less at mid frequencies and increase at the extremes of the assessment range, below 100Hz and above 3000Hz. These results indicate that the prediction models are reasonably robust at mid-frequencies but would benefit from improvement at both the upper and lower extremities of the assessed frequency range.

ACKNOWLEDGEMENTS

Keith Ballagh’s advice and assistance reviewing this paper is gratefully acknowledged.

REFERENCES

1. Vigran, T.E. Building Acoustics, Talyor & Francis, Oxon, 2008
2 Ver, I.L., Impact noise isolation of composite floors, J Acoust Soc Am, 1971, 50(4): 1043-1050.
3 Hopkins, C. Sound insulation, Butterworth-Heinemann, Oxford, 2007.
4 Brunskog, J, & Hammer, P. The interaction between the ISO tapping machine and light weight floors, Acta Acustica United with Acustica, 2003, 89:296-308.
5 Cremer, L., Heckl, M., Petersson, B.A.T., Structure-borne sound: Structural vibrations and sound radiation at audio frequencies, Springer, Berlin, 2005
6 Standards Australia, Australia Standard AS ISO 140-6 Acoustics - Measurement of sound insulation in building and of building elements: Part 6: Laboratory measurements of impact sound insulation of floors, Sydney, Australia 2006.
7 Sharp, B.H., Prediction methods for the sound transmission of building elements, Noise Control Engineering, 1978, **11**, 53-63
8 Rabold, A., Buchschmid, A.D., Muller, G. & Rank, E. Modelling the excitation force of a standard tapping machine on lightweight floor structures, Building Acoustics, 2010 17(3), 175-197.
9 Mayr, A., Gibbs, B. & Fischer, H., Spatial variation of the point mobility of a timber joist floor, Proc DAGA2008, 10-13 March 2008, Dresden, 2008
10 International Organisation for Standardization, International Standard 140-2 Determination, verification and application of precision data, Geneva, Switzerland, 1991
11 International Organisation for Standardization, International Standard ISO 12999 Acoustics - Determination and application of measurement uncertainty in building acoustics Part 1: Sound insulation, Geneva, Switzerland, 2014
12 Warnock, A.C.C. & Brita, J.A., Detailed report for consortium on fire resistance and sound insulation of floors: Sound transmission and impact insulation data in 1/3 octave bands (IRC Internal Report IR-811), National Research Council Canada, Ottawa, Canada, July 2000.
13 Warnock, A.C.C., Summary report for consortium on fire resistance and sound insulation of floors: Sound transmission and impact insulation data (IRC IRR-169), National Research Council Canada, Ottawa, Canada, January 2005.